Net-zero Flexible Power Project Review Meeting - Summary and Key Findings

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2024 FECM / NETL Carbon Management Research Project Review Meeting

August 7th, 2024

U.S. DEPARTMENT OF ENERGY

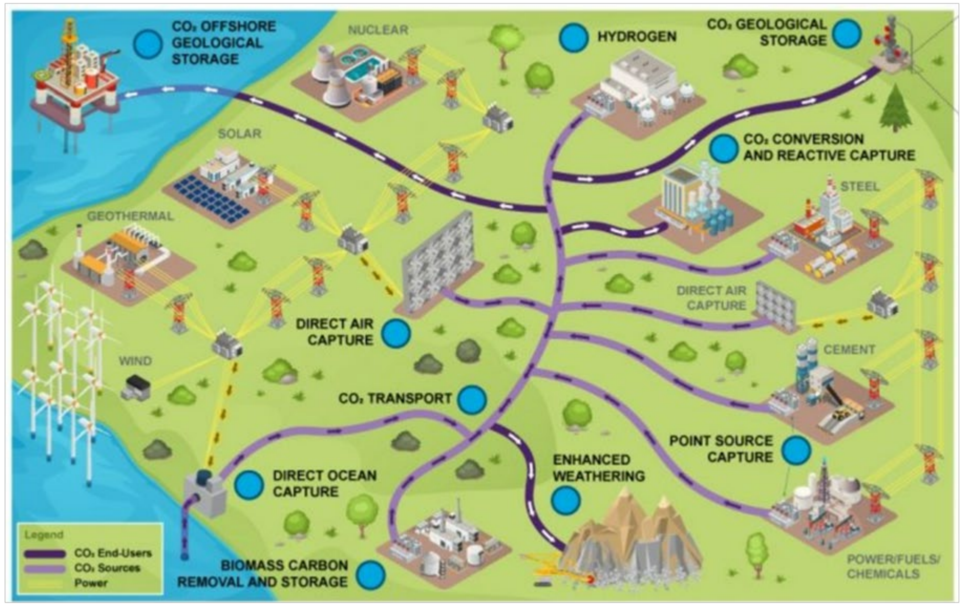
Fossil Energy and Carbon Management

PSC Strategic Vision

Support demonstration of first-of-a-kind carbon capture on power and industrial sectors coupled to dedicated and reliable carbon storage, that will lead to commercially viable carbon hub opportunities for widescale deployment and facilitate a carbon-free economy by 2050, emphasizing robust analysis of life cycle impacts, and understanding air/water quality impacts.

Secure Carbon Storage

Carbon Dioxide Removal & Low C Electricity and Heat



Low C Industry & Flexible Power + PSC

CO_2 Conversion into durable Products

Focus Area 1: Support Power Retrofit Demos

- Enabling technologies

Focus Area 2: Net Zero, Flex Power

- Technology development to support flexible CCS with high capture efficiency
- FEEDs to seed the formation of Carbon Hubs.

Focus Area 3: Support Industrial Retrofit Demos

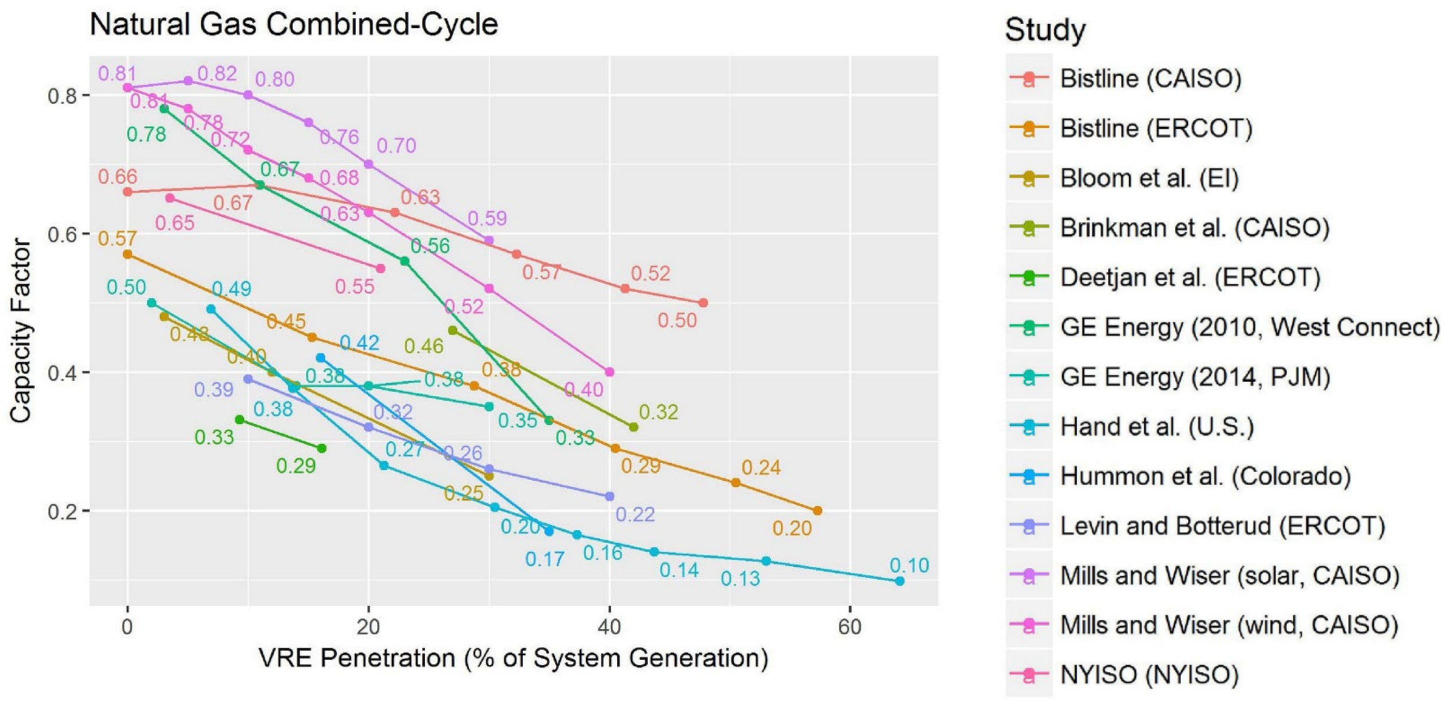
- Enabling technologies

Focus Area 4: Integrated decarbonized industrial + CCS

- Technology development for integrated decarbonized industrial processes coupled with transformational CCS
- FEEDs to seed the formation of Carbon Hubs.

Motivation: CCS in future electricity systems

As the penetration of intermittent renewables in the grid increases, the **capacity factor of NGCC will decrease** and **frequency of start-up and shut-down events of power plants with CCS will increase**



Flexible CCS needed: *the existing paradigm that CCS is a technology intended for steady state operation is being challenged for both electric generation and industrial applications*

Mills et al. *Impacts of variable renewable energy on wholesale markets and generating assets in the United States.* Renewable and Sustainable Energy Reviews 120 (2020)

Motivation: CCS in future electricity systems

Need to achieve **high integrated CO_2 capture rates to achieve net-zero targets**

- Distinguish between the instantaneous Degree of Capture (DoC) and the Integrated Degree of Capture (IDoC)

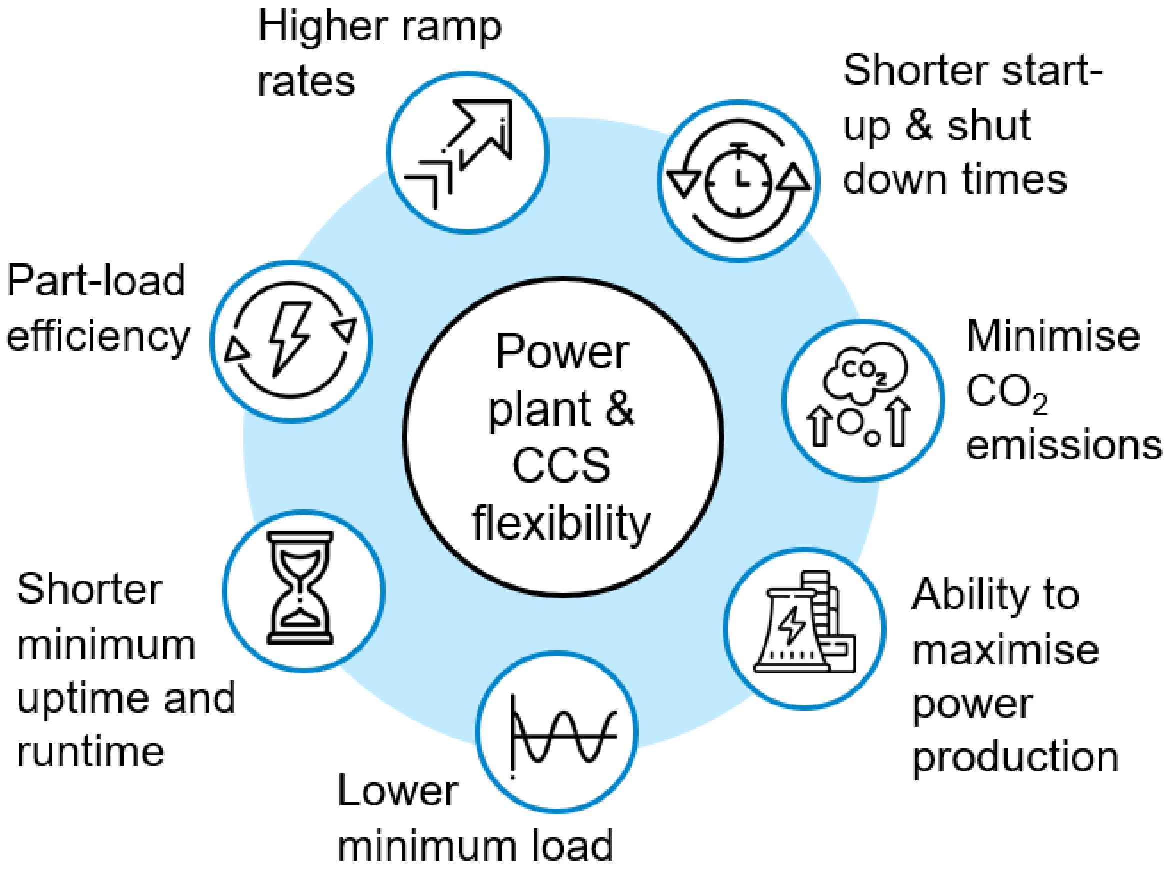
$$DoC = 100.\left(\frac{CO_2^{Generated} - CO_2^{Emitted}}{CO_2^{Generated}}\right) \qquad IDoC = \int_{t_0}^{t_f} DoC\,dt$$

Degree of Capture $_{\text{Duty Cycle}}$ = f (Capture Rate$_{\text{steady state}}$, Flexibility)

Challenge of Net-Zero Flexible Power: Flexible CCS with High Integrated CO_2 Capture Rates

Mac Dowell et al. *Optimization of post-combustion CO_2 capture for flexible operation.* Energy Procedia (2014)

Net-Zero Flexible Power



Challenge of Net-Zero Flexible Power: Flexible CCS with High Integrated CO_2 Capture Rates

How to achieve CO_2 high capture rates?

Capture Technology	90% CO_2 Capture	99% CO_2 Capture	Comments
Chemical absorption	+	+	
Physical absorption	+	+	
Solid sorbent – chemical	+	+	
Solid sorbents – physical	+	+/-	Trade off with CO_2 purity Process design optimization
Chemical looping	+	+	
Polymeric membranes*	+	-	Trade-off with CO_2 purity High compression/low vacuum needed
Metal membranes (H_2)	+	+	
Refrigeration	+	+/-	Higher capture rates achievable with CO_2-solid formation; purity issues with liquid formation

(+) achievable, (-) not achievable
*technically achievable with higher selectivity

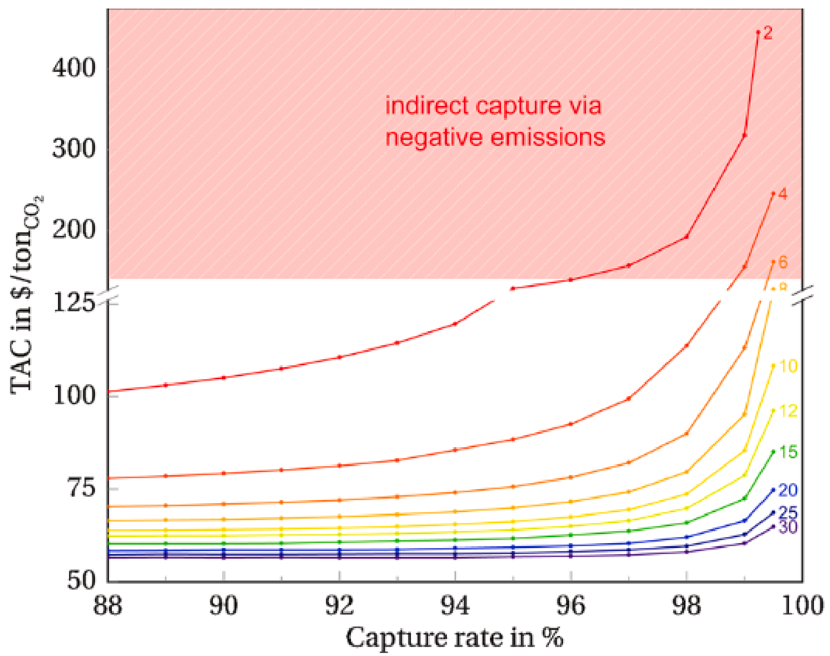
Adapted from IEAGHG (2019)

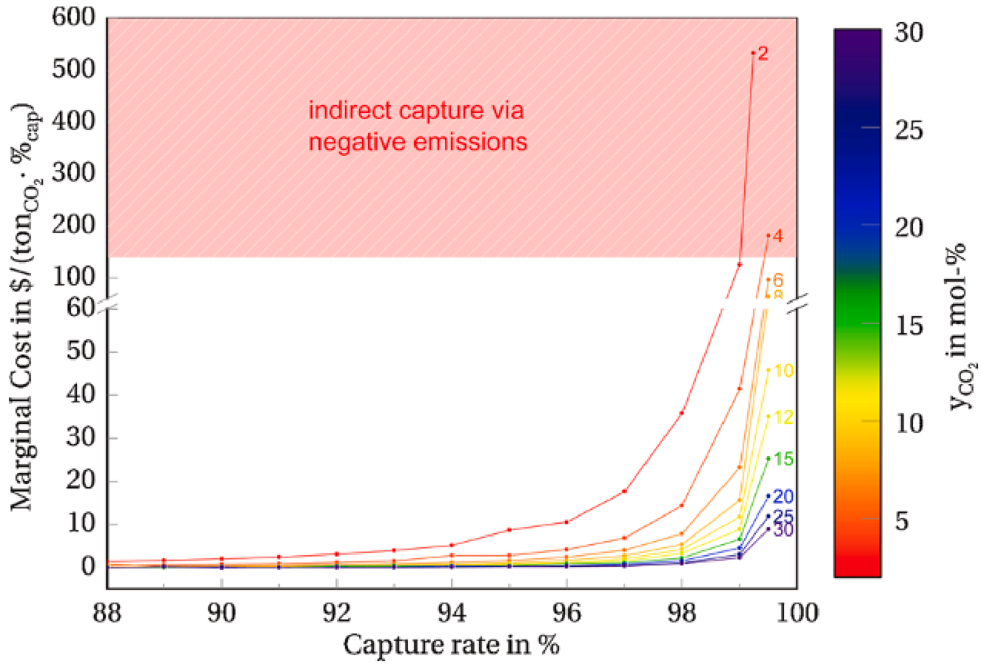
IEAGHG. *Towards zero emissions CCS in power plants using high capture rates or biomass* (2019)

At what cost?

- Capture rates above 95% technically feasible for capture from power and industrial sources of CO_2 (solvent PCC)
- The economical feasibility at high capture rates varies by technology and CO_2 concentration. Marginal cost of capture can be used to evaluate technology cost competitiveness relative to CDR

Data for Capture Cost 30 wt. % MEA





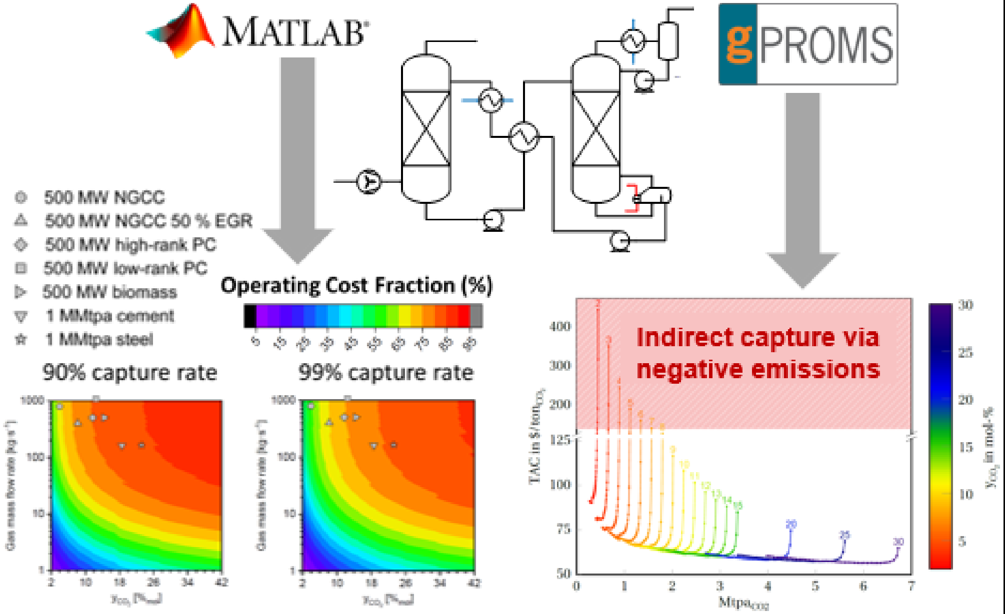
Brandl et al. *Beyond 90% capture: Possible, but at what cost?* International Journal of Greenhouse Gas Control 105 (2021)

Demonstrating Net-Zero Flexible Power

Process modelling

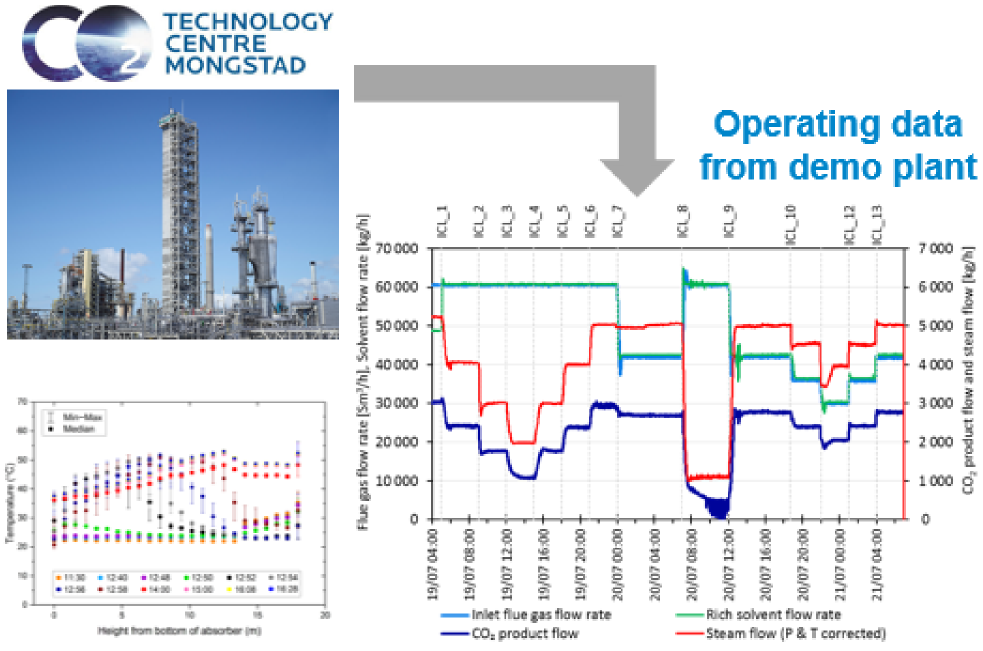
Develop understanding of the impacts on cost and technical performance

Process modelling in gPROMS and MATLAB



Demonstration

Demonstrates feasibility and develop understanding of plant operation



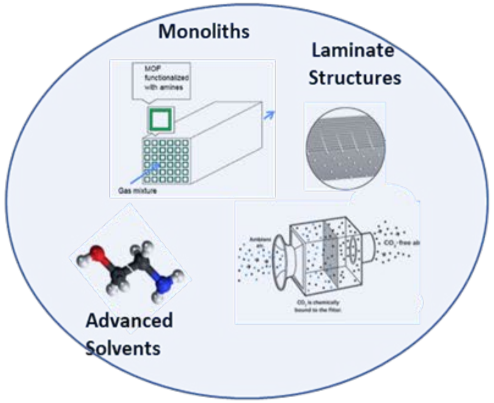
Adapted from Mai Bui, U.S. DOE Net-zero Flexible Power: High Capture Rate Project Review Meeting, 6th June 2024

Brandl et al. *Beyond 90% capture: Possible, but at what cost?* International Journal of Greenhouse Gas Control (2021)
Bui et al. Demonstrating flexible operation of the Technology Centre Mongstad CO_2 capture plant. International Journal of Greenhouse Gas Control (2020)
IEAGHG. *Start-Up and Shutdown Protocol for Natural Gas-Fired Power Station with CO_2 Capture* (2022)

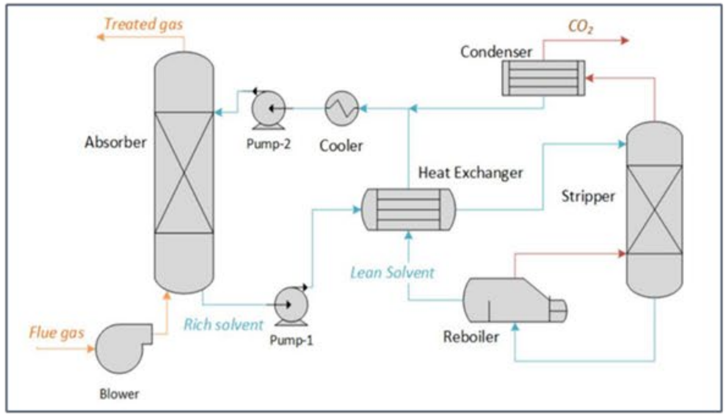
FECM Projects High CO_2 Capture Rates

AOI 1: *Bench-Scale Testing of Highly-Efficient Components and Processes for NGCC Plants*

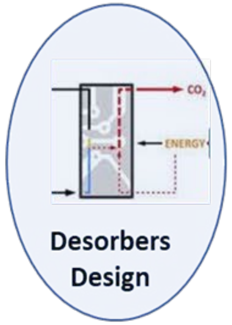
AOI1a: Components: Simulated Exhaust / Bench Scale, Batch Testing
AOI1b: Integrated Process: Simulated or Real Exhaust / Bench Scale, Continuous Testing



Components (AOI1a)



Integrated Process (AOI1b)



Components (AOI1a)

Inputs

Carbon Capture Materials (TRL 2)* or Components/ Processes (TRL 3)**

- Material Systems Advanced Solvents (no aq. Amines)
- Hybrid/novel processes**
- No membranes

Research Objectives (Targets)

- Improve stability for hydrothermal & oxidative degradation
- Increase vol. productivity (300 mol CO_2/l h)
- Reduce pressure drop (<150 Pa)
- Lower Heat Duty (<2 GJ/ton)

Success Criteria

- 95+% Carbon capture efficiency
- 1 month steady-state operation**
- Progress towards 20% reduction in cost
- TRL 3*, TRL 4**
- Cost = f (% capture efficiency)
- Pathways to Net zero C

* AOI1a
** AOI 1b

FECM Projects High CO_2 Capture Rates

Prime	Sub-recipients	Material	Innovation to achieve 95%
GE	TDA Research, Inc., University of California Berkeley, and University of South Alabama	TEPA, Covalent organic framework (COF)	Plastic, tri-furcated structure, rotating contactor with indirect heating
SRI International	OLI Systems Inc.; Trimeric Corporation; Baker Hughes	Ammonia Mixed Salt Process (MSP)	Ultra-lean regenerator coupled with 2-absorber system to achieve 95% capture efficiency & produce almost dry, pressurized CO2.
UK University of Kentucky	EPRI, Louisville Gas & Electric and Kentucky Utilities	Dual Solvent System: Water-lean amines (bulk removal) + KOH-based electrochemical system (polishing step)	Coupled water-lean solvent with KOH polishing step to achieve up to 99% capture efficiency
TDA Research	Membrane Technology Research, Schlumberger, Dr. Ashok Rao	Polymer laminates of functionalized mixed matrix polymer (MMP) sheets: TEPA, PMA, PES	Microwave assisted temperature swing adsorption (MTSA) & vacuum desorption
Cormetech Reliability. Delivered.	Global Thermostat, Middle River Power, Southern Company, Zero Carbon Partners	Extruded silica monolith with amine functionality (PEI)	Vacuum-free desorption, Multi-brick contactor design (~ SCR installations), with no inlet air dilution

FECM Projects High CO_2 Capture Rates

Prime	Sub-recipients	Carbon Capture Technology
GTI ENERGY solutions that transform	University of Buffalo	Nano-confined ionic liquid (NCIL) membrane combined with a dehydration membrane
Susteon	University of Wyoming	Amino acid/MDEA based solvent and ionic liquid catalyst (ILC)
UK UNIVERSITY OF KENTUCKY	Electric Power Research Institute	Novel carbon capture materials and absorber reactor components that contribute to increased CO_2 mass transfer through increased turbulent gas-liquid interface and improved solvent wetting
RTI INTERNATIONAL	Pacific Northwest National Lab Partner: Schlumberger	Next generation non-aqueous solvent technology (GEN2NAS) in smaller footprint capture plants with rotating packed bed absorbers

Addressing CCS Flexibility: ARPA-E FLECCS

ARPA-E FLExible Carbon Capture and Storage (FLECCS)

Jack Lewnard, Program Director
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Chris Vandervort, T2M Advisor
(Chris.Vandervort@hq.doe.gov

Phase 1: 2019-2022

- 18 months, $11.5MM, 12 technology teams
- Modeling studies and economics based on future dispatch scenarios
- Deliverables: PFD, H&M balance, equipment list, general arrangement, TEA

Phase 2: 2022-2025

- 36 months, $33MM, 5 technology teams
- Lab to large pilot demonstrations focused on carbon capture system

2024 ARPA-E FLECCS Phase 2 Annual Meeting –

Point Source Capture Breakout (Friday 8/9/24)

Net Zero-Flexible Power Meeting (June 2024)

Key Objectives

1. Review **FECM projects** targeting high CO_2 capture rates and ARPA-E FLECCS findings
2. Identify **promising approaches to achieve high capture rates** from point sources
3. Identify **challenges and R&D needs** to achieve high capture rates and flexible operation
4. Determine **economic trade-offs of achieving high capture rates**
5. Identify opportunities to **co-deploy PSC and DAC** to reach net-zero

Findings to inform future funding opportunity announcement

Participants

Technology Developers

MTR Carbon Capture, ION Clean Energy, Shell, RTI International, Carbon America, Aker Carbon Capture, Svante, The Ohio State University

Operator & Utilities

Calpine, PPL, National Carbon Capture Center, GE Vernova

Current FECM-funded Projects

ARPA-E (Changing What's Possible), U.S. Department of Energy Fossil Energy and Carbon Management, National Energy Technology Laboratory

+ Participants from academia, industry, government

Key Take-Aways: Technology Approaches for High Capture Rates and Flexible Operation

Solvent technologies

- 99%+ capture rate technically feasible
- Many developers report cost < 100 $/t CO_2 (TEA) even at high capture rates
- Anticipate possible challenges with emissions at high capture rates, additional engineering controls may be needed
- Greatest challenge is flexible operation

Other technologies (membrane, sorbents and cryogenic)

- Generally more flexible systems and can start/up shut down in minutes vs. hours
- Achieving > 95% operation challenging in some cases:
  - Membranes: hybrid options (membrane + sorbent) can boost capture rate
  - Sorbents: compromise with product purity, R&D needed

Economic Analysis at High Capture: Marginal Capture Cost

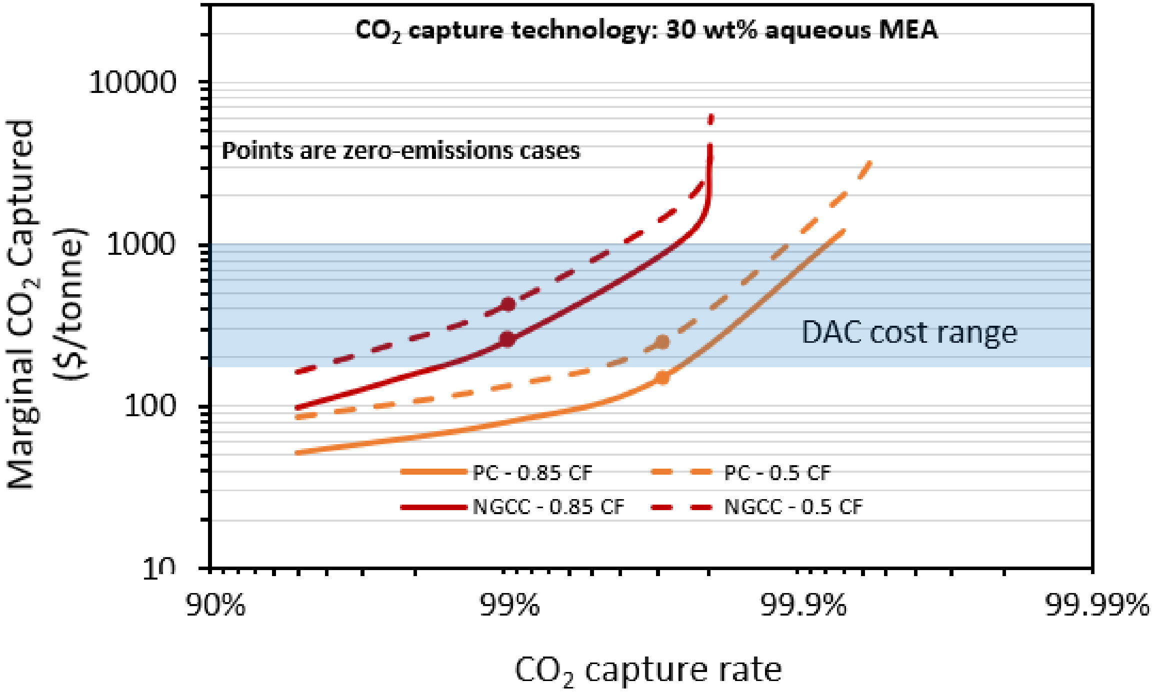
- Important to determine limiting level of CO_2 capture for CCS: at what point do we rely on DAC to achieve zero-emissions from power plants?

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

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

C = CO_2 capture cost

- When CF is low, it may be beneficial to couple CCS with DAC



How does marginal capture cost change for other capture technologies? Future TEA studies needed

Du et al. *Zero- and negative-emissions fossil-fired power plants using CO_2 capture by conventional aqueous amines*. Int J of GHG Control (2021)

Key Take-Aways: Materials and Processes

- *What CO_2 capture materials and/or processes are best suited to achieve high capture flexible operation?*
- *What are the costs associated with achieving net-zero flexible power for different CO_2 capture technologies?*

Key Points

- **Technology advancements needed for non-steady state operation**: how to control processes, manage degradation and emissions
- **Capture cost impacted by high capture/non-steady operation**: account for equipment overdesign, storage buffers…

RD&D Needs

1. **Standardized datasets start up/ shutdown operation** (cooling water and steam availability, temperature profiles, emissions…)
2. **Design capture technologies and process configurations** for non-steady state operations
3. **Techno-economic analyses** to understand implications of flexible operation

Key Take-Aways: Materials Degradation and Emissions

- *What is the impact of operational variability and high capture rates on degradation of capture materials and non-CO_2 emissions?*
- *What CO_2 capture materials and processes minimize non-CO_2 emissions under operational variability?*

Key Points

- **Operational fluctuations** (temperature, O_2 spikes, impurities) from flexible operation **impact materials degradation and emissions**
- High capture operation may increase **solvent degradation:** higher-solvent make-up and reclaiming

RD&D Needs

1. **Stress testing** of capture media
2. **Long term testing pilots at relevant conditions** to understand impact on emissions and solvent degradation
3. **Additional engineering controls and air dispersion modelling**

Key Take-Aways: Reliability of Flexible CCS

- *What are some upstream and downstream balance of plant issues that arise with flexible CCS operation?*
- *What are challenges in reliability of unit operations of capture processes?*
- *What are challenges in existing process controls and models when operating flexibly?*

Key Points

- **Challenges upstream:** heat extraction, cooling water (availability, temperature)
- **Challenges downstream:** pipelines and intermittent production of CO_2, CO_2 Specs
- Challenge to develop **dynamic process models** for flexible CCS operation

RD&D Needs

1. **Integrated process models on CO_2 capture, transport and storage**
2. **Dynamic process models for flexible capture operation**
3. **Stakeholder coordination** (power plant, pipeline owners, carbon capture technology providers)

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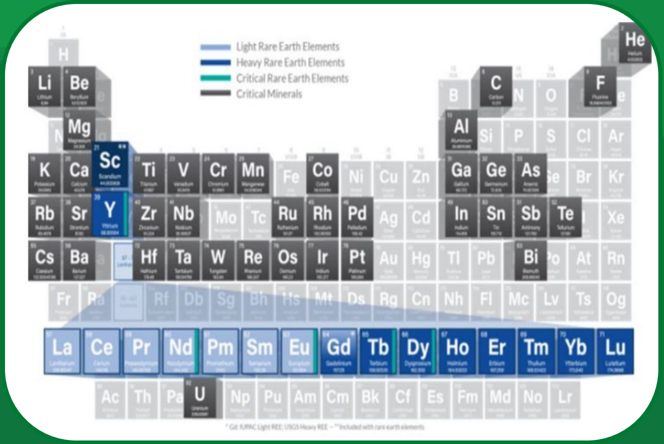
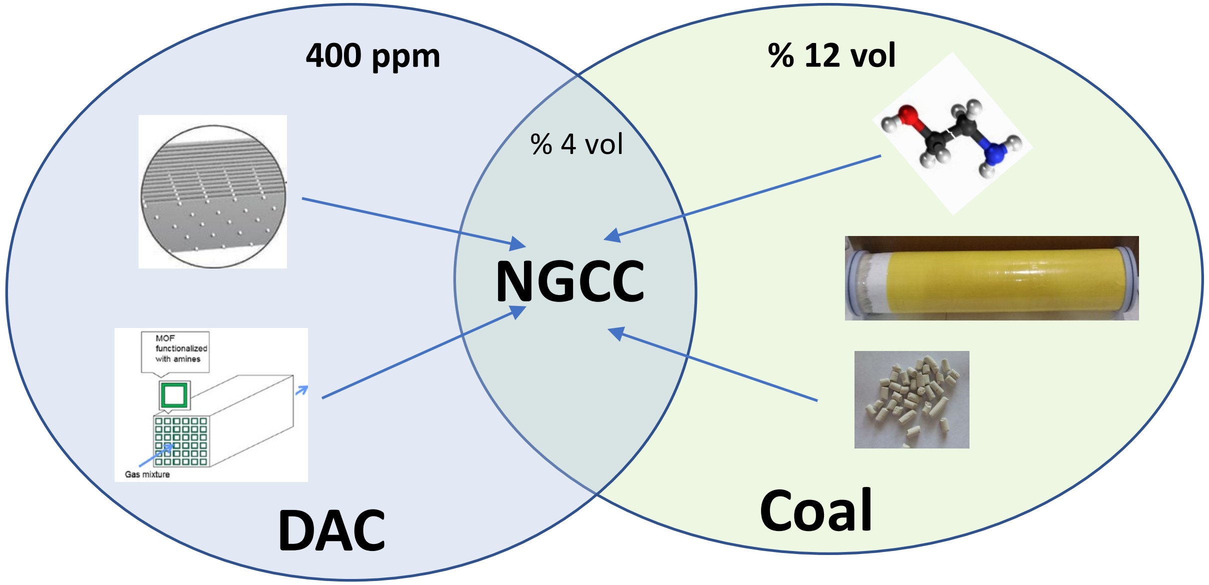
Questions?



95+% NGCC Solution.. Leverage both PSC & DAC developments?



Mismatch of Component Dynamics

Component	Cold start-full load	Warm start-full load	ramp rate	Operating range	Comments
Gas turbine/ steam turbine/ HRSG *	< 1 hr (GT) 2-3 hours (HRSG, ST)	0.5 – 2 hours	10%-15%/minute	20-100%	F, H Class
ID Fan(s)/ Damper(s)	?	?	?	?	Multiple fans?
Flue Gas Cooler	?	?	?	?	Gas/liquid distribution
Absorber	12-24 hours	2-10 hours	5%-50%/hr	50(?)-100%	24 hours for large CCS and NG amines
Regen	12-24 hours	?	?	50(?)-100%	ST impact? Offline regen?
CO_2 compressors	2+ hours	?	?	?	Need multiple units
CO_2 dehydration	?	?	?	?	Columns/flash
CO_2 pipeline	?	?	?	?	Supercritical CO_2

* https://www.epa.gov/system/files/documents/2023-05/TSD%20-%20Efficient%20Generation%20Combustion%20Turbine.pdf

System-level challenges (some may be beyond FLECCS)

- Operations
  - Mis-match in system dynamics
  - Maintaining CO_2 purity through transients (start-ups, load swings, shut-downs)
  - Managing power derate
  - Matching steam supply/demand through load cycle
  - Purge times

- Unknown dynamics for the “other” components
  - Fans/dampers/flue gas hydraulics, esp if multiple units
  - CO2 compressors/dehydration
  - Rapid flowrate changes may challenge CO_2 pipeline and downstream sequestration

- System Optimization for Load Following
  - Part load; short runs; offline for extended periods, esp. during shoulder months
  - Solvent storage?
  - Multiple trains to load follow?
  - Exhaust gas recycle?
  - Run at loss to maximize revenue?

Issues – CO_2 Pipelines

- Pipeline Contracts specify composition and “rateable” flow
  - Composition
    - Almost all US and global experience is with CO2 from sources without free oxygen. May contain H2S and NH3.
    - Flue gas will have O2. May contain SO2/HSO3, NO2, possibly HCl
    - Uncertainty in water phase diagram for supercritical CO2
    - Water drop-out/acid/O2 may cause pitting corrosion
  - Flow
    - Pipeline contracts usually require “rateable” or constant flow
    - Power plants and other sources may have variable flow, frequent stops/starts
    - Supercritical CO2 is incompressible. Flow/pressure fluctuations may cause problems
- CO_2 pipeline permitting uncertainty

Recommendations

- CO_2 specs are a system-level issue
  - At a minimum, start measuring and reporting key trace species (O2, SO2, NO2, HCl, H2O, other)

- Need input from all stakeholders in the CO2 chain. Many DOE offices engaging.
  - Flue gas source (composition, flow)
  - Carbon capture technology vendor (quality of CO2, esp during transients)
  - CO2 compressor/CO2 "polishing" (esp H2O)
  - Pipeline operator (PRCI)
  - CO2 "end game"
    - CCS
    - EOR
    - CO2 utilization

Summary

- CCS retrofit to NGCC plants is hard, esp due to intermittent operation
  - Steady state operation of components is not sufficient for assessing how these system will work
- Unsteady-state operations may result in off-spec CO2 during transients
  - Capture rates need to address disposition of potentially off-spec CO2
- FLECCS evaluating novel carbon capture systems
  - Will likely tee up more issues than it will resolve
- Recommend DOE coordinate information sharing for system-level issues
  - Need collaboration among power plant operators, CCS process developers, component OEMs, pipeline operators, and EOR/CO2 utilization/sequestration stakeholders to define critical design cases

Meeting Structure

- **Full workshop agenda**: Net-zero Flexible Power: High Capture Rate Project Review Meeting | netl.doe.gov
  - ***3 panel discussions:*** perspectives from technology developers, OEMs and utilities
  - ***2 sessions current FECM projects report-out***: 9 projects
  - ***3 talks*****:** research findings on feasibility of high capture rates and flexible operation
  - ***Report out from ARPA-E FLECCS program***
  - ***Breakout sessions:*** 3 topics to cover
- **Summary report** will follow the meeting

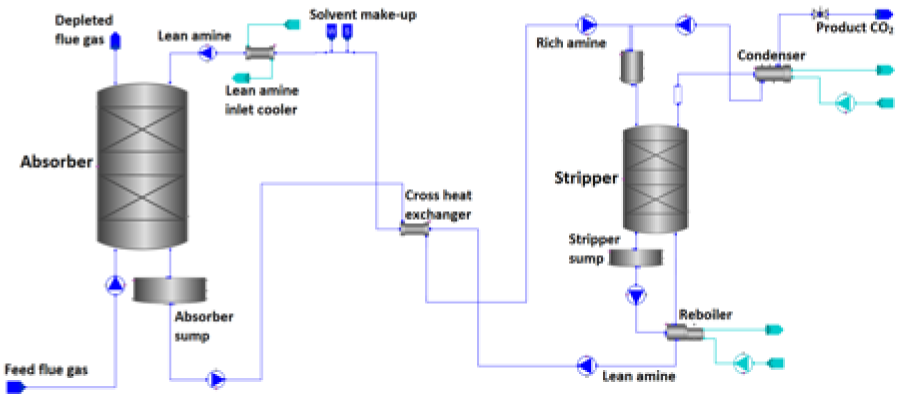
Conclusions and future work

These learnings will help improve the performance of flexible operation and SUSD strategies in CO_2 capture plants.

The data from this study will help in the development more robust process control systems, as well as improve the description of flexible and dynamic operation in process & systems models.

Future work:

- Investigate the impact of different process configurations and process control systems that could improve plant flexibility and SUSD performance, e.g., via process modelling.
- Effect of different solvent types on CO_2 capture plant flexibility and SUSD performance.
- Study dynamic interactions between the power plant and CCS process, also upstream/downstream effects.
- Techno-economic analysis to understand the cost implications of different SUSD strategies.
- Understand the impact of SUSD cycles at a systems scale, i.e., effect on ability to reach net zero.



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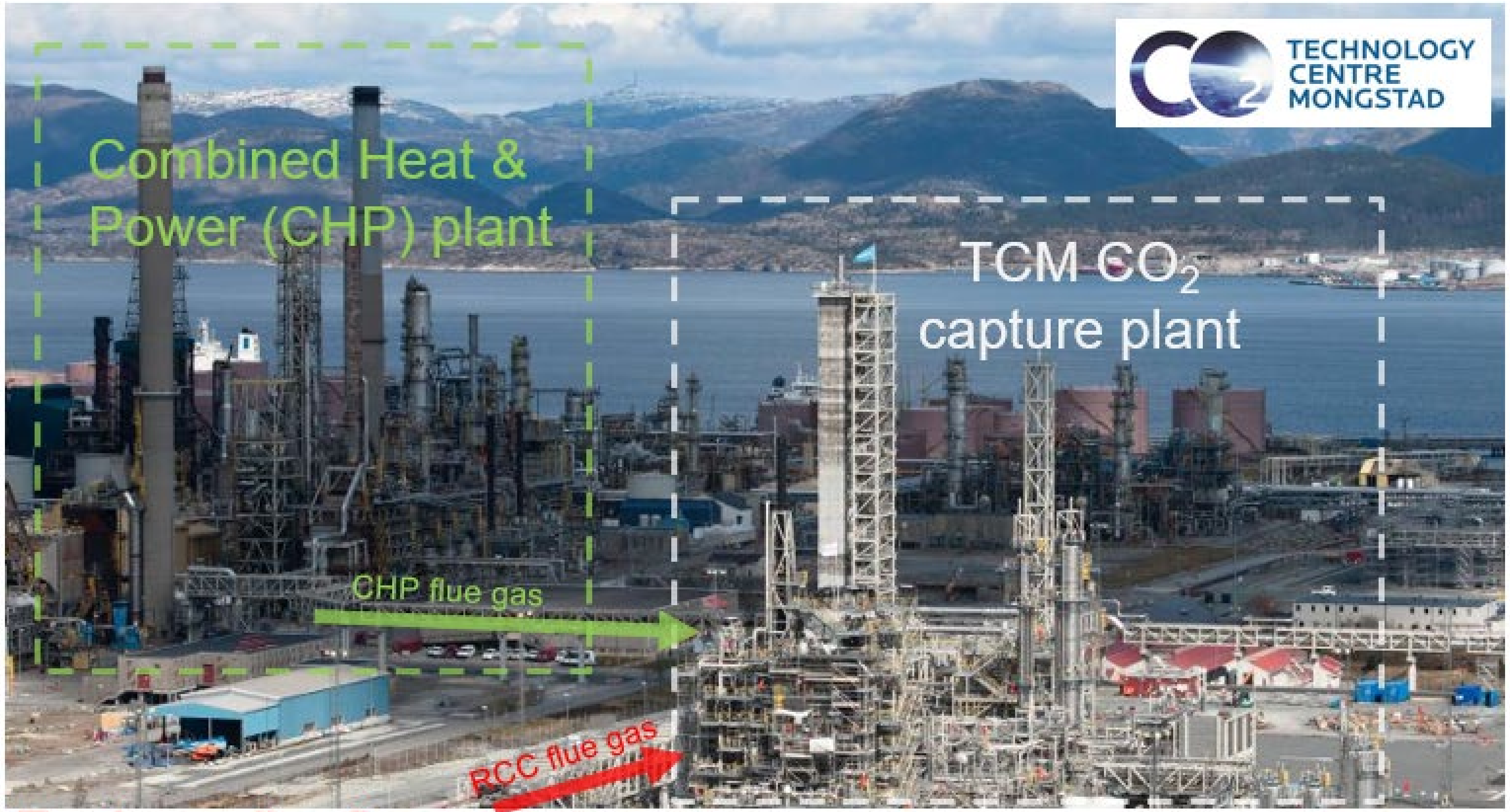
Imperial College London

Flexible operation of a demonstration-scale CO_2 capture plant

In 2020, we studied the effect of start-up & shut down on CO_2 emissions at TCM.

Studying the following: (i) hot vs cold start-up, (ii) timing of steam availability (conventional vs preheat vs delayed), (iii) solvent inventory capacity, (iv) start-up solvent loading/composition.



Equinor oil refinery (not shown)

http://cdn3.spiegel.de/images/image-349556-860_poster_16x9-ygkk-349556.jpg

Bui, M., Flø, N. E., de Cazenove, T., Mac Dowell, N., (2020). International Journal of Greenhouse Gas Control, 93, 102879

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Key learnings

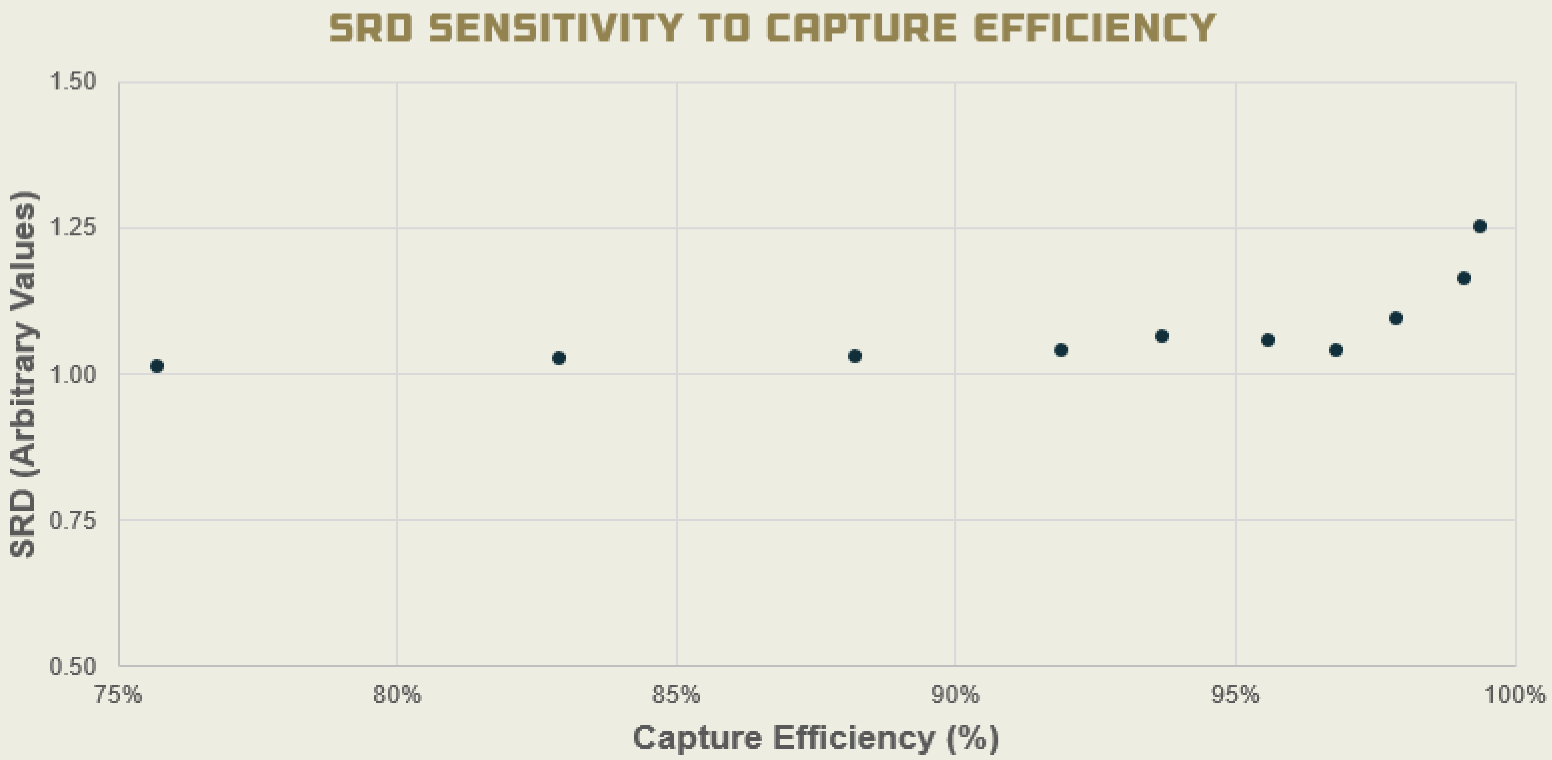
- High capture rates above 90% is techno-economically feasible (at steady state).
- During dynamic operation, 90% capture rate is feasible with load following regimes (e.g., ramp up/down) and hot start-up and shut down.
- During cold start-up and shut down, CO_2 capture rates can reduce to 50% or lower.
- Increased start-up and shut down cycles could increase CO_2 emissions of a CCGT significantly.

	Zero emissions intensity steam		With an NG auxiliary boiler for SUSD	
82 min start-up (SU) combined with shut down (SD)	Cumulative specific reboiler duty (MJ/kg CO_2)	Cumulative CO_2 captured (%)	Cumulative specific reboiler duty (MJ/kg CO_2)	Cumulative CO_2 captured (%)
Cold SU 53 m^3 & SD	8.15	80.0	12.42	52.5
Cold SU 42 m^3 & SD	8.51	66.3	13.04	43.3
Hot SU 53 m^3 & SD	6.06	97.3	7.26	81.2
Hot SU 42 m^3 & SD	5.94	96.5	6.93	82.9
Hot SU 42 m^3 delayed steam & SD	6.17	67.7	7.35	56.8

Bui, M., et al., (2020). International Journal of Greenhouse Gas Control, 93, 102879.
IEAGHG, 2022. Start-Up and Shutdown Protocol for Natural Gas-Fired Power Stations with CO_2 Capture", technical report 2022-08, 2022.

CAPTURE EFFICIENCY SKEW [DROP-IN AT TCM]

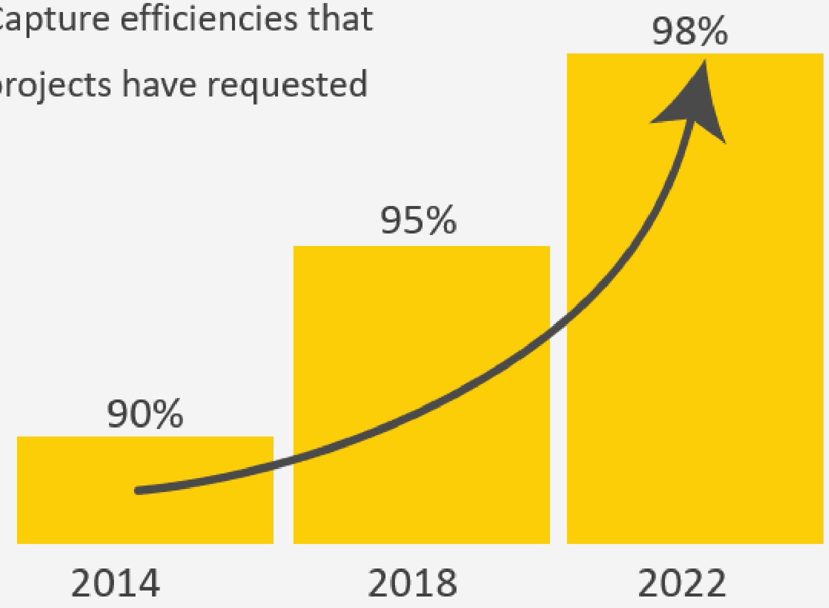
- Minimal additional energy consumption from 76-96% capture efficiency
- Energy penalty associated with deep decarbonization >99% capture efficiency
- Evaluation of techno-economic analysis for deep decarbonization with LLNL

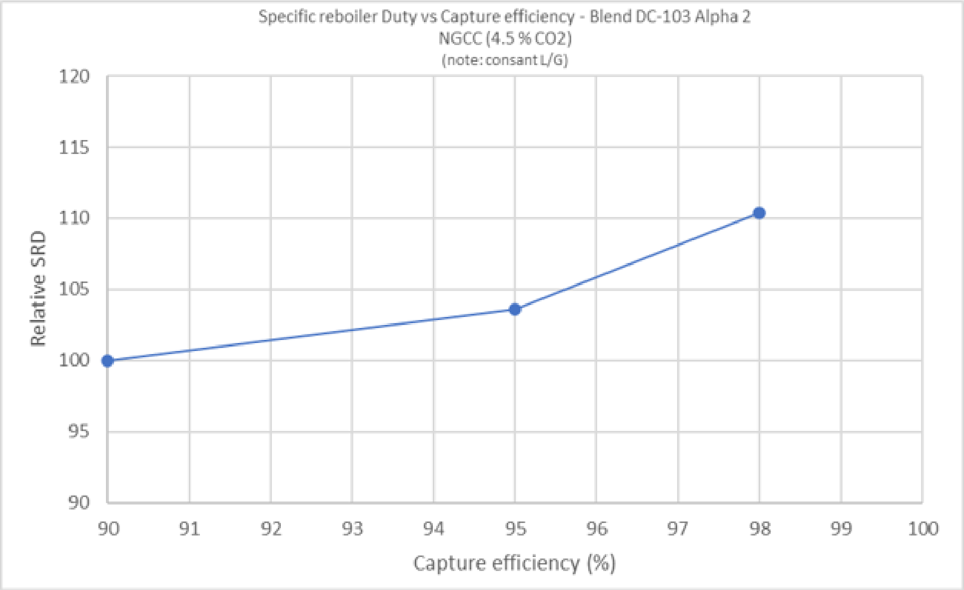


Shell

MOVING TOWARDS HIGHER CAPTURE EFFICIENCIES

Capture efficiencies that projects have requested

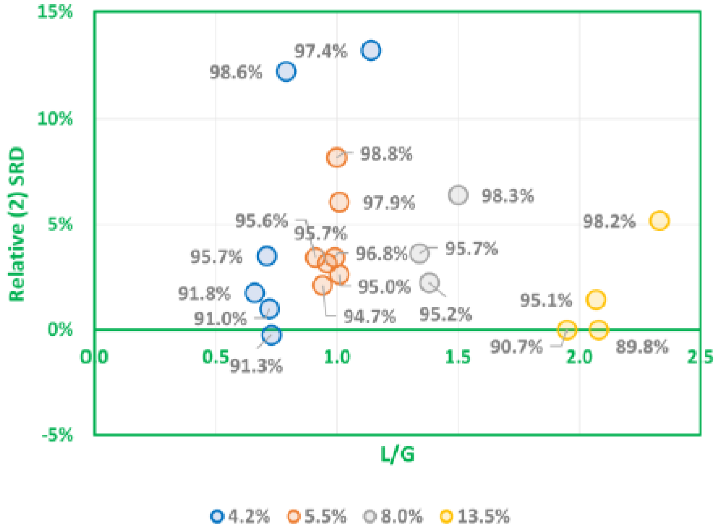


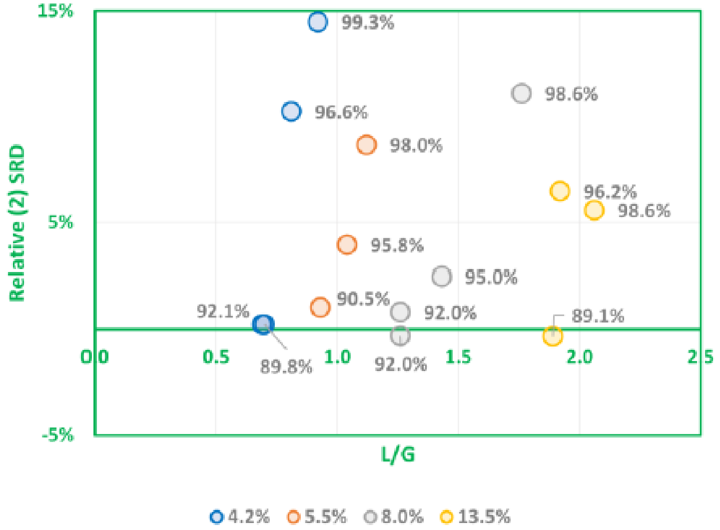


CANSOLV can achieve high – up to 98%+ – capture efficiencies, even at low CO_2

High capture rates – delivering 95% and above

- ACC demonstration with SINTEF at Tiller pilot plant
  - campaign to qualify ACC proprietary solvent technology for high capture rates in dilute flue gases
- Targeting 90%-98% capture with proprietary solvent
  - 'aged solvent', over 3,700 hours of prior use at MTU
- No challenge with delivering 95-98% capture rates
  - standard configuration: moderate increases in SRD
  - also 99% capture OK with 4% CO_2 but SRD penalty
- Non-linear correlation between capture rates and SRDs, sharper SRD increase for leaner flue gases
- Realised some optimised performance from tuning solvent concentration
- Key observation - high (98%+) capture rates saw narrower optimum operational windows, higher vulnerability to issues like flue gas fluctuations, column behaviour and liquid distribution





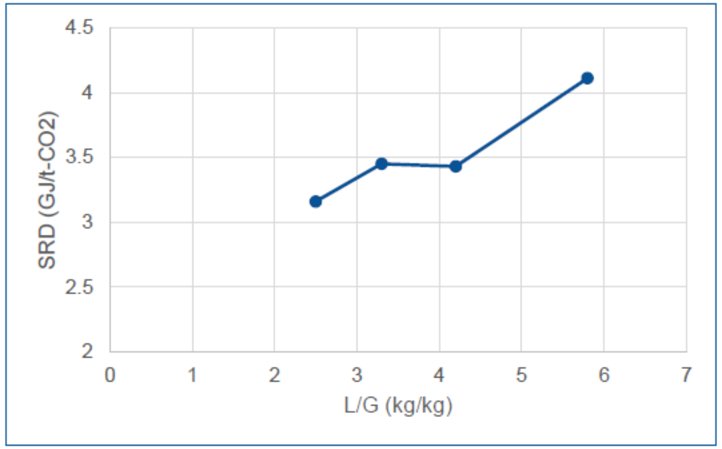
Liquid-to-gas ratios (mass basis) versus relative specific reboiler duties for flue gases with different CO_2 content and capture rates (charts show two batches of data)

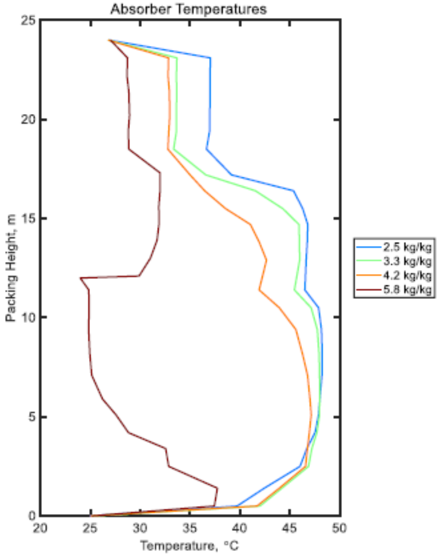
NB: SRD comparison is vs. 13.5% CO2 stream and 90% capture rate

AKER CARBON CAPTURE

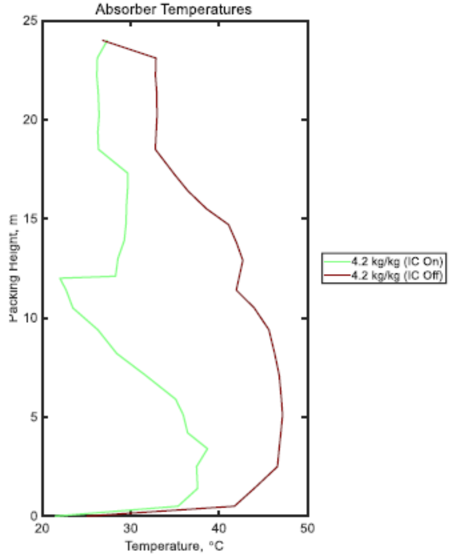
RTI

NGCC Performance: L/G Optimization

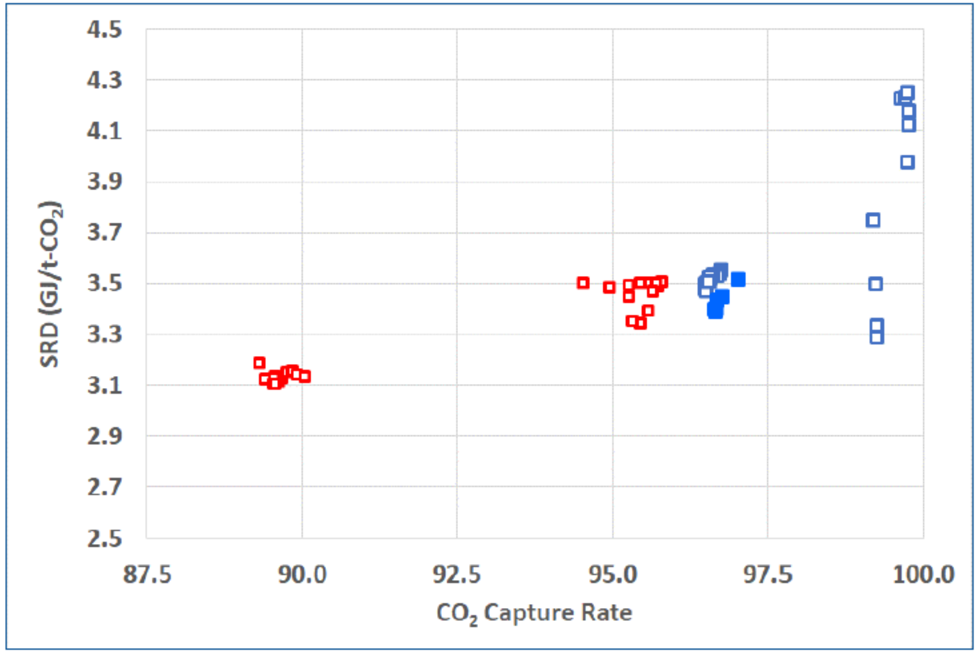




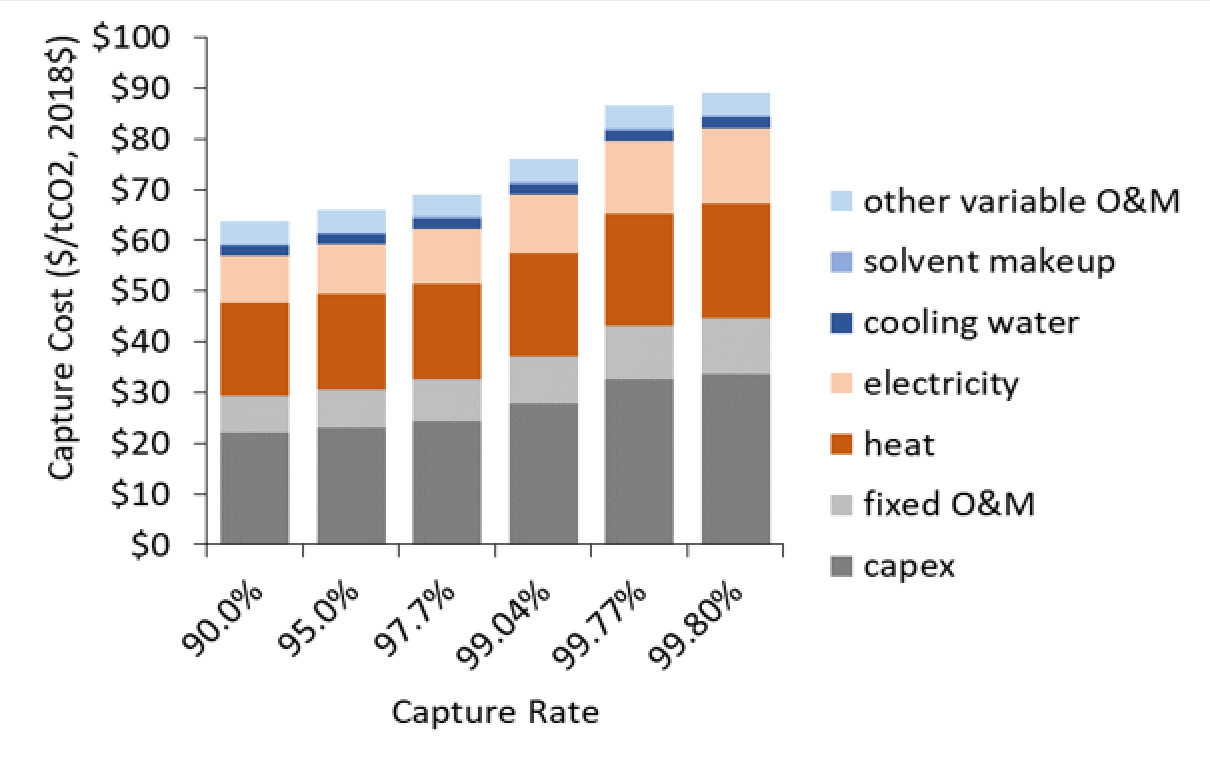
L/G Impact on bulge



Intercooler impact on bulge



COST ANALYSIS [LLNL FOR MEA]



Source: Wenqin Li, Tom Moore, Mengyao Yuan, Tracie Owens; *High-Rate Post Combustion Capture for Natural Gas Power Plant 2023 FECM Project*; LLNL 2023.

OPEX

- Increase T(str.sump)
- Increase L/G
- Decrease gas flow rate
- Increase STR pressure

CAPEX

- Extra packing height

Future work:

- Evaluation of techno-economic analysis for deep decarbonization with advanced CO_2 capture systems
- Same with ION's ICE-31

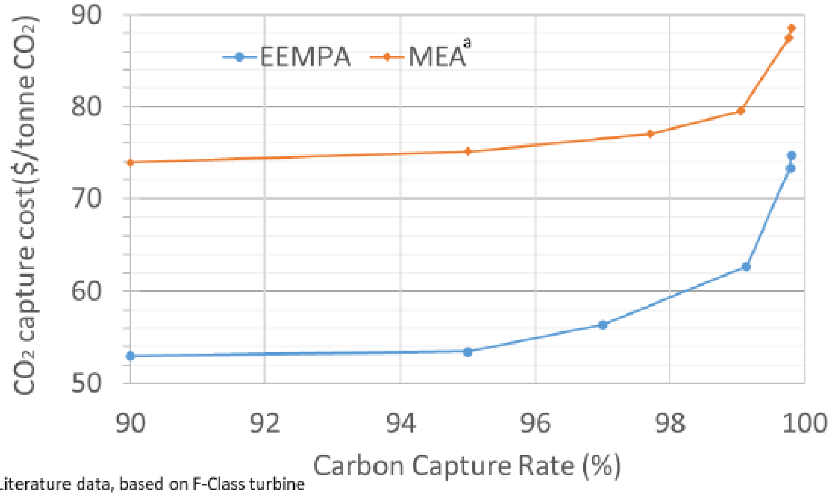
EEMPA for Zero- and Negative-Emissions NGCC Plants and Comparison with MEA

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

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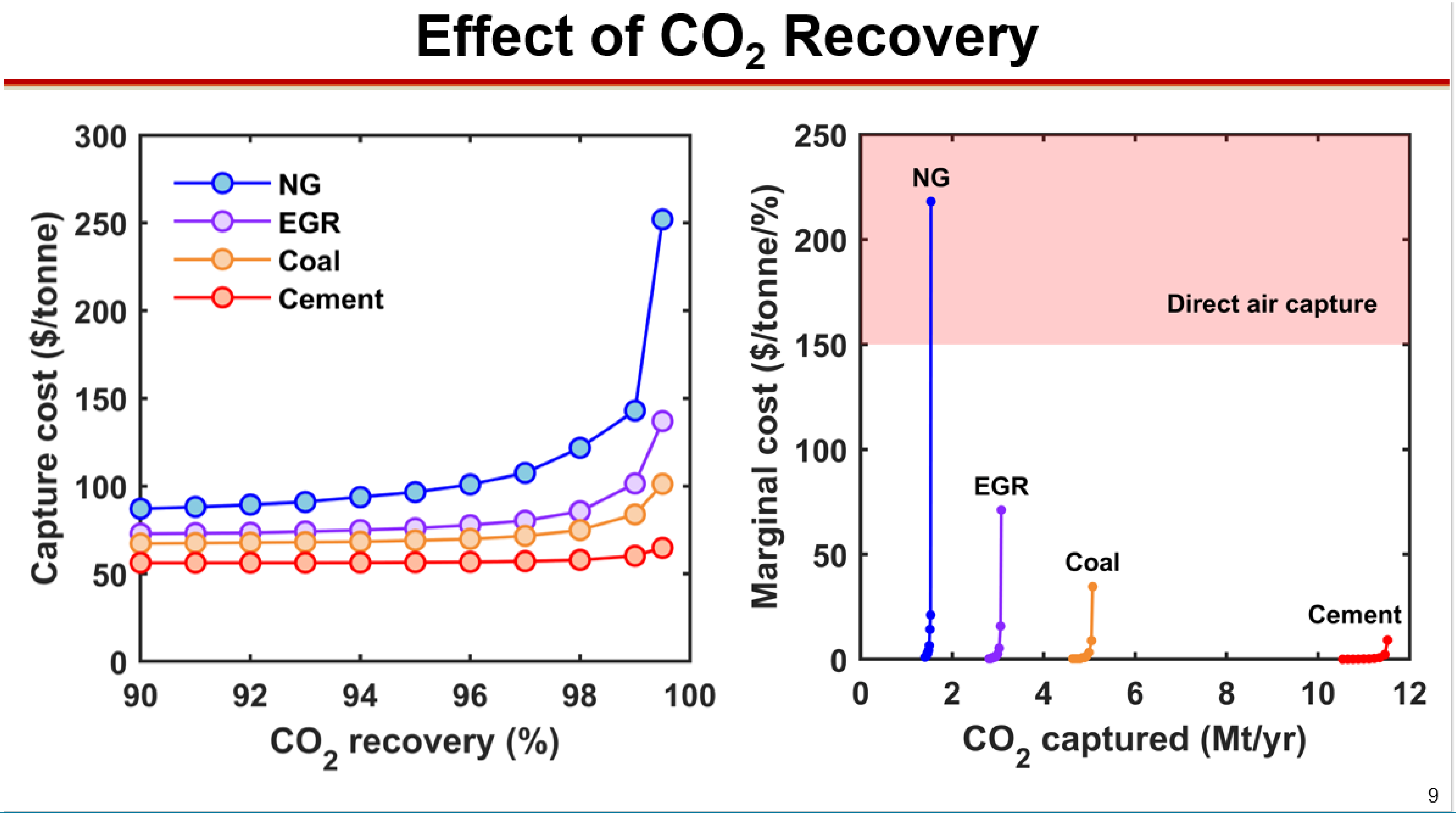
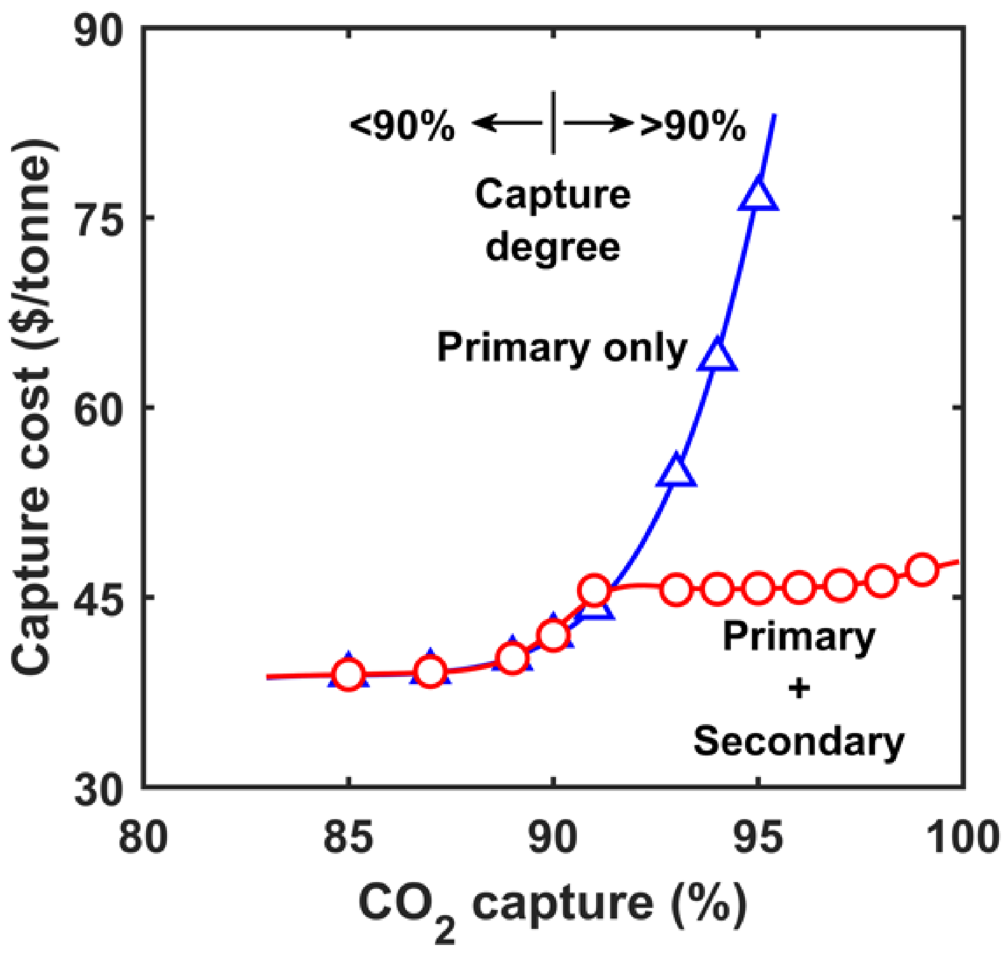
OSU

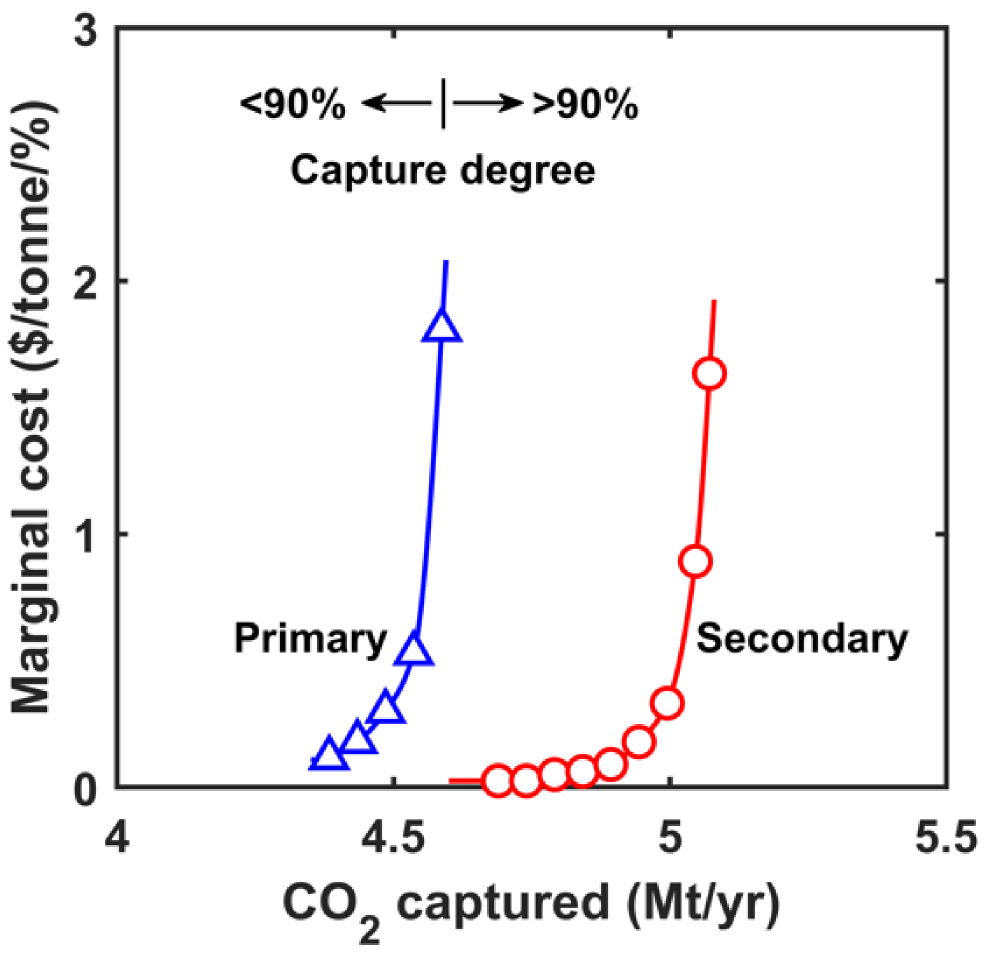


Effect of CO_2 Recovery
300
250
200
150
100
50
0
Capture cost ($/tonne)
NG
EGR
Coal
Cement
90
92
94
96
98
100
CO_2 recovery (%)
250
200
150
100
50
0
Marginal cost ($/tonne/%)
NG
Direct air capture
EGR
Coal
Cement
0
2
4
6
8
10
12
CO_2 captured (Mt/yr)
9

O

Marginal Costs for Beyond 90% Capture





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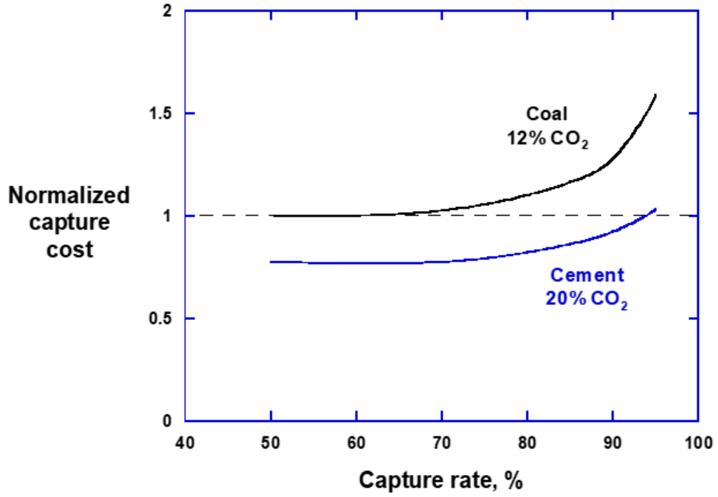
High Capture Rates with Membranes are More Affordable for High CO_2 Content Industrial Streams

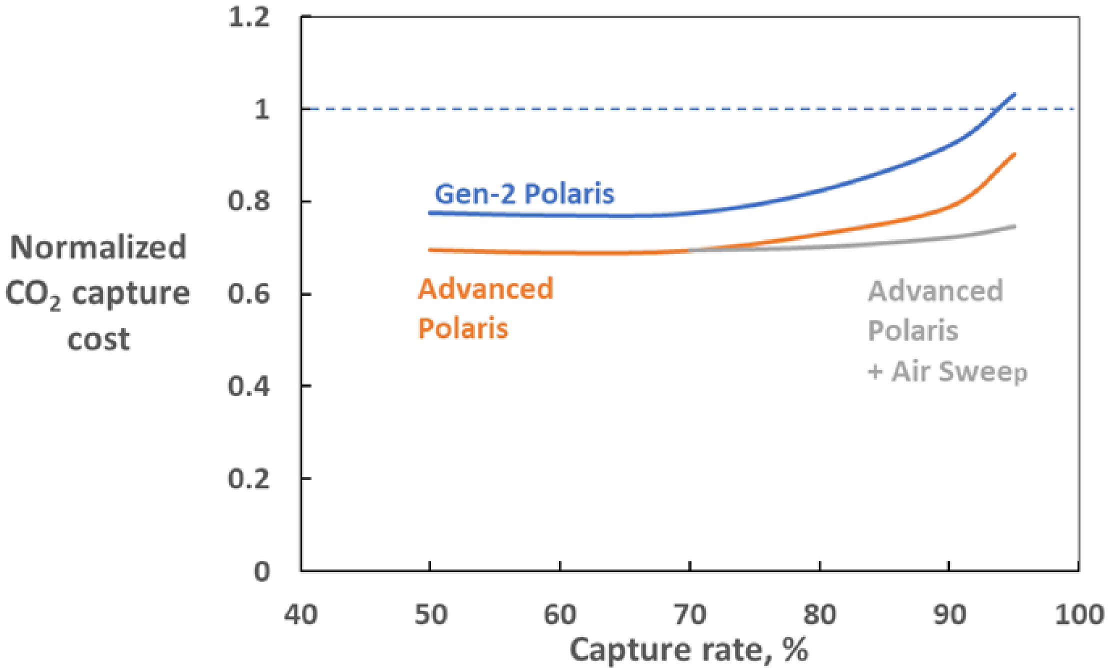


Capture cost is normalized to 60% capture from coal using Polaris Gen2 membranes

- Membrane capture costs increase with increasing capture rate, particularly above 90% capture
- However, membrane capture cost is less sensitive to capture rate for higher feed CO_2 content; higher capture is more affordable for industrial streams (cement, steel, refinery, etc)
- Calculations are for a two stage membrane design with no selective recycle

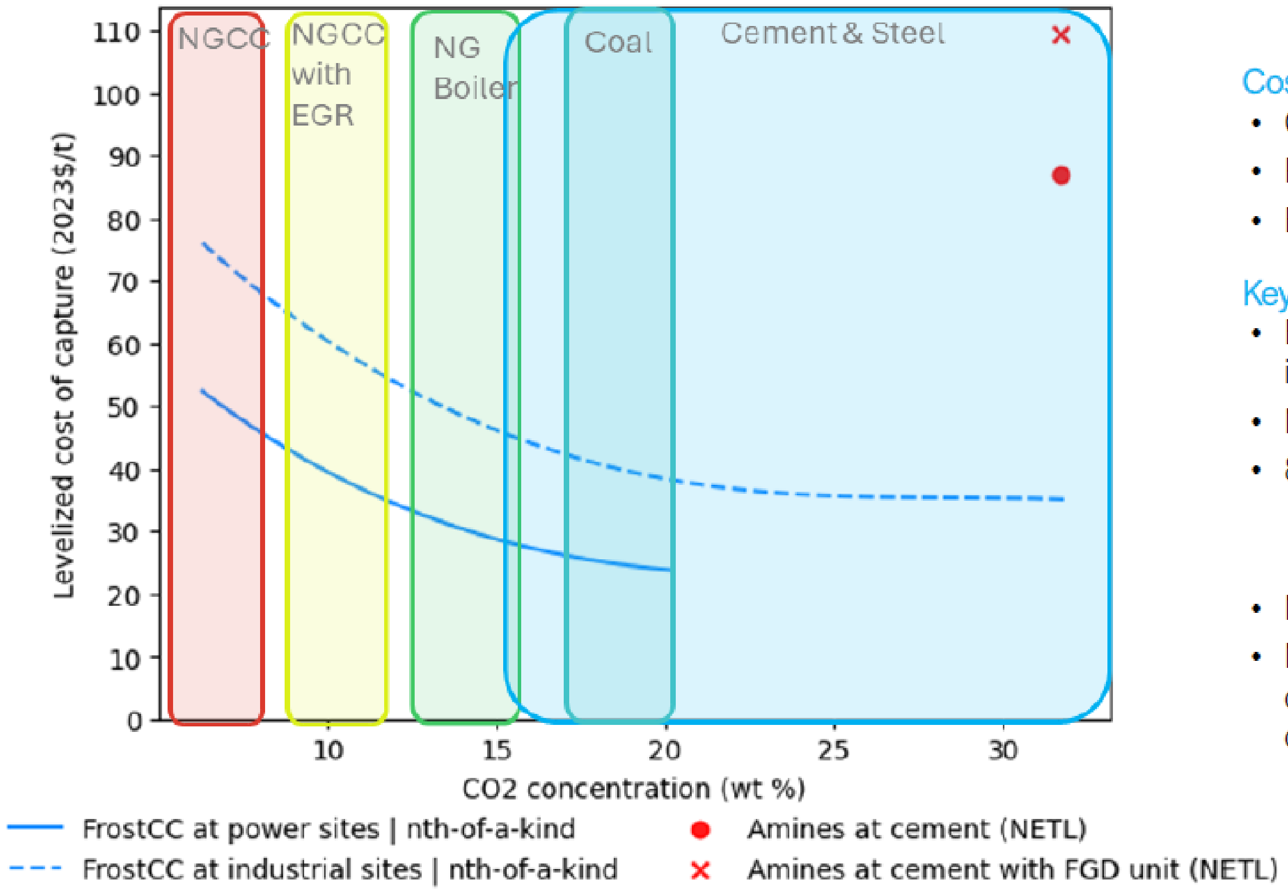
MTR

5



Capture cost is normalized to 60% capture from coal using Polaris Gen2 membranes

Economics at 99% Capture*



Cost Optimizations

- Co-pollutant capture value
- Preferred / advantaged electrical rates
- Behind the meter renewable power options

Key Assumptions

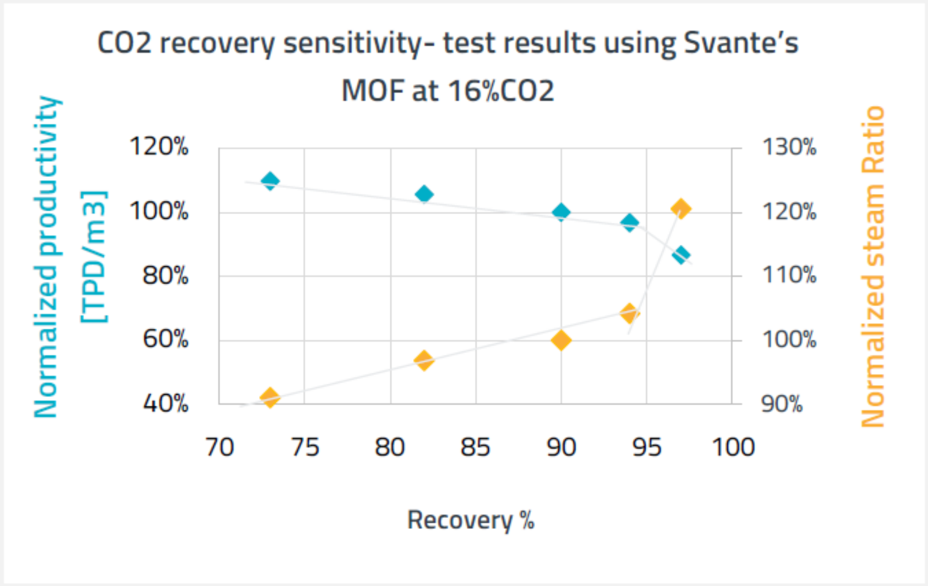
- Electricity price: $35/MWh at power sites, $70/MWh at industrial sites
- NG price at cement: $4.59/MMBtu
- 85% capacity factor
    - Low capex enables application to low capacity factor plants as well
- NETL reference capital cost recovery
- Nth-of-a-kind estimates assume 10 MMTPY cumulative installed FrostCC capacity across all commercial projects

*Negligible cost of capture change between 90-99% capture

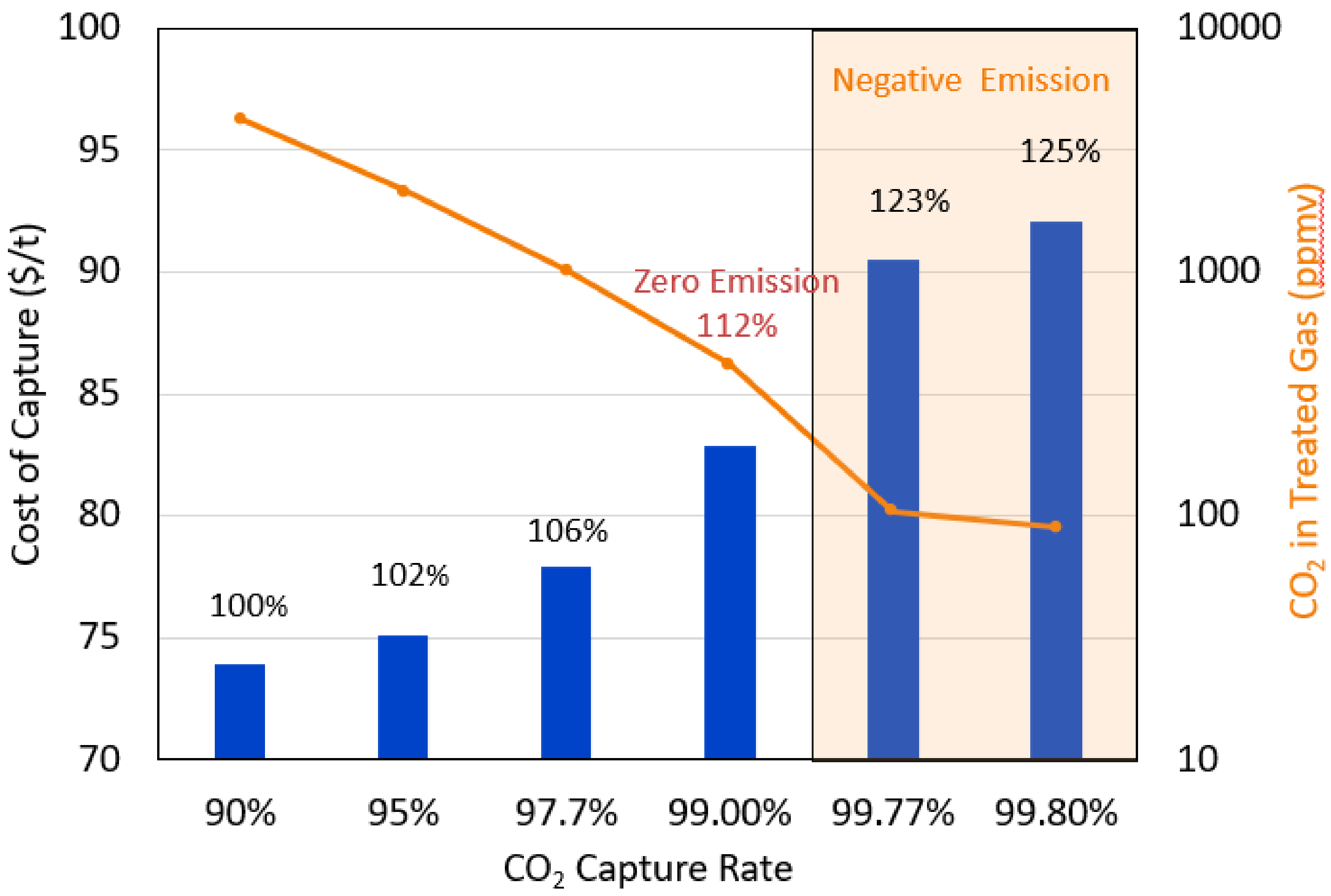
SVANTE

Achieving 95+% CO2 capture recovery with Svante technology

- Svante Rapid Temperature Swing (RTSA) capture cycle can achieve 95+% recovery
- The drawbacks of 95+% recovery targets are on the energy demand and manufacturing performance
- Methods to enhance CO2 recovery in Svante's RTSA process include
  - Optimizing structured adsorbent bed
  - Process cycle and plant process optimization
- 2-stage system can be another option to enhance CO2 capture rate



CO_2 Capture Cost at Different Capture Rates – NGCC



- For NGCC to achieve zero-emissions, the cost is 12% higher than that at 90% capture. For negative emissions, the cost is ~25% higher.
- The larger cost penalty is due to the low L/G in the NGCC case which makes the simple intercooling not as efficient for temperature control

Process configuration: Absorber with simple solvent intercooler