The Impact of Cement Plant Air Ingress on Membrane-Based CO_2 Capture Retrofit Cost

Clearwater Clean Energy Conference

June 18, 2024

Sydney Hughes

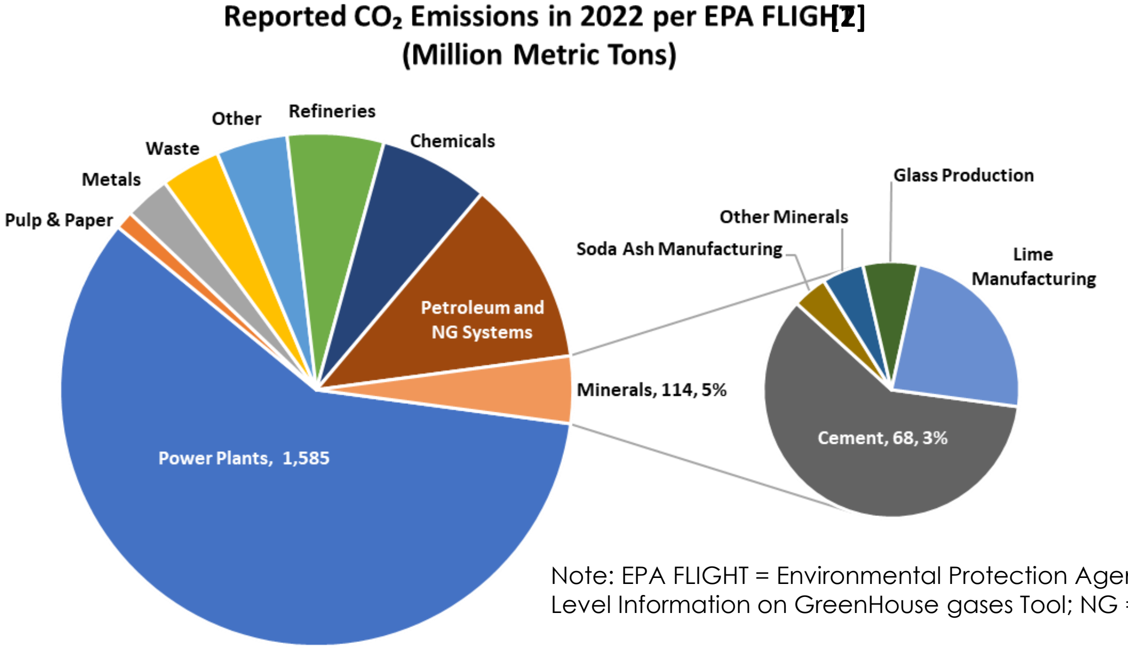
National Energy Technology Laboratory support contractor

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

Background

- The U.S. DOE recently announced its long-term strategy to reach net-zero greenhouse gas emissions by 2050[1]—a goal that necessitates rapid mobilization of resources and implementation of a portfolio of technologies including, but not limited to, carbon capture storage from industrial point-sources such as cement production.



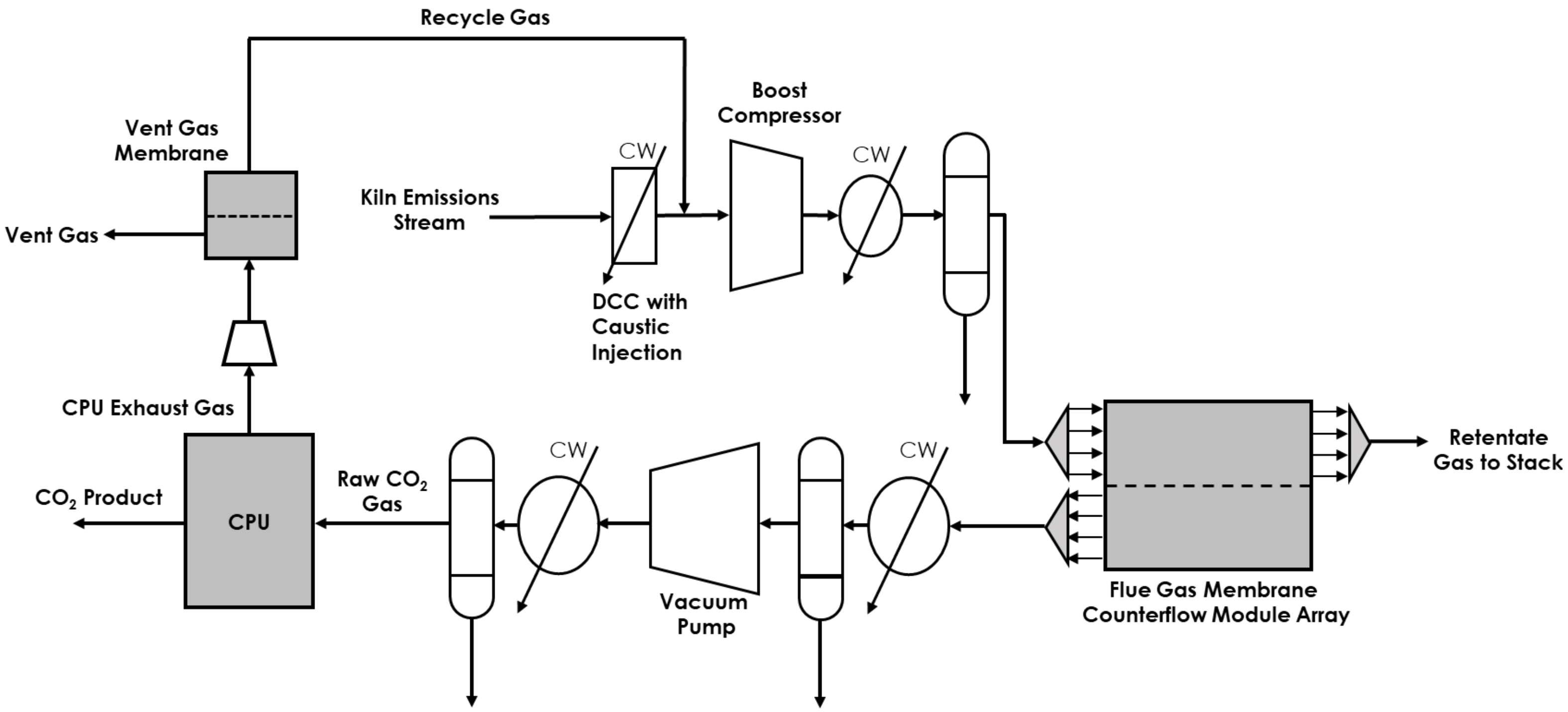
Note: EPA FLIGHT = Environmental Protection Agency Facility Level Information on GreenHouse gases Tool; NG = natural gas

- The objective of this study is to highlight the importance of considering false air ingress—a standard cement production process occurrence that dilutes kiln CO_2 emissions—when utilizing membrane-based capture for cement plant decarbonization.
  - A conventional solvent-based capture system from NETL's 2023 report *Analysis of Carbon Capture Retrofits for Cement Plants* is presented for comparison.[3]

1. U.S. Department of State, "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050," United States Department of State and the United States Executive Office of the President, Washington, D.C, 2021.
2. EPA, "Facility Level Information on Greenhouse Gases Tool (FLIGHT)," 2023, http://ghgdata.epa.gov/ghgp/main.do.
3. S. Hughes, P. Cvetic, "Analysis of Carbon Capture Retrofits for Cement Plants," NETL, Pittsburgh, 2023.

Study Approach (continued)

- Correlations for ideal countercurrent membrane separation and a CPU model[4] are used within an Aspen Plus® simulation of balance of plant equipment (e.g., boost compression, inlet conditioning, recycle) to estimate the performance of a simplified two-stage membrane system with CPU and permeate recycle.



Note: CW = cooling water; DCC = direct contact cooler; CPU = compression and purification unit

The configuration chosen for this analysis is not optimized and is not particularly sensitive to changes in membrane performance. Other configurations, particularly configurations that do not consider such high flue gas compression (5 atm), would likely be more sensitive to membrane performance metrics.

4. NETL, "Development of Carbon Dioxide Purification Unit and Compression System Spreadsheet Tool," U.S. DOE, Pittsburgh, 2015

Study Approach (continued)

NATIONAL ENERGY TECHNOLOGY LABORATORY

- The base cement kiln is characterized as a pre-heater/pre-calciner kiln firing natural gas fuel.
  - For this specific configuration, compression of the resulting emissions stream to 5 atm is required to meet the net CO_2 capture rate goal of 95%; the net capture target and CO_2 purity requirements are theoretically attainable using a downstream CPU with vent gas membrane separation and recycle.
- Membrane parameters are varied, with permeance ranging from1,000 to10,000 GPU and CO_2:N_2 selectivity ranging from 25 to 200.
  - The range of permeance and selectivity values evaluated in this study reflects current commercially available membranes through future stretch performance of yet-to-be-developed membranes.
- The capital and operating costs and resulting cost of CO_2 captured (COC) are estimated for each permeance-selectivity coupling under two scenarios:
  - No false air ingress—CO_2 conc. **25 mol%** and vol. flowrate **255,000 ACFM**
  - Maximum expected false air ingress—CO_2 conc. **8.35 mol%** and vol. flowrate **700,000 ACFM**
    - The expected false air ingress scenarios considered in this study were initially developed for NETL's *Analysis of Carbon Capture Retrofits for Cement Plants*[3] based on input from the Portland Cement Association.

3. S. Hughes, P. Cvetic, "Analysis of Carbon Capture Retrofits for Cement Plants," NETL, Pittsburgh, 2023.

Cost Estimation Methodology

NATIONAL ENERGY TECHNOLOGY LABORATORY

- COC, excluding transport and storage, is calculated using the equation below

$$\left(\frac{\$}{tonne\ CO_2}\right) = \frac{TOC * CCF + FOM + VOM + PP}{tonnes\ CO_2\ captured\ per\ year}$$

Where

- TOC – Total overnight costs of all equipment added to support application of CO_2 capture
  - A factor of 1.52 is applied to the membrane bare erected costs to estimate its associated total plant cost (TPC).
  - A factor of 1.05 is applied to TPC of the total system to estimate retrofit installation difficulty.
- CCF – Capital charge factor
- FOM – Annual fixed operation and maintenance (O&M) costs
- VOM – Annual variable O&M costs
- PP – Purchased power cost at $67.3/MWh

- Financial parameters specific to the cement industry were developed by NETL to reflect November 2022 conditions.

Financial Parameters[5]	Real Dollar Values
Capital Charge Factor (CCF = FCR * TASC/TOC)	8.84%
Fixed Charge Rate	7.91%
TASC/TOC Ratio	1.118
Debt/Equity Ratio	42/58
Payback Period	30-year operational period
Interest on Debt	8.82%
Levered Return on Equity (Asset Weighted)	4.90%
WACC	6.56%
Capital Expenditure Period	3 year
Capital Distribution	1st year – 10% 2nd year – 60% 3rd year – 30%

Note: FCR = fixed charge rate; TASC = total as-spent costs; WACC = weighted average cost of capital

5. NETL, "Quality Guidelines for Energy Systems Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance," U.S. DOE/NETL, Pittsburgh, 2019.

Design Basis

Membrane Characterization

- For each case, a correlation for ideal countercurrent membrane separation, the CO_2 permeance and selectivity, and inlet and permeate pressures are used to calculate separation efficiencies for CO_2, H_2O, SO_2, N_2, and O_2.
- An empirical correlation[4] is used to calculate the CPU separation efficiency and energy requirement.
- Aspen Plus® simulation of the process is used to generate material and energy balances for scaling and costing the different process equipment, membrane components, and O&M.
- Other performance factors (e.g., pressure drop, membrane life) and cost factors (e.g., cost of membrane material, seals, vessel, nozzles, supports, manifolds, and piping) are detailed-design dependent and are treated as assumption parameters in this analysis.
  - The published manuscript and supplemental information provide more detail: The Impact of Cement Plant Air Ingress on Membrane-Based CO_2 Capture Retrofit Cost

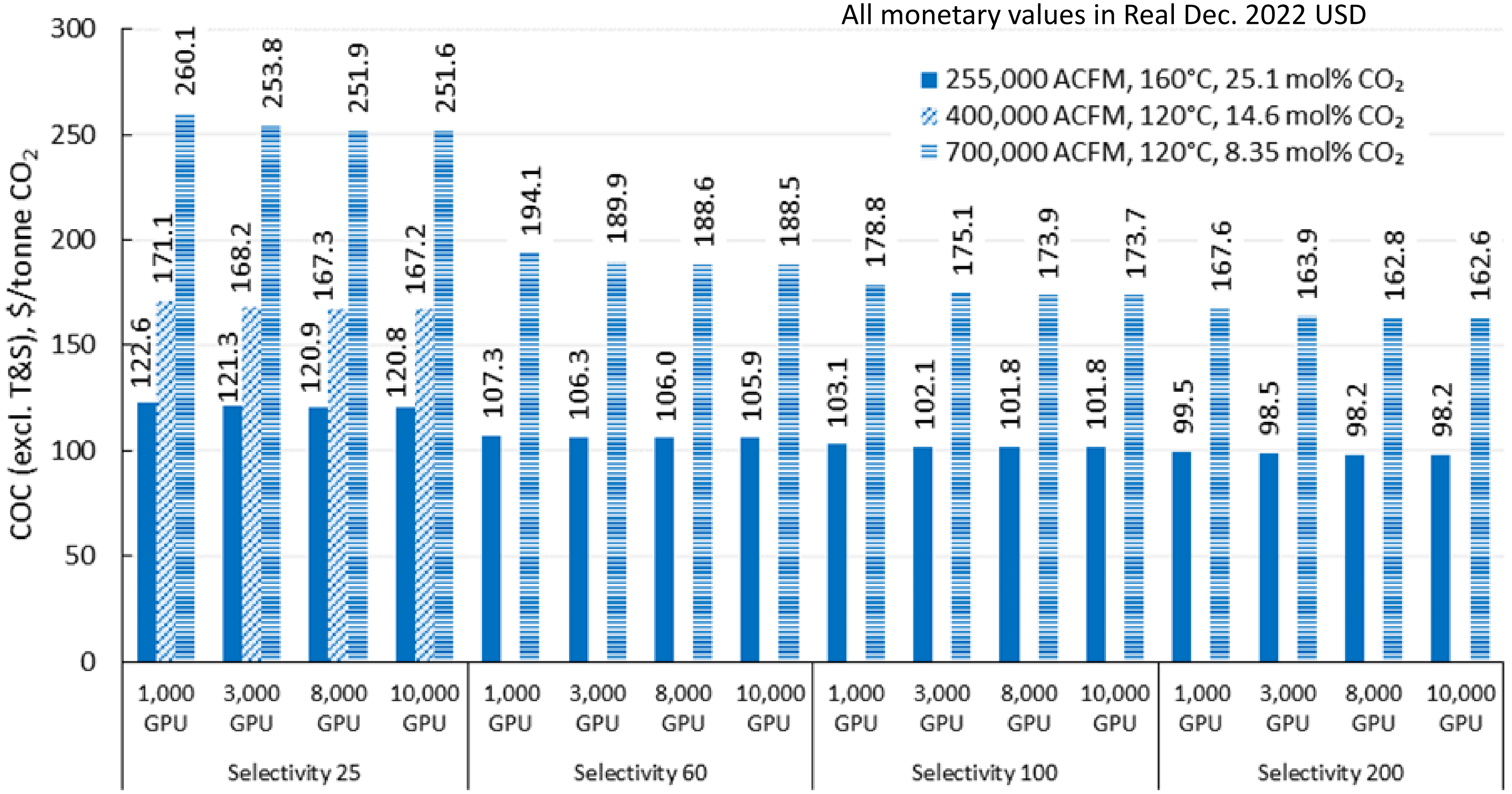
4. NETL, "Development of Carbon Dioxide Purification Unit and Compression System Spreadsheet Tool," U.S. DOE, Pittsburgh, 2015

Cost and Performance Results

NATIONAL ENERGY TECHNOLOGY LABORATORY

Membrane System COC (continued)

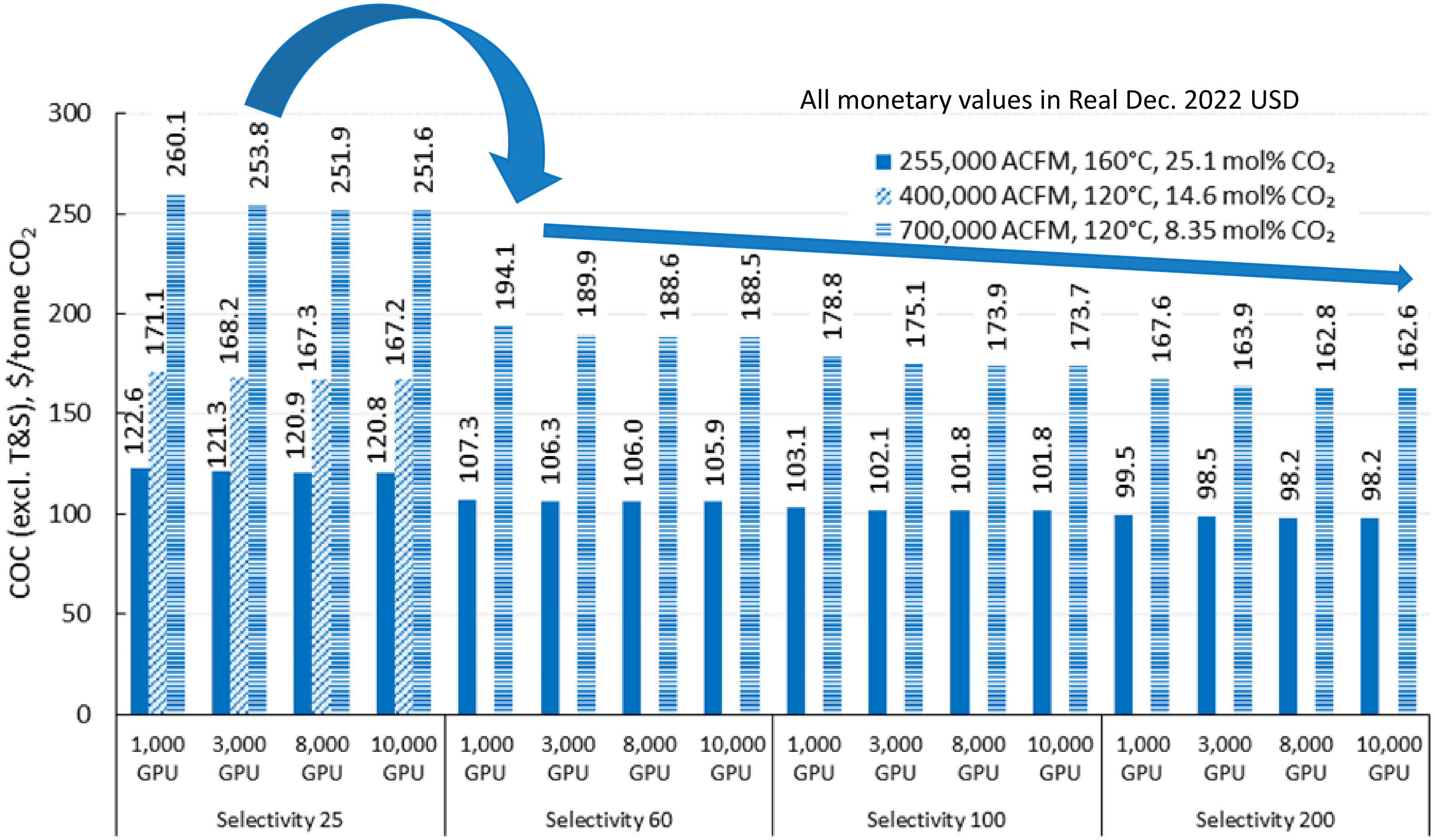
- The normalized COC ranges from $98. to 122.6/tonne CO_2 for the cases without false air ingress.
- False air ingress into the emissions stream can dramatically increase COC (by 66 to112%, ranging $162.6 to 260.1) for the unoptimized system considered, depending on the scenario analyzed.



Cost and Performance Results

Membrane System COC (continued)

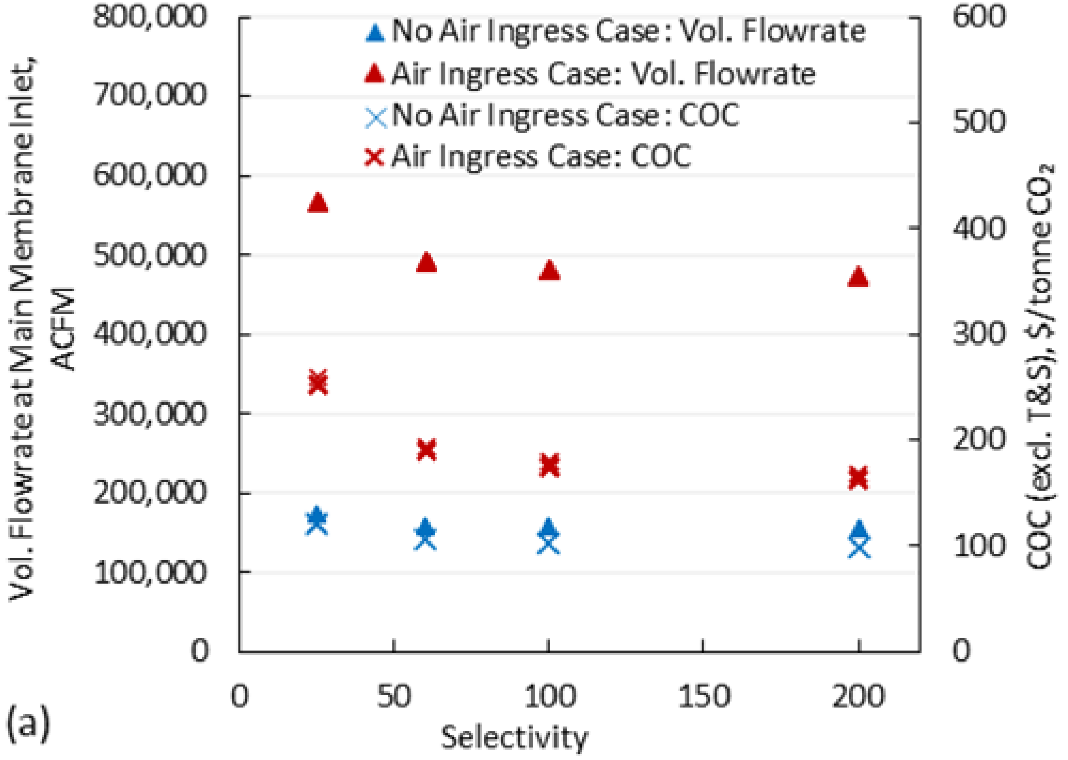
- Increasing CO_2:N_2 selectivity from 25 to 60 significantly reduces the cost for the system configuration examined, providing a 12% COC reduction for the base case and a 25% COC reduction for the 700,000 ACFM air ingress case.
- Further improving selectivity has incremental impact.

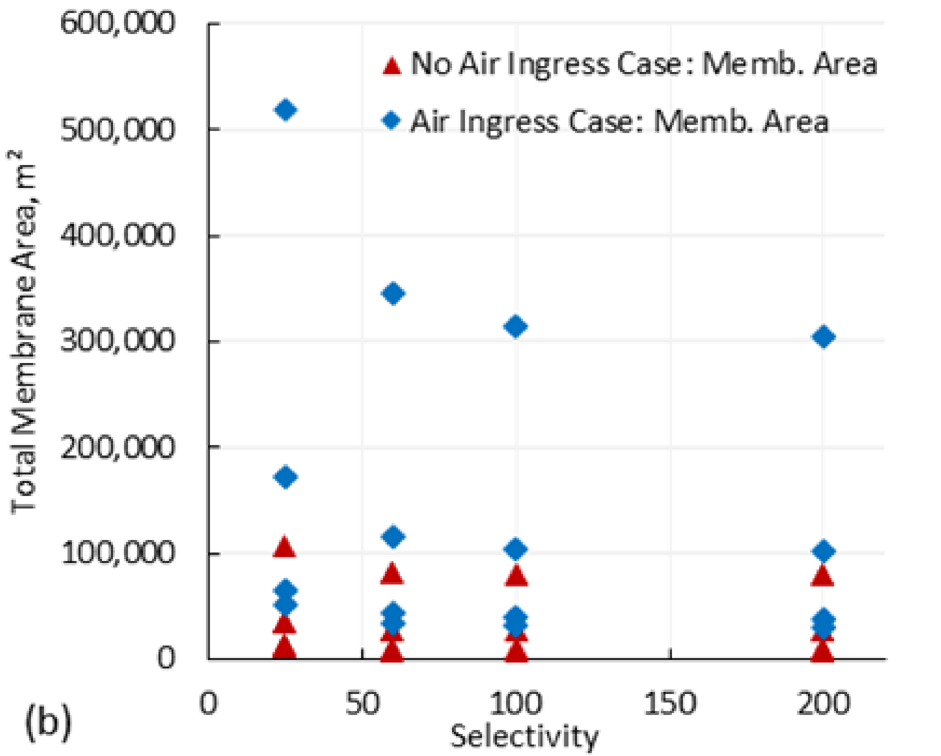


Cost and Performance Results

Volumetric Flowrate and Required Membrane Area

Increasing CO_2 selectivity from 25 to 200 reduces the volumetric flowrate at the inlet to the main counterflow membrane module array from 172,500 ACFM to 150,100 ACFM for the base cases and from 565,500 ACFM to 474,100 ACFM for the air ingress cases.





The reduction in the volumetric flow of the treated emission stream contributes to a reduced system size, capital cost, energy usage, and O&M cost. Moreover, increasing the membrane CO_2 selectivity reduces the total membrane area.

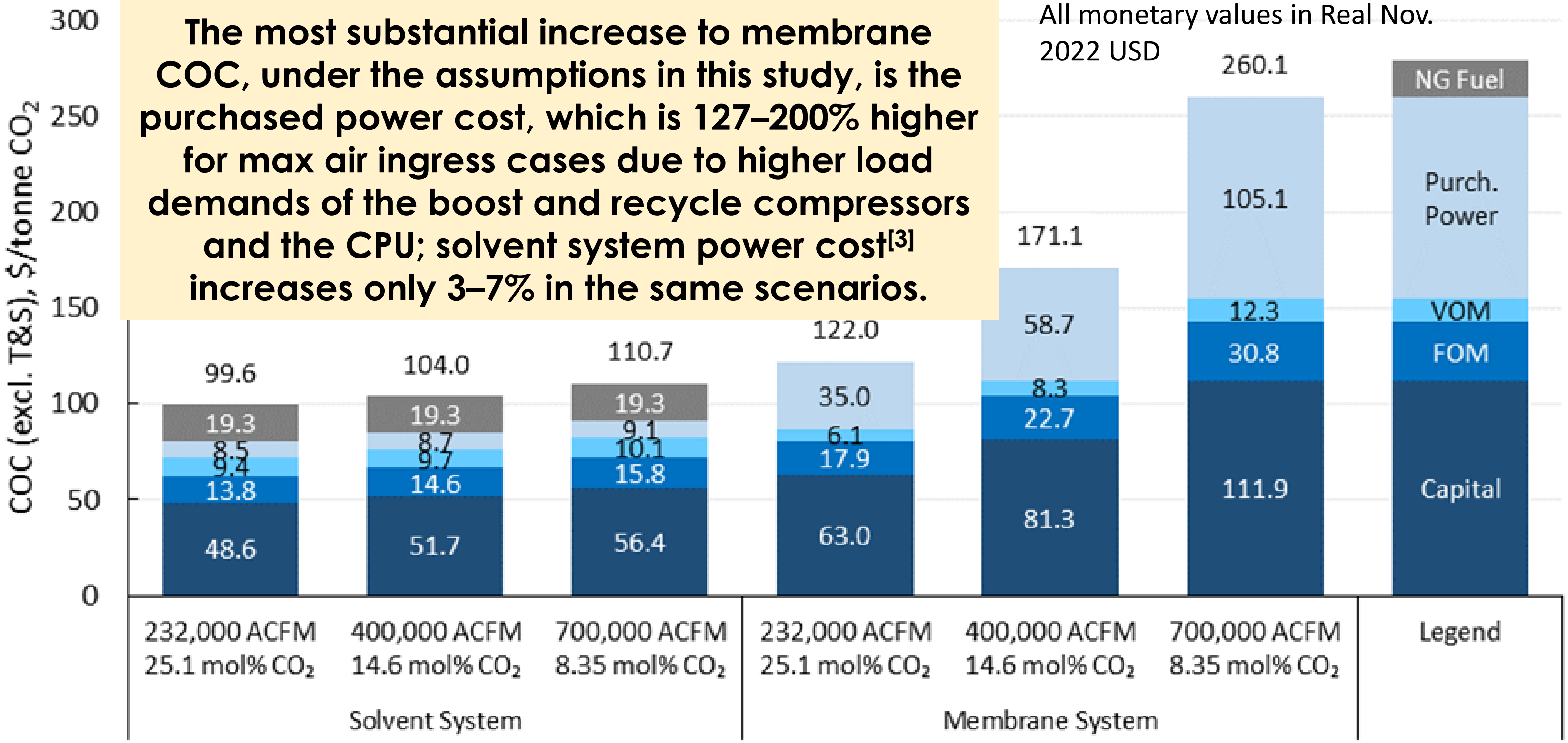
Cost and Performance Results

Membrane-Based System Versus Solvent-Based System

- Without false air ingress, capture costs for the integrated membrane-based capture system, under the design assumptions evaluated in this analysis, are comparable to a solvent-based system in the same application.
- The impact is notably more substantial for the membrane system examined in this study than for the solvent-based system.[3]

The most substantial increase to membrane COC, under the assumptions in this study, is the purchased power cost, which is 127–200% higher for max air ingress cases due to higher load demands of the boost and recycle compressors and the CPU; solvent system power cost[3] increases only 3–7% in the same scenarios.

All monetary values in Real Nov. 2022 USD



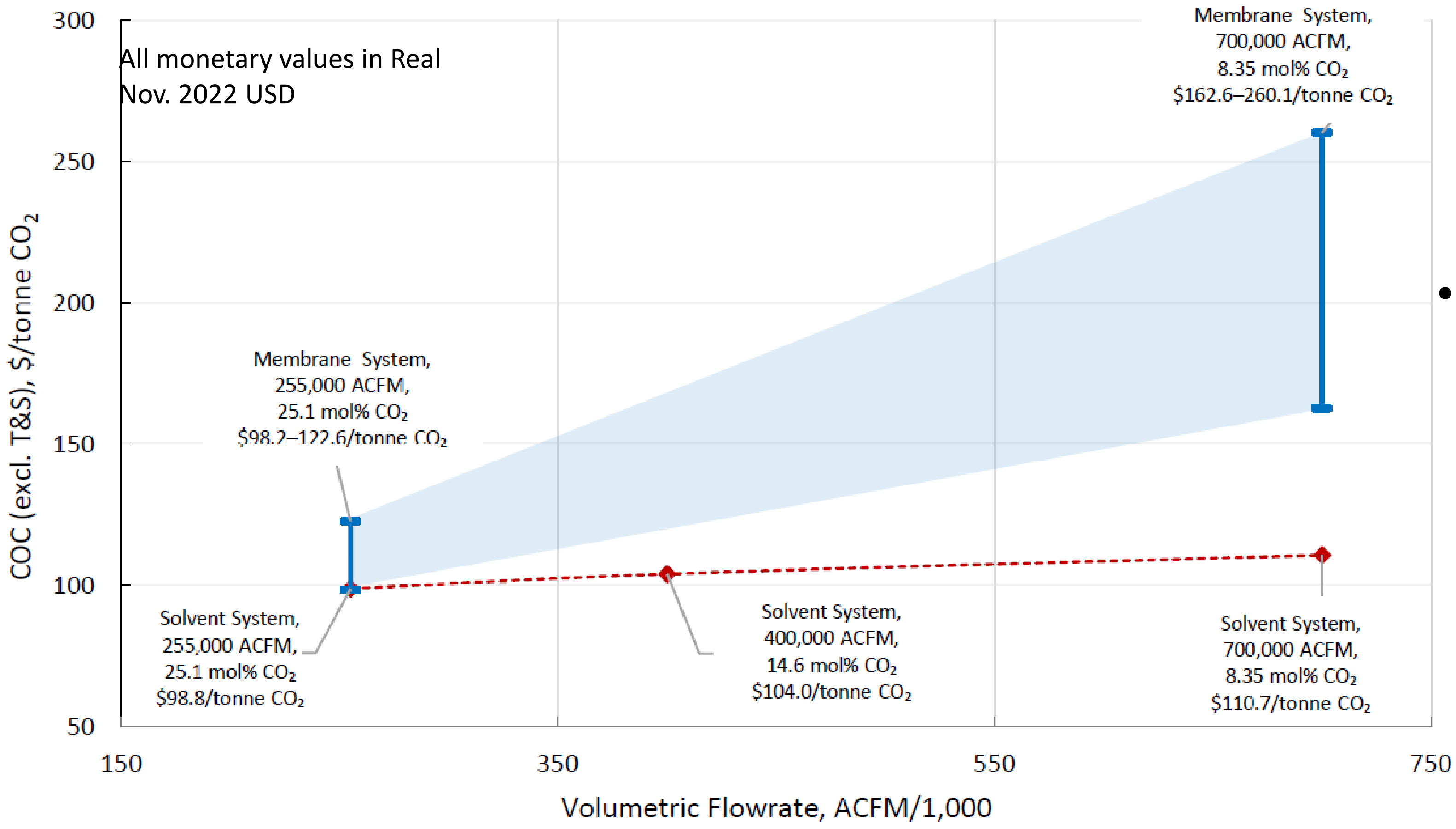
Selectivity 25, Permeance 1,000 GPU

The capital costs for the membrane-based system examined in this study are 45–77% higher under air ingress scenarios than would be predicted when air ingress is neglected; the comparative solvent system[3] shows a 9–19% increase in capital costs in the same scenarios.

3. S. Hughes, P. Cvetic, "Analysis of Carbon Capture Retrofits for Cement Plants," NETL, Pittsburgh, 2023.

Cost and Performance Results

Membrane-Based System Versus Solvent-Based System (continued)



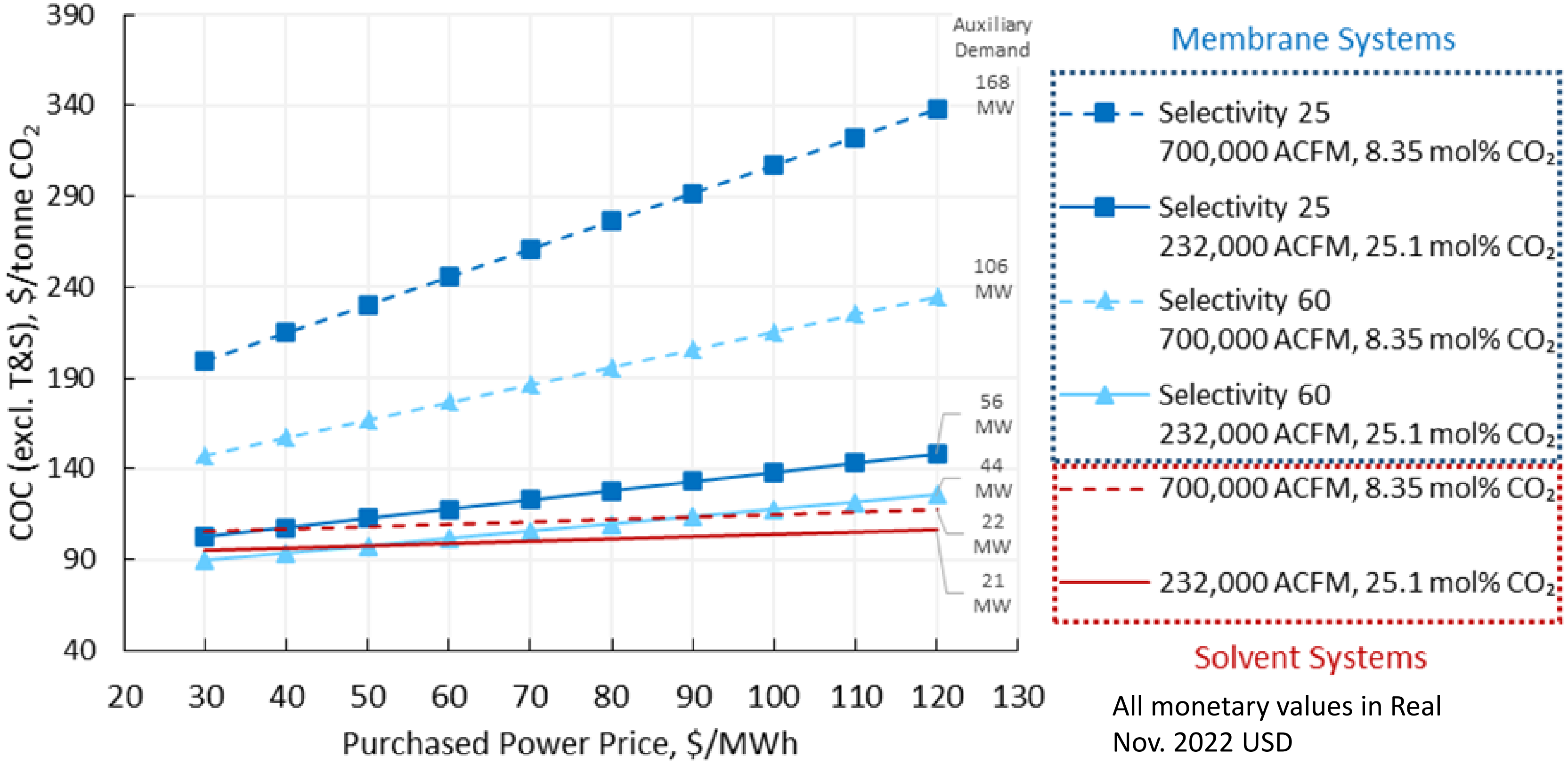
- False air ingress results in a membrane system COC that is 47–135% higher than that of a solvent-based system in the same application[3] if the membrane system design does not account for false air ingress.
- Alternate configurations or operating scenarios for the membrane-based capture system are likely to be considered and have more favorable economics if the design accounts for false air ingress into the emissions stream, which is inherent to the cement production process.

3. S. Hughes, P. Cvetic, "Analysis of Carbon Capture Retrofits for Cement Plants," NETL, Pittsburgh, 2023.

Cost and Performance Results

Sensitivity to Purchase Power Price

- The membrane system design selected for this study requires inlet gas compression (5 atm), has a high auxiliary load requirement, and is more sensitive to purchased power price fluctuations than the solvent-based system[3], especially when false air ingress is considered.
- Operating the membrane units at lower retentate-side pressures or recovering energy by including a vent gas expander may reduce costs. Considering additional membrane stages and alternate configurations may also increase system performance and reduce costs.



All monetary values in Real Nov. 2022 USD

3. S. Hughes, P. Cvetic, "Analysis of Carbon Capture Retrofits for Cement Plants," NETL, Pittsburgh, 2023.

Conclusions

- This analysis highlights the impact of changing membrane performance on COC and the influence of false air ingress on those COC results.
  - Without false air ingress, the COC for the unoptimized membrane capture system configuration considered in this study could be comparable with solvent-based COC.[3]
    - Note that under different scenarios (e.g., purchased fuel price, electricity price, membrane material costs, financial assumptions), these cases may compare differently.
  - In scenarios where false air ingress is present, the predicted COC impact for solvent-based systems is incremental[3], while the impact on membrane-based COC is significant for the configuration analyzed in this study.
- False air ingress—an expected occurrence in cement production—necessitates optimization of membrane capture system configuration with membrane performance (i.e., permeance and selectivity) and cost.
  - It may be the case that cost premiums associated with better membrane performance (i.e., higher membrane material costs, both initially and for replacement) outweigh cost advantages provided by increasing selectivity and/or permeance.
    - Such cost considerations for improved membrane performance were not considered in this manuscript; instead, a fixed membrane assembly cost of $50/m^2 was assumed.

These conclusions are specific to the membrane configuration selected in this study; different configurations may be more sensitive to membrane performance improvements.

3. S. Hughes, P. Cvetic, "Analysis of Carbon Capture Retrofits for Cement Plants," NETL, Pittsburgh, 2023.

Project Contributors

***Sydney Hughes*[1,2]: Conceptualization, Methodology, Formal Analysis, Visualization, Writing – Original Draft, Writing – Review & Editing; *Patricia Cvetic*[1,2]: Formal Analysis, Methodology, Writing – Original Draft, Writing – Review & Editing; *Sally Homsy*[2*]: Conceptualization, Formal Analysis, Validation, Writing – Original Draft, Writing – Review & Editing, Supervision; *Richard Newby*[1,2]: Conceptualization, Methodology Formal Analysis, Writing – Original Draft; *Alexander Zoelle*[1,2]: Writing – Review & Editing, Supervision; *Mark Woods*[1,2]: Supervision, Project Administration, Writing – Review & Editing; *Eric Grol*[2]: Writing – Review & Editing, Project Administration; *Timothy Fout*[3]: Conceptualization, Project Administration*

[1]National Energy Technology Laboratory (NETL) support contractor
[2]NETL
[3]Department of Energy Office of Fossil Energy and Carbon Management
*Corresponding contact: Sally.Homsy@netl.doe.gov, 412-386-9166

The authors would like to thank NETL support contractors Sandeep Pidaparti, Selcuk Can Uysal, and Troy Teel for reviewing the process simulations and cost and performance data used in this analysis, and Hannah Hoffman for editing this presentation.

References

1. U.S. Department of State, "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050," United States Department of State and the United States Executive Office of the President, Washington, DC, 2021.
2. EPA, "Facility Level Information on Greenhouse Gases Tool (FLIGHT)," 2020, http://ghgdata.epa.gov/ghgp/main.do.
3. S. Hughes, P. Cvetic, "Analysis of Carbon Capture Retrofits for Cement Plants," NETL, Pittsburgh, 2023.
4. NETL, "Development of Carbon Dioxide Purification Unit and Compression System Spreadsheet Tool," NETL, Pittsburgh, 2015
5. NETL, "Quality Guidelines for Energy System Studies: Cost Estimation Methodology for NETL Assessments of Power Plant Performance," NETL, Pittsburgh, 2019.

Disclaimer

NATIONAL ENERGY TECHNOLOGY LABORATORY

This project was funded by the Department of Energy, National Energy Technology Laboratory an agency of the United States Government, through a support contract. Neither the United States Government nor any agency thereof, nor any of its employees, nor the support contractor, nor any of their employees, makes any warranty, expressor implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Questions/ Comments

VISIT US AT: **www.NETL.DOE.gov**

@NETL_DOE

@NETL_DOE

@NationalEnergyTechnologyLaboratory

CONTACTS:

Sally Homsy
Sally.Homsy@netl.doe.gov

Greg Hackett
Gregory.Hackett@netl.doe.gov

Sydney Hughes
(support contractor)
Sydney.Hughes@netl.doe.gov