# Analysis of Carbon Capture Retrofits for Cement Plants

## Cement & Lime Decarbonization Workshop

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# Project Contributors

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This report was reviewed by personnel at PCA. As a step beyond standard internal quality assurance and quality control procedures, the U.S. Department of Energy Office of Fossil Energy and Carbon Management/NETL is committed to rigorous peer review of key work product to meet the quality standards of the research community. The following individuals at PCA are acknowledged, along with several of their industry members, for their efforts in reviewing the development methods and results of this analysis:

- **Richard Bohan, P.E., F.A.C.I., Senior Vice President, Sustainability**
- **Louis Baer, Esq., CPEA, Senior Director and Counsel, Government Affairs**
- **Sean O'Neill, Senior Vice President, Government Affairs**
- **Christine McCarthy, Director, Government Affairs**

# Study Objectives

- Establish baseline cost of $CO_2$ capture estimates for program direction, and comparison of “advanced” decarbonization strategies
- Examine the impact of operating parameters such as auxiliary utility pricing (e.g. supplemental natural gas and power), air ingress rate, kiln exhaust gas cleanup, and others
- Identify opportunities for $CO_2$ capture cost reduction, and the tradeoffs associated with achieving those reductions

# Study Approach

- For each design case, develop a process model of the $CO_2$ capture system, $CO_2$ drying and compression, and associated utility installations in Aspen Plus

- Evaluate system capital and operating costs using model outputs, vendor data and EPC guidance

- Estimate the Cost of $CO_2$ Capture, inclusive and exclusive of transport and storage costs, based on methodologies adapted from NETL's "Quality Guidelines for Energy System Studies" guidance

# Case Matrix

| Case Number | CM99-B | CM95-B | CM95-B1 | CM95-B2 | CM95-B3 | CM95-B4 | CM95-B5 | CM95-B6 | CM95-B7 | CM95-B8 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capture Rate* | 99 Percent | 95 Percent | | | | | | | | |
| Kiln Type | Pre-heater/Pre-calciner | | | | Wet Process | | Pre-heater/Pre-calciner | | | |
| Kiln Off-Gas** $CO_2$ mol % | 31 | 31 | 25 | 30 | 17 | 13 | 31 | | 25 | |
| Kiln Fuel Type | Coal/Coke | | NG | Oil | Coal/Coke | NG | Coal/Coke | | NG | |
| Heat Integration | N/A | N/A | N/A | N/A | N/A | N/A | 10 | 30 | 10 | 30 |

*The capture rate is indicative of the percentage of $CO_2$ captured from all emissions sources considered (i.e., the cement kiln, the NG boiler required to raise steam for solvent regeneration heating needs, and additional air in-leakage through raw mill processing, where applicable)

**The kiln off-gas $CO_2$ mol% is the assumed concentration directly from the kiln, before processing through raw mill operations (i.e., prior to any additional air in-leakage) and excluding comingled $CO_2$ from the NG boiler

# Study Limitations

- For all cases, the base cement plant is not modeled (limited ability to identify heat integration opportunities)
- Kiln off-gas stream characteristics are based on average data points provided by PCA
- More detailed studies (e.g. Front End Engineering Design) would require individualized cost and performance estimates based on actual operating conditions
- $CO_2$ transport and storage costs can be highly variable
- Study utility is not in the absolute cost values themselves, but in comparison across cases

# Economic Figure-of-Merit

## Financial Methodology

- The cost of capture, excluding T&S, is calculated using the equation below, where T&S costs would be an additive cost if included

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

- Where:
  - TOC – Total overnight costs of all equipment added to support application of $CO_2$ capture
  - CCF – Capital charge factor
  - FOM – Annual fixed O&M costs
  - VOM – Annual variable O&M costs
  - PF – Purchased fuel
  - PP – Purchased power

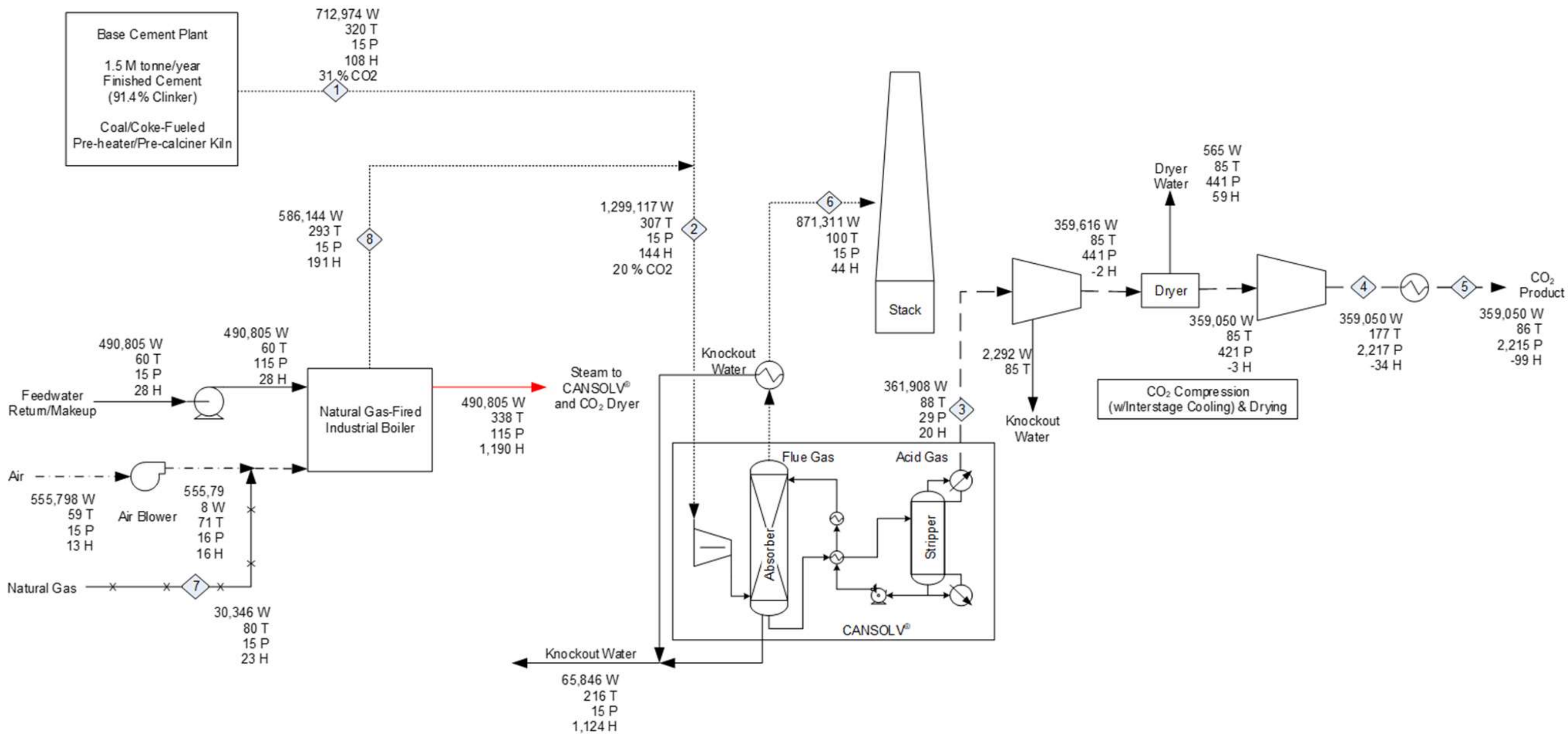
- Financial parameters specific to the cement industry were developed by NETL's Energy Markets Analysis Team reflecting 2022 market conditions

| Financial Parameter | Cement Manufacturing [Real] |
|---|---|
| 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 | 4.90% |
| WACC | 6.56% |
| Capital Expenditure Period | 3 year |
| Capital Distribution | $1^{st}$ year – 10%<br>$2^{nd}$ year – 60%<br>$3^{rd}$ year – 30% |

Note: FCR = Fixed charge rate; TASC = Total as-spent costs; WACC = Weighted average cost of capital

# Cost and Performance Results

## Base Cases (Represented by CM95-B)



# Study Assumptions

## Case Matrix

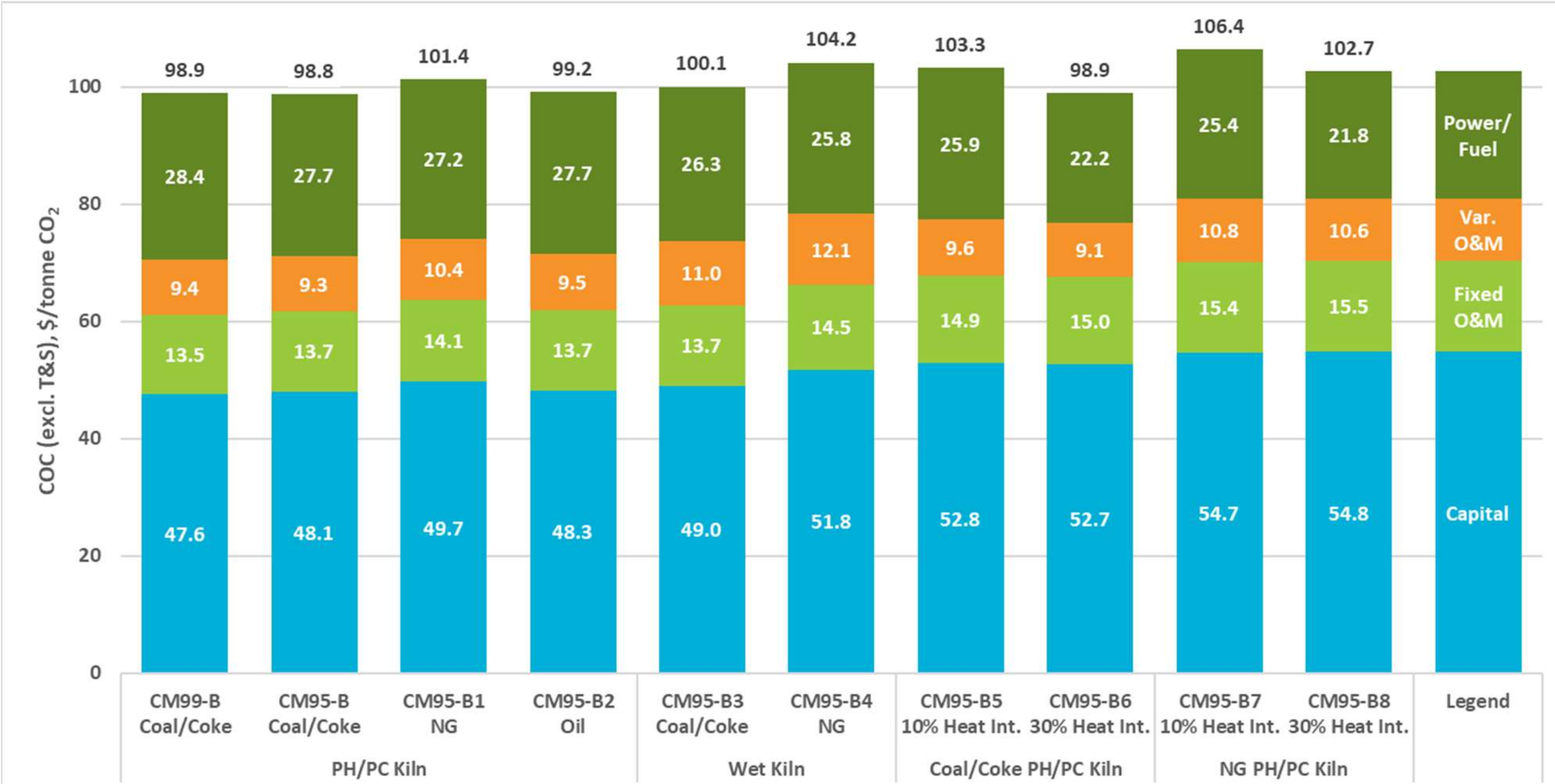
- Captured $CO_2$ streams:
  - Cement kiln combustion flue gas and $CO_2$ produced via calcination
  - Natural gas-fired industrial boiler flue gas
    - Add-on boiler that generates steam for $CO_2$ capture unit and $CO_2$ dryer heat requirements
  - Dilution of $CO_2$ for solid fuel cases

| Case Number | CM99-B | CM95-B[A] | CM95-B1[A] | CM95-B2 | CM95-B3[A] | CM95-B4[A] | CM95-B5 | CM95-B6 | CM95-B7 | CM95-B8 |
|---|---|---|---|---|---|---|---|---|---|---|
| Capture Rate[B] | 99 Percent | 95 Percent | | | | | | | | |
| Kiln Type | Pre-heater/Pre-calciner | | | | Wet Process | | Pre-heater/Pre-calciner | | | |
| Kiln Exit Gas $CO_2$ Concentration[C], mol % | 31 | 31 | 25 | 30 | 17 | 13 | 31 | | 25 | |
| Kiln Fuel Type | Coal/Coke | | NG | Oil | Coal/Coke | NG | Coal/Coke | | NG | |
| Heat Integration | N/A | | | | | | 10 | 30 | 10 | 30 |
| Combined Stream $CO_2$ Concentration[D], mol % | 21 | 21 | 19 | 21 | 15 | 12 | 22 | 23 | 19 | 20 |

[A] Sensitivity cases regarding $SO_x$ and $NO_x$ concentrations are performed for these cases. $SO_x$ at 100, 300, & 500 ppmv. $NO_x$ at 500, 1000, and 1,500 ppmv
[B] The capture rate is indicative of the percentage of $CO_2$ captured from all emissions sources considered (i.e., the cement kiln, the NG boiler required to raise steam for solvent regeneration heating needs, and additional air in-leakage through raw mill processing, where applicable)
[C] The kiln off-gas $CO_2$ mol% is the assumed concentration directly from the kiln, before processing through raw mill operations (i.e., prior to any additional air in-leakage) and excluding comingled $CO_2$ from the NG boiler
[D] The combined stream $CO_2$ mol% is the assumed concentration of the comingled streams from the NG boiler and from the cement kiln before processing through raw mill operations (i.e., prior to any additional air in-leakage)

# Cost and Performance Results

**1) $Cost_{NG}$>$Cost_{coal}$ 2) No free rides with heat integration!**




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

Note: All monetary values Real, Nov. 2022 USD

# Cost and Performance Results

## Base Cases (cont'd)

| Case Number | CM99-B | CM95-B | CM95-B1 | CM95-B2 | CM95-B3 | CM95-B4 | CM95-B5 | CM95-B6 | CM95-B7 | CM95-B8 |
|---|---|---|---|---|---|---|---|---|---|---|
| PERFORMANCE | | | | | | | | | | |
| Operating Basis | **85%** | **85%** | **85%** | **85%** | **85%** | **85%** | **85%** | **85%** | **85%** | **85%** |
| $CO_2$ Captured, tonnes/year | 1,516,106 | 1,426,677 | 1,415,169 | 1,424,904 | 1,688,297 | 1,673,262 | 1,391,847 | 1,325,543 | 1,381,155 | 1,316,892 |
| $CO_2$ Captured, tonnes/hr | 173 | 163 | 162 | 163 | 193 | 191 | 159 | 151 | 158 | 150 |
| $CO_2$ Compressor Load, kW | 13,270 | 12,490 | 12,390 | 12,470 | 14,780 | 14,650 | 12,180 | 11,600 | 12,090 | 11,530 |
| Circulating Water Flow Rate, gpm | 72,800 | 67,058 | 65,439 | 66,974 | 75,927 | 73,552 | 65,774 | 63,216 | 64,217 | 61,563 |
| Cooling Tower Duty (calculated), MMBtu/hr | 728 | 671 | 654 | 670 | 759 | 736 | 658 | 632 | 642 | 616 |
| COST | | | | | | | | | | |
| Total Plant Cost ($/1000) | 573,135 | 544,376 | 557,714 | 545,922 | 656,587 | 687,283 | 583,992 | 554,481 | 599,812 | 572,780 |
| *Bare Erected Cost* | 372,272 | 353,837 | 362,108 | 354,793 | 425,737 | 445,120 | 379,614 | 360,505 | 389,444 | 371,893 |
| *Home Office Expenses* | 65,148 | 61,921 | 63,369 | 62,089 | 74,504 | 77,896 | 66,432 | 63,088 | 68,153 | 65,081 |
| *Project Contingency* | 95,522 | 90,729 | 92,952 | 90,987 | 109,431 | 114,547 | 97,332 | 92,414 | 99,969 | 95,463 |
| *Process Contingency* | 40,192 | 37,888 | 39,284 | 38,053 | 46,914 | 49,720 | 40,613 | 38,474 | 42,247 | 40,342 |
| Total Overnight Cost ($MM) | 694 | 659 | 676 | 661 | 796 | 833 | 707 | 671 | 726 | 694 |
| Total Overnight Cost ($/1000) | 694,192 | 659,341 | 675,757 | 661,257 | 795,743 | 833,149 | 707,054 | 671,212 | 726,493 | 693,706 |
| *Owner's Costs* | 121,057 | 114,965 | 118,043 | 115,334 | 139,157 | 145,866 | 123,062 | 116,731 | 126,681 | 120,926 |
| Total As-Spent Cost ($/1000) | 776,123 | 737,159 | 755,513 | 739,301 | 889,660 | 931,480 | 790,503 | 750,431 | 812,237 | 775,580 |
| *Capital Costs ($/tonne $CO_2$)* | 47.6 | 48.1 | 49.7 | 48.3 | 49.0 | 51.8 | 52.8 | 52.7 | 54.7 | 54.8 |
| *Fixed Costs ($/tonne $CO_2$)* | 13.5 | 13.7 | 14.1 | 13.7 | 13.7 | 14.5 | 14.9 | 15.0 | 15.4 | 15.5 |
| *Variable Costs ($/tonne $CO_2$)* | 9.4 | 9.3 | 10.4 | 9.5 | 11.0 | 12.1 | 9.6 | 9.1 | 10.8 | 10.6 |
| *Purchased Power and Fuel ($/tonne $CO_2$)* | 28.4 | 27.7 | 27.2 | 27.7 | 26.3 | 25.8 | 25.9 | 22.2 | 25.4 | 21.8 |
| *Cost of $CO_2$ Capture (ex. T&S), $/tonne $CO_2$* | **98.9** | **98.8** | **101.4** | **99.2** | **100.1** | **104.2** | **103.3** | **98.9** | **106.4** | **102.7** |
| *Cost of $CO_2$ Capture (incl. T&S), $/tonne $CO_2$* | **108.9** | **108.8** | **111.4** | **109.2** | **110.1** | **114.2** | **113.3** | **108.9** | **116.4** | **112.7** |



Note: All monetary values Real, Nov. 2022 USD

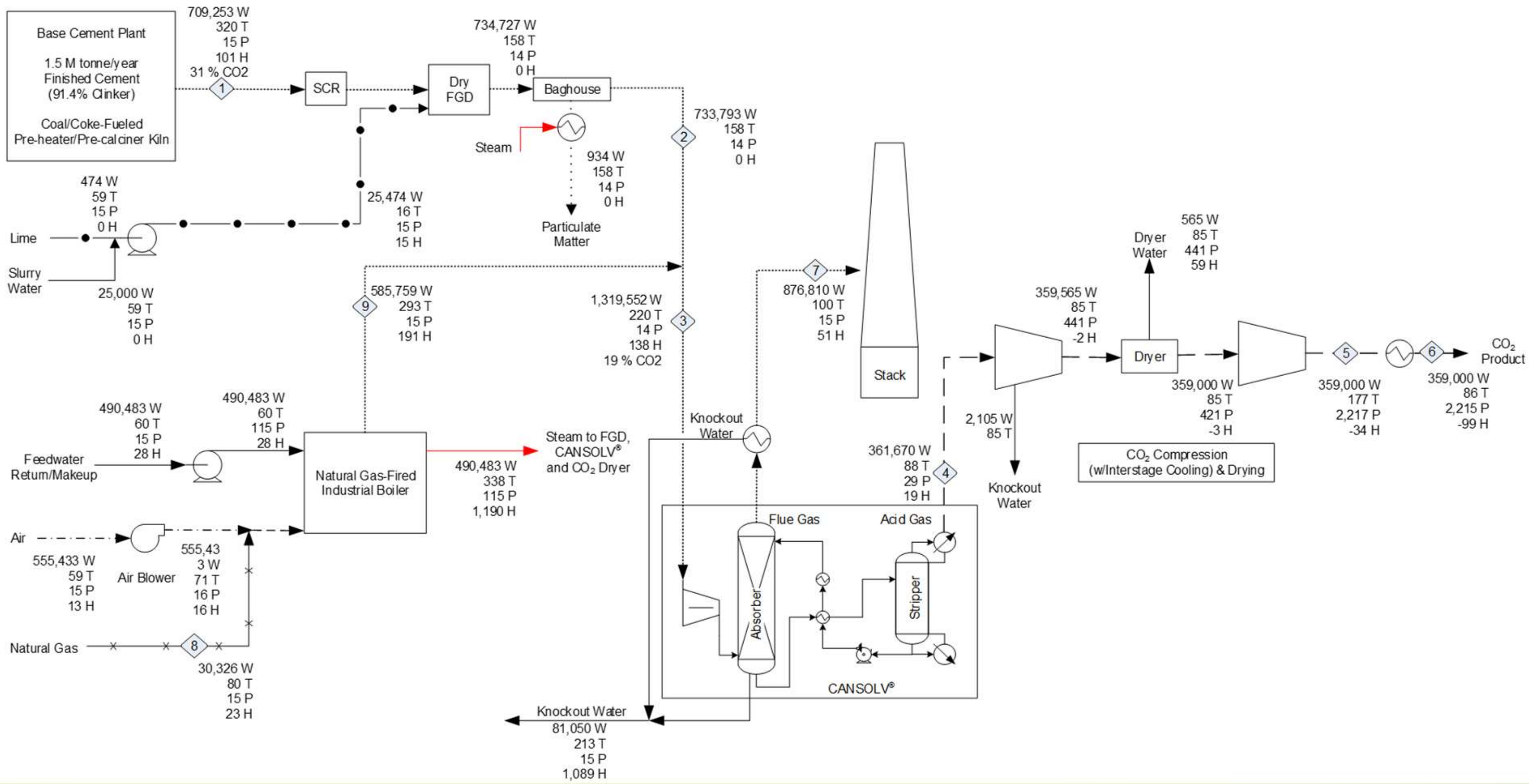
# Cost and Performance Results

## FGD + SCR Sensitivity Summary

- An analysis of the effects of capture stream contaminants (e.g., $NO_x$, $SO_x$) are included for coal/coke, gas-fired preheater/precalciner and wet fed cases (CM95-B, CM95-B1, CM95-B3, CM95-B4)
- The $CO_2$ emissions stream from the kiln was treated for removal of $SO_x$ and $NO_x$
- Kiln exhaust SOx/NOx levels varied between 100-500 ppmv/500-1,500 ppmv, respectively
  - A dry lime flue gas desulfurization (FGD) system was employed to scrub $SO_2$ from the kiln off-gas, such that the $SO_2$ content ≤ inlet maximum of 37 $ppm_v$
    - Along with the polishing scrubber in the capture system (~97 percent removal efficiency), $SO_x$ emissions are essentially zero for all cases
  - SCR was evaluated upstream of the FGD unit for $NO_x$ removal such that the $NO_x$ content ≤ inlet maximum of 2 $ppm_v$ $NO_x$ (assuming 5% $NO_2$ and the balance NO)

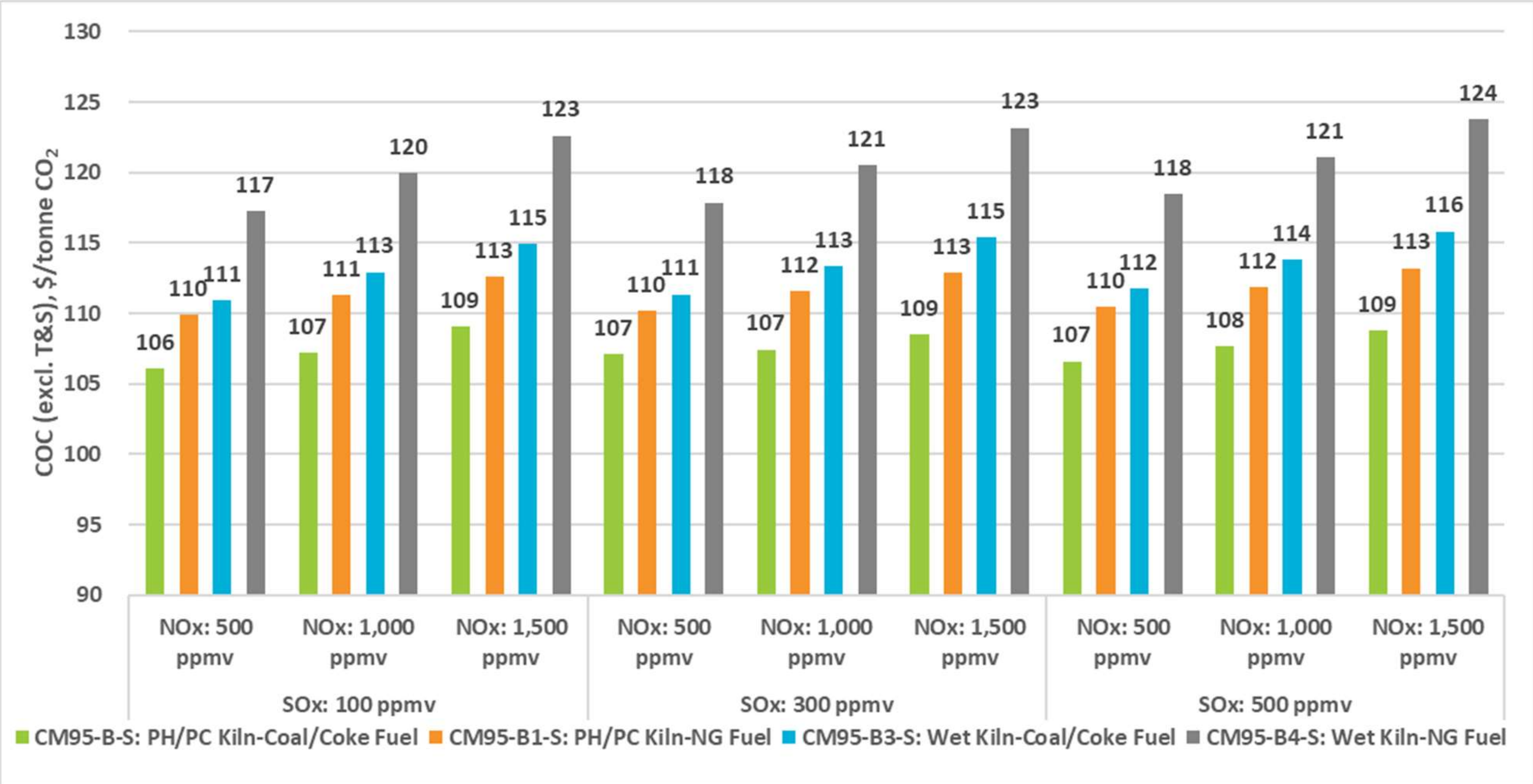
# Cost and Performance Results

## Coal/coke-fired, preheater/precalciner FGD + SCR Sensitivity Cases (Represented by CM95-B-S300-N1000)



# Cost and Performance Results

## FGD + SCR Sensitivity Summary (cont'd)

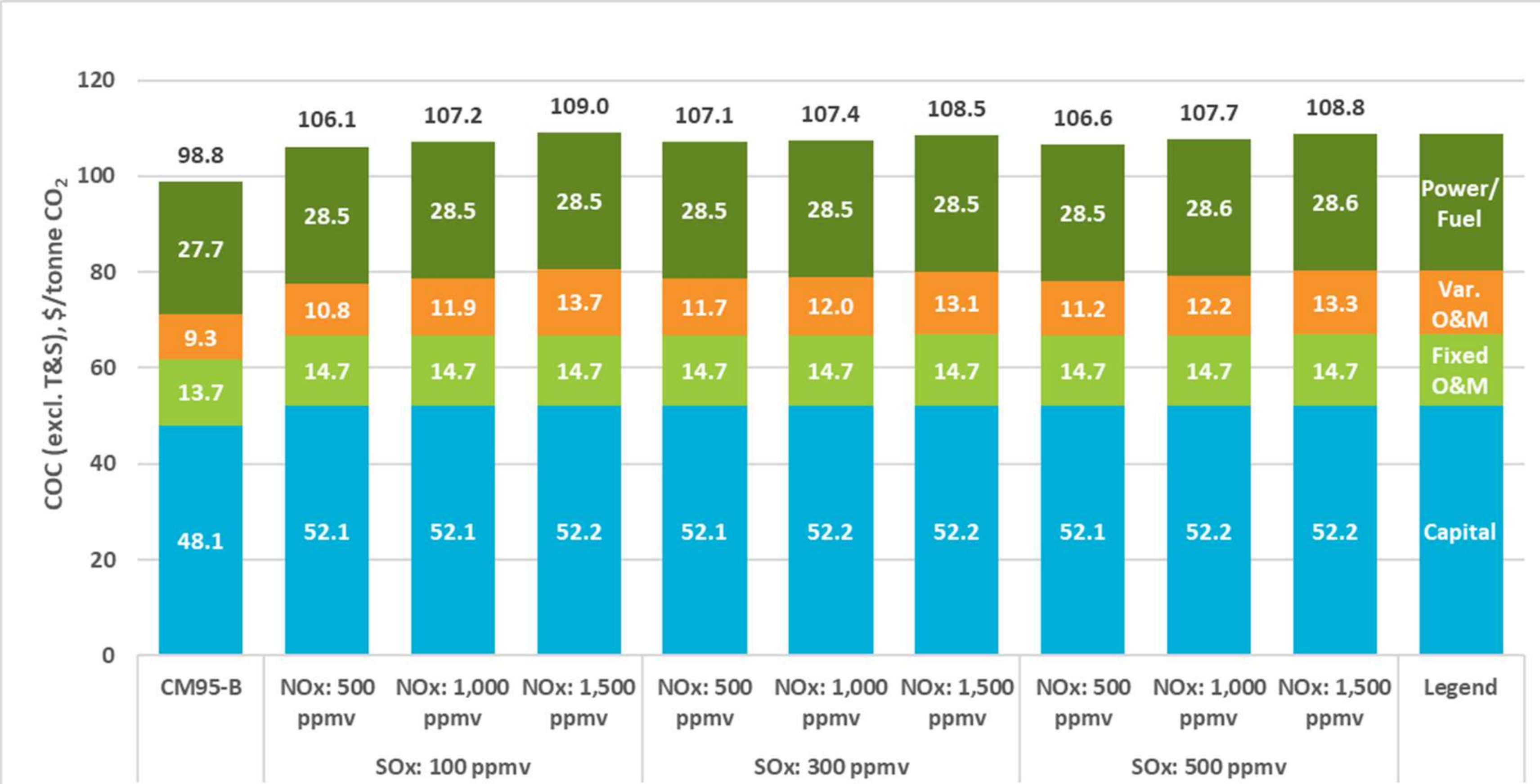



$$\left(\frac{\$}{tonne\ CO_2}\right) = \frac{TOC * CCF + FOM + VOM + PF + PP}{tonnes\ CO_2\ captured\ per\ year}$$

Note: All monetary values Real, Nov. 2022 USD

# Cost and Performance Results

## Coal/coke-fired, preheater/precalciner (CM95-B) FGD + SCR Sensitivity




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

Note: All monetary values Real, Nov. 2022 USD

# Cost and Performance Results

## Air In-Leakage Scenario Analysis Summary

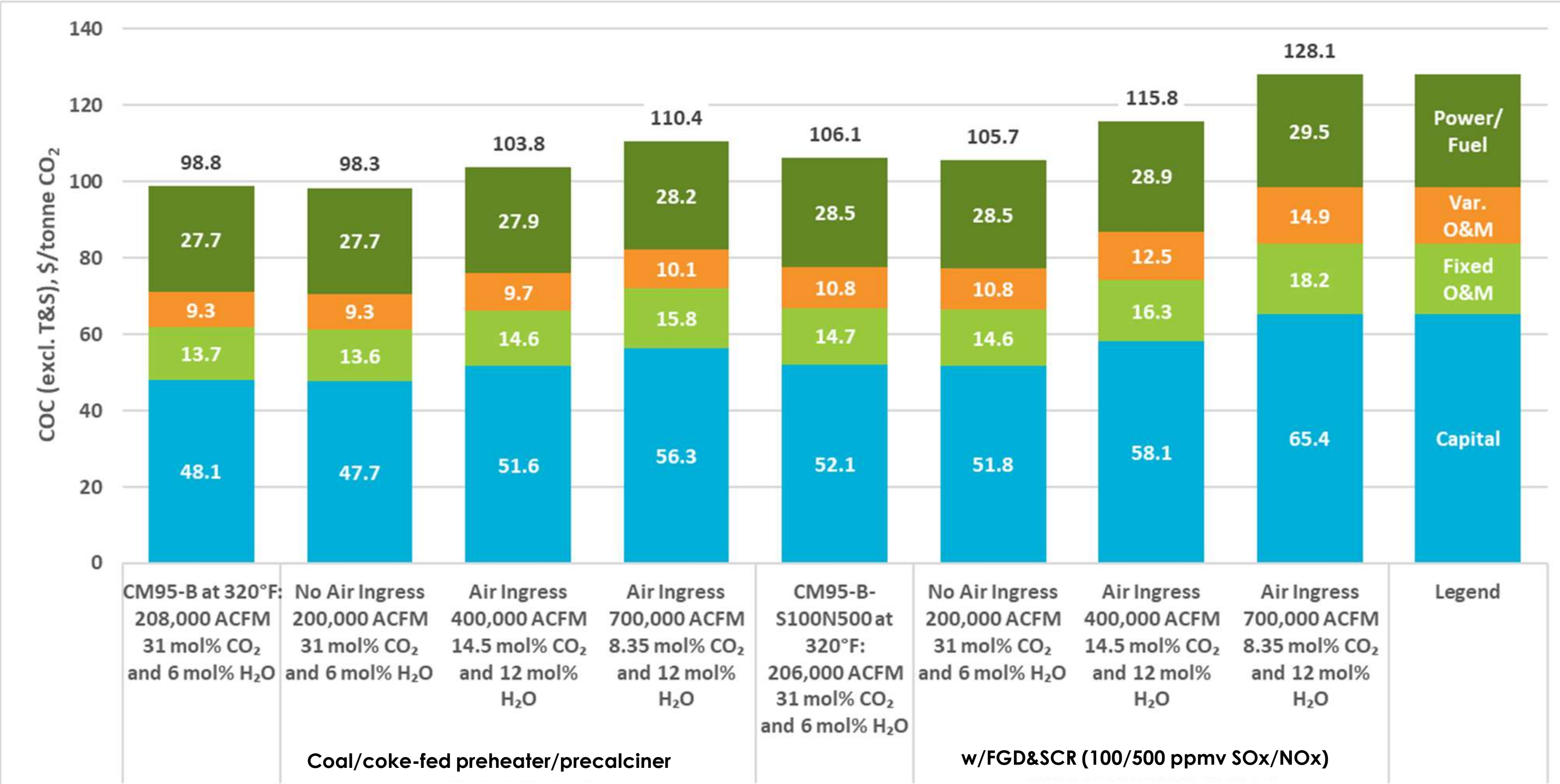
- Kiln off-gas often used for heating/drying the raw mill, and moisture content and volumetric flowrate increase, as air leaks into the stream when passing through raw mill units and water is absorbed from the raw mill
- Coal/coke-fed preheater/precalciner design cases (w/ & w/out SCR, FGD) varied to show effects of air ingress:
  1. Kiln off-gas at 250°F with base case composition and flowrate (i.e. no extra air, moisture)
  2. Kiln off-gas at 250°F with additional moisture, air (12 mol% $H_2O$, air added to achieve 400,000 ACFM)
  3. Kiln off-gas at 250°F with additional moisture, air (12 mol% $H_2O$, air added to achieve 700,000 ACFM)

| Case | Coal/coke-fed preheater/precalciner | | | | w/FGD&SCR (100/500 ppmv SOx/NOx) | | | |
|---|---|---|---|---|---|---|---|---|
| Air In-leakage Scenario | | Entering Capture System at 250°F | | | | Entering Capture System at 250°F | | |
| | Base Case 320°F | Base Case | 400,000 ACFM | 700,000 ACFM | Base Case 320°F | Base Case | 400,000 ACFM | 700,000 ACFM |
| Kiln Type | Pre-heater/Pre-calciner | | | | | | | |
| Fuel Type | Coal/Coke | | | | | | | |
| Treated Stream Temperature, °F | 320 | 250 | | | 320 | 250 | | |
| Treated Stream $H_2O$ Concentration, mol % | 5.95 | | 12 | | 5.95 | | 12 | |
| Treated Stream $CO_2$ Concentration, mol % | 30.8 | | 14.6 | 8.4 | 31.1 | | 14.6 | 8.4 |
| Treated Stream Volumetric Flowrate, 1,000 ACFM | 208 | 200 | 400 | 700 | 206 | 200 | 400 | 700 |

Note: ACFM = actual cubic feet per minute

# Cost and Performance Results

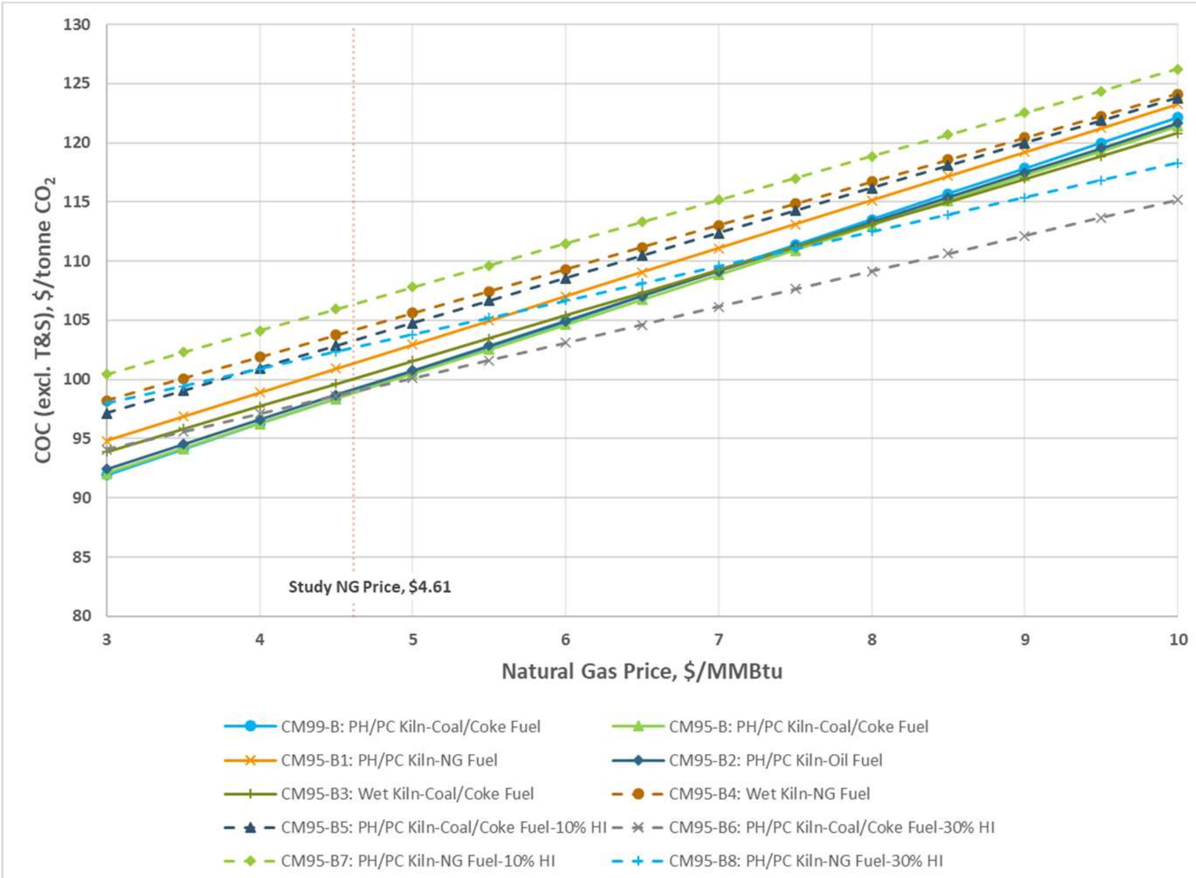
## Air In-Leakage Scenario Analysis Results




Note: All monetary values Real, Nov. 2022 USD

# Sensitivity Analyses

## Natural Gas Price

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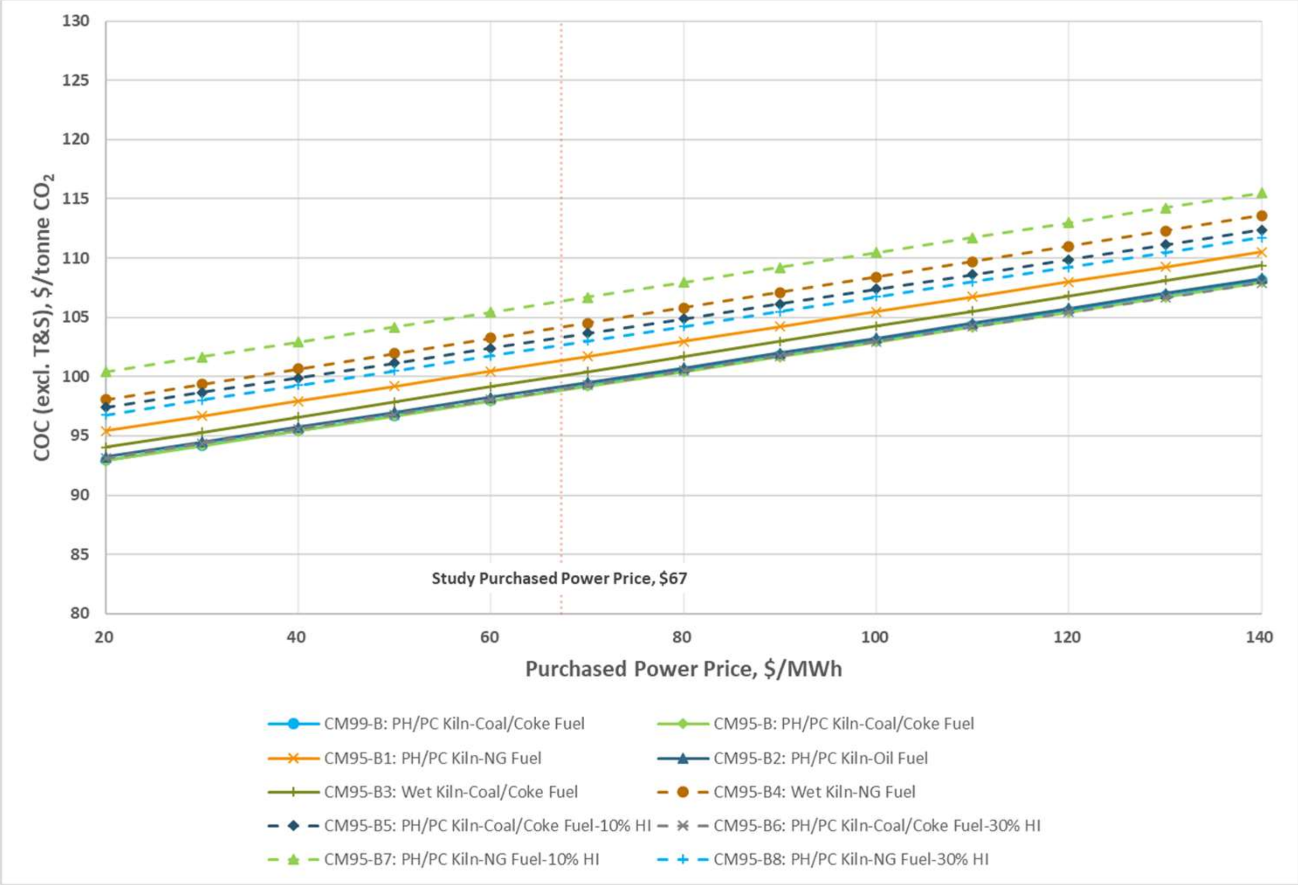
Note: All monetary values Real, Nov. 2022 USD

# Sensitivity Analyses

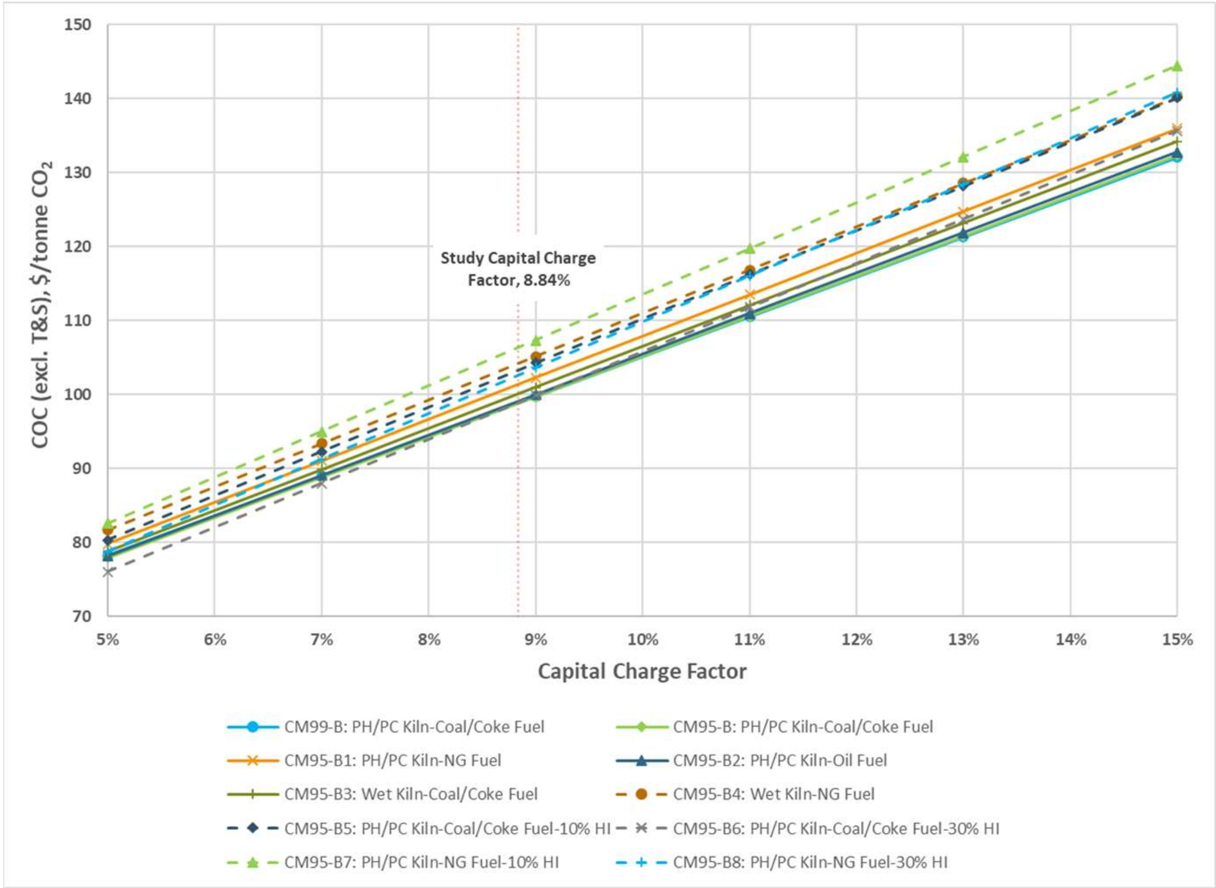
## Purchased Power Price




Note: All monetary values Real, Nov. 2022 USD

# Sensitivity Analyses

## Capital Charge Factor



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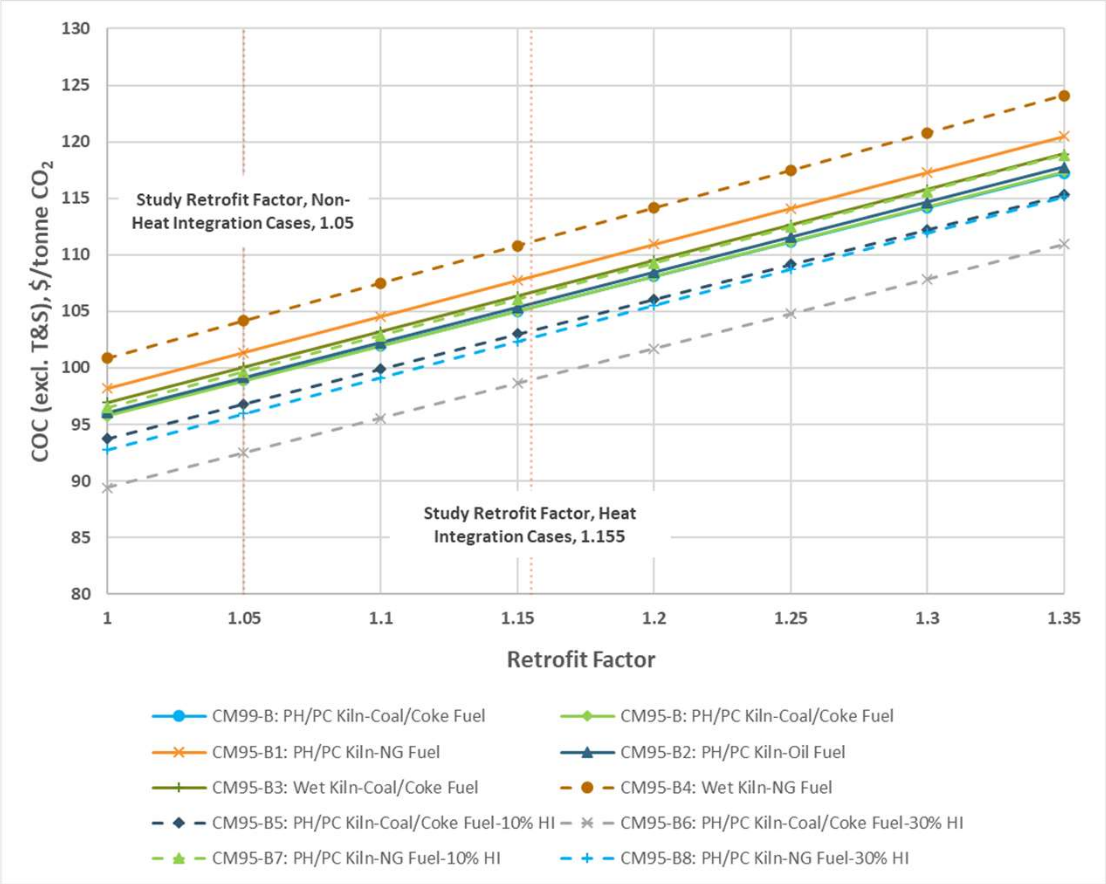
# Sensitivity Analyses

## Retrofit Difficulty Factor



# Cost Comparison: 2018 vs 2022 US Dollars

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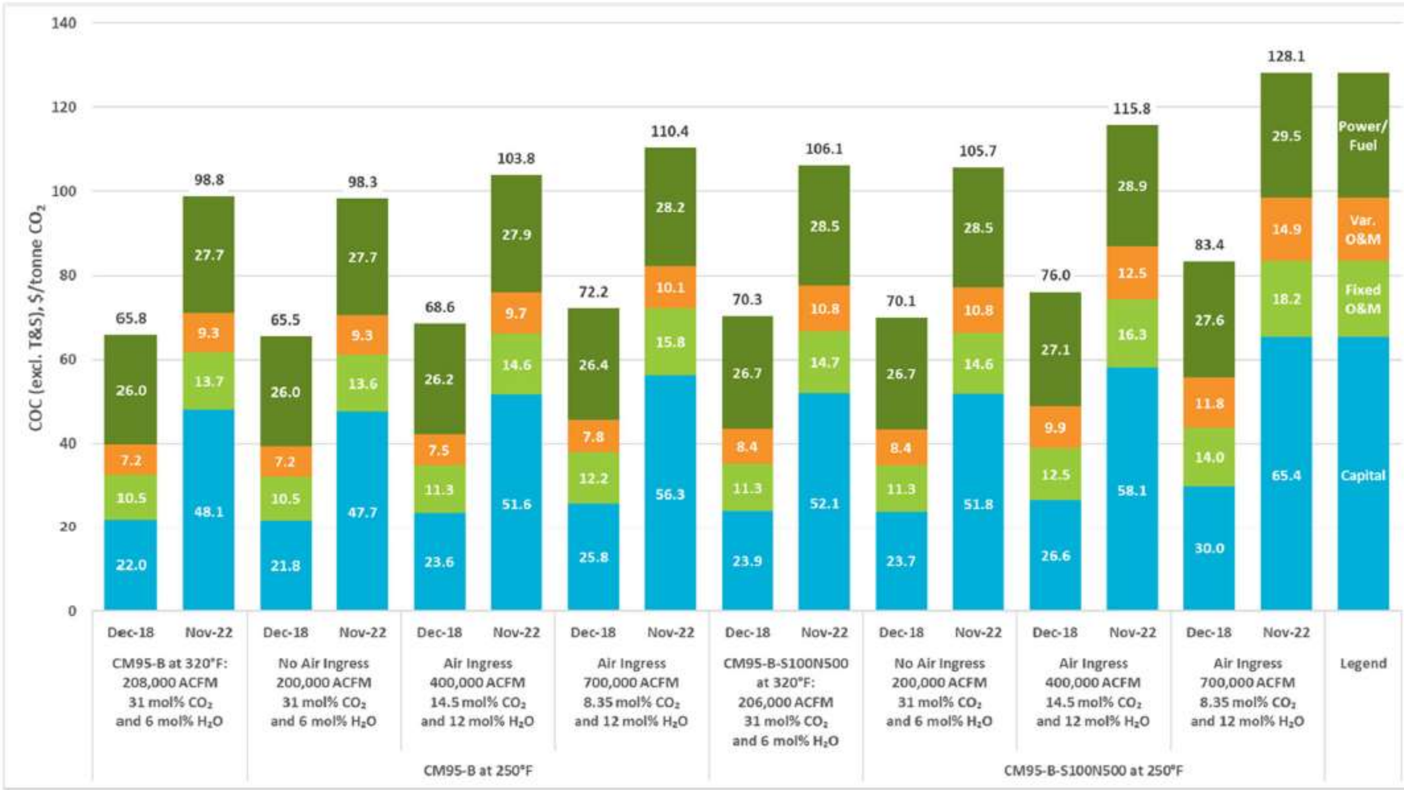
- Increases in cost of money, escalation resulted in cost of capture increases ~50% (+)
- Increases in utility pricing (i.e. natural gas, auxiliary power) had minimal impact



# Final Report

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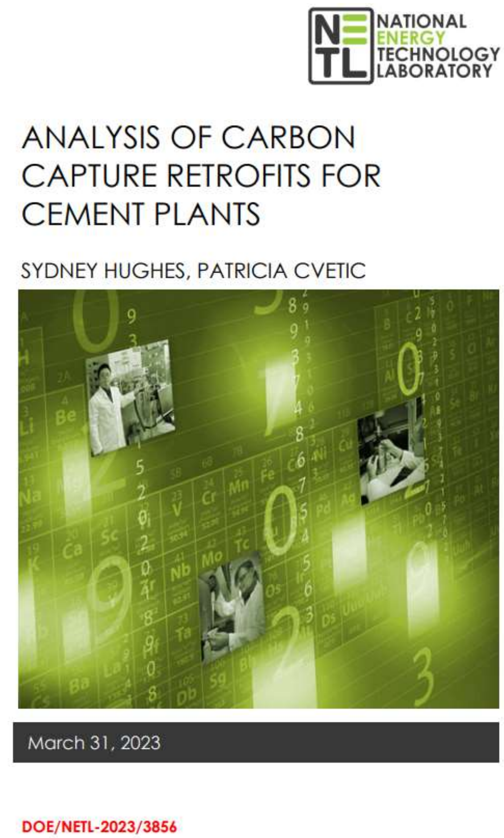
- Final report is available on NETL website
- Detailed cost tables, mass/energy balances
- All costs expressed in 2022 USD, but 2018 costs retained in appendix for comparison (price escalation, cost of money impacts, etc)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ANALYSIS OF CARBON CAPTURE RETROFITS FOR CEMENT PLANTS

SYDNEY HUGHES, PATRICIA CVETIC

March 31, 2023

DOE/NETL-2023/3856

# Questions/ Comments

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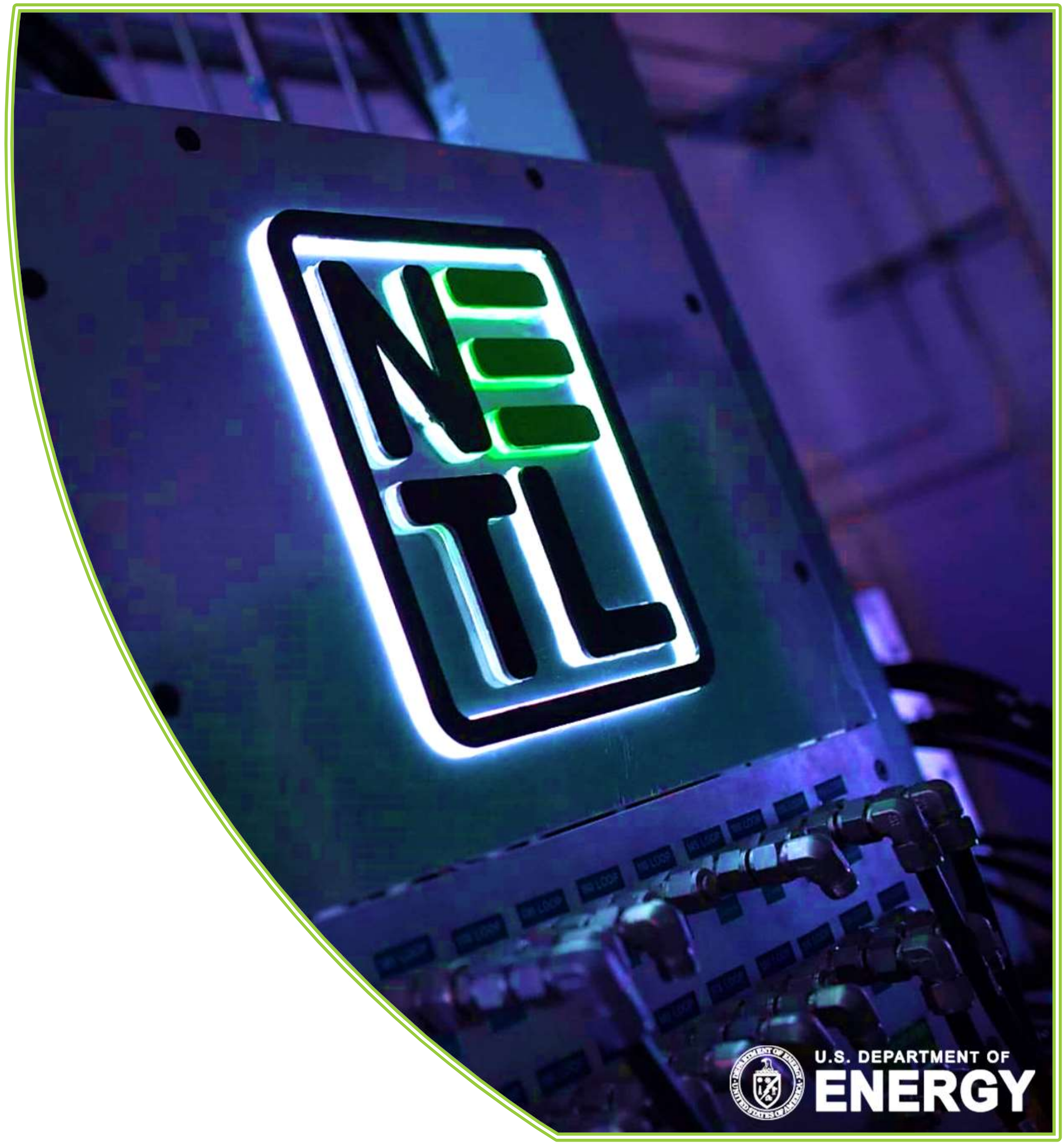

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