Analysis of Carbon Capture Retrofits for Cement Plants

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Project Contributors

Several NETL federal and contract support staff, as well as third-party technical advisors, helped develop the report detailed in this presentation:

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This report was reviewed by technical experts at the PCA to ensure that the information presented is based on sound and credible science and considered technically adequate, competently performed, properly documented, and in compliance with established quality requirements. The following individuals at PCA are acknowledged, along with several of their expert industry members, for their technical expertise and 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.
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Background

- Current data suggest an anticipated cement market growth.
  - The U.S. government passed the $1 trillion infrastructure bill in Q3 2021 with the intent to rebuild the nation's deteriorating roads and bridges and fund new climate resilience and broadband initiatives.
- 45Q has driven increased interest in carbon capture and storage retrofit opportunities, including in the non-power sector.
  - Cement manufacturing produced about 2.3 gigatons of carbon dioxide (CO_2) emissions in 2019, representing ~7% of total global CO_2 emissions [1].
  - According to the National Minerals Information Center, 1.5% of U.S. CO_2 emissions are attributable to the cement industry [2].

Objectives

- Develop Aspen Plus® process models and associated performance templates for solvent-based CO_2 capture and compression applied to the emissions streams characteristic of representative cement plants.
- Evaluate system cost and performance estimates to
  - Characterize the cement plant CO_2 capture system at each representative cement plant in terms of major stream flows, temperatures, pressures, compositions, etc.
  - Estimate the capital and operating costs of representative cement plants using model outputs and vendor data, and engineering, procurement, and construction guidance.
  - Quantify the cost implications of retrofit installation of CO_2 capture units at representative cement plants.

Study Assumptions

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Cost Estimation Methodology

- NETL has a library of legacy system analysis studies that serve as a basis for cost scaling references, cement plant-specific vendor data for CO_2 capture systems, balance of plant performance and cost information, financial methodologies, and other components of systems analysis. These references are applied as appropriate to this study.
- Costs of capturing CO_2 are quantified both excluding and including transport and storage (T&S) costs. Assuming (1) the base plant is located at a Midwest site and (2) transport to and storage in the Illinois Basin by means of a 100-km (62-mile) pipeline, a T&S cost of $10/tonne CO_2 is adopted [3].
- The base cement plants are not modeled. Emissions streams from representative plants are characterized, which include varying degrees of air ingress and moisture increases through raw mill processing for select cases.
  - Heat integration potential and retrofit difficulty factors are applied as a mathematical exercise without consideration of host plant specifics.

Study Assumptions

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Financial Methodology

- The cost of capture (COC), 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 operation and maintenance (O&M) costs.
  - VOM – Annual variable O&M costs.
  - PF – Purchased fuel ($4.61/MMBtu).
  - PP – Purchased power ($67.3/MWh).

- Financial parameters specific to the cement industry were developed by NETL's Energy Markets Analysis Team and reflect 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	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

Study Assumptions

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Kiln Exit Gas Conditions

- Average CO_2 emissions factors for the representative cement plants are based on Global Cement and Concrete Association (GCCA) "Getting the Numbers Right Project" data [4].
  - Each average total emissions rate is based on data collected from U.S. producers based on kiln type and accounts for kiln combustion fuel emissions and CO_2 from calcination.
  - No factor for long-dry kilns was provided, and the long-dry kiln was not included in this study, as none are in service in the U.S. as of the GCCA data sampling.

	For PH/PC Kilns	For Wet Kilns	Units
Cement Production Rate	**1,500,000**	**1,500,000**	tonnes per year
Percentage Clinker	91.4%	91.4%	per PCA EPD [5]
Clinker Production Rate	1,371,000	1,371,000	tonnes per year
Total Emissions Rate	**848 [4]**	**1,026 [4]**	kg CO_{2e} per tonne clinker
Annual CO_2 Emissions from Kiln	1,162,608	1,406,646	tonnes per year
CO_2 Emissions from Kiln	**297,370**	**359,790**	lb/hr at 100% operating basis
Applicable Cases	CM99-B; CM95-B CM95-B1; CM95-B2 CM95-B5; CM95-B6 CM95-B7; CM95-B8	CM95-B3 CM95-B4	

Note: PH = pre-heater; PC = pre-calciner PCA = Portland Cement Association; EPD = Environmental Product Declaration

Study Assumptions

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Case Matrix

- The representative cement plant produces 1.5 million tonnes of finished cement per year (assuming 91.4% clinker) and with the addition of capture emits CO_2 via two streams, both at atmospheric pressure.
  - Cement kiln combustion flue gas and CO_2 produced via calcination.
  - Natural gas (NG)-fired industrial boiler flue gas.
    - Add-on boiler that generates steam for CO_2 capture unit and CO_2 dryer heat requirements.

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 (HI)	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 oxides of sulfur (SO_x) and oxides of nitrogen (NO_x) concentrations are included with SO_x at 100, 300, & 500 ppmv. NO_x at 500, 1000, and 1,500 ppmv.

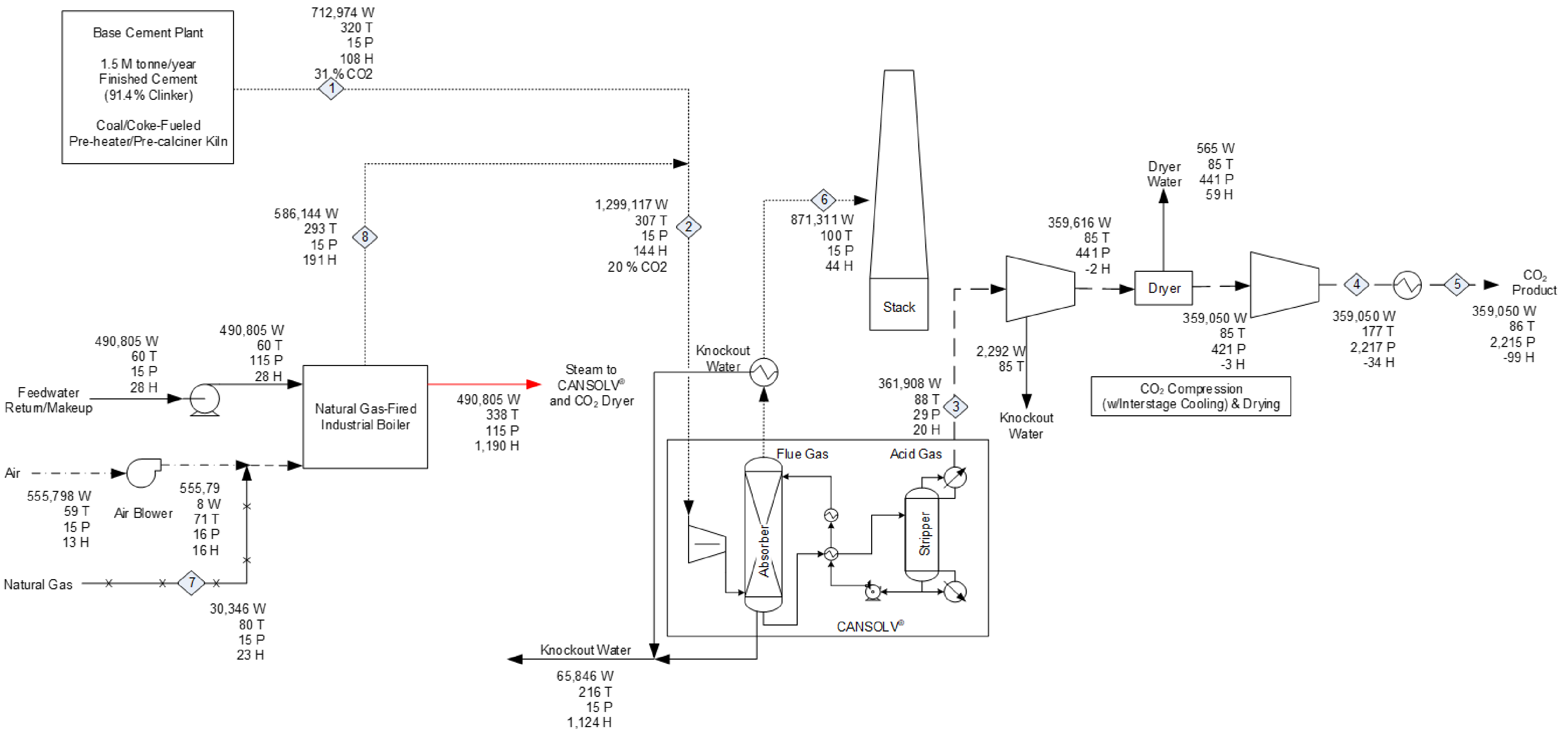
[B]The capture rate is indicative of the percentage of CO_2 captured from all emissions sources considered (i.e., the cement kiln, the NG boiler required to raise steam for solvent regeneration heating needs, and additional air in-leakage through raw mill processing, where applicable).

[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 not including 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

Base Cases (Represented by CM95-B)



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Cost and Performance Results

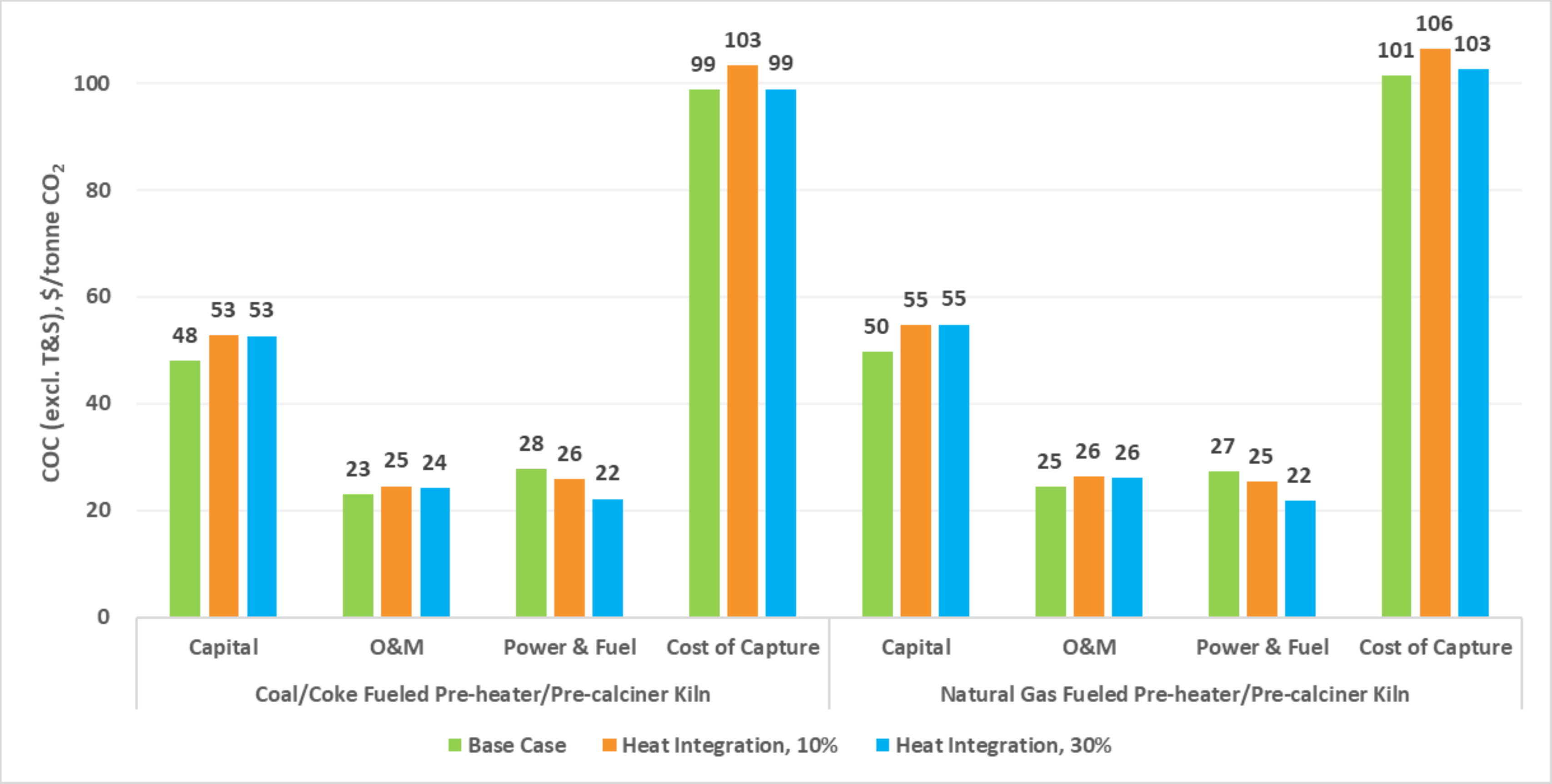
Base Cases

Note: All monetary values Real, Nov. 2022 U.S. Dollars (USD)

Cost and Performance Results

Heat Integration Cases

- Heat integration potential was considered at 10 and 30% based on cases CM95-B and CM95-B1.
  - An additional 10% increase to the retrofit difficulty factor (i.e., retrofit factor of 1.155) was considered for Heat Integration cases.



Note: All monetary values Real, Nov. 2022 USD

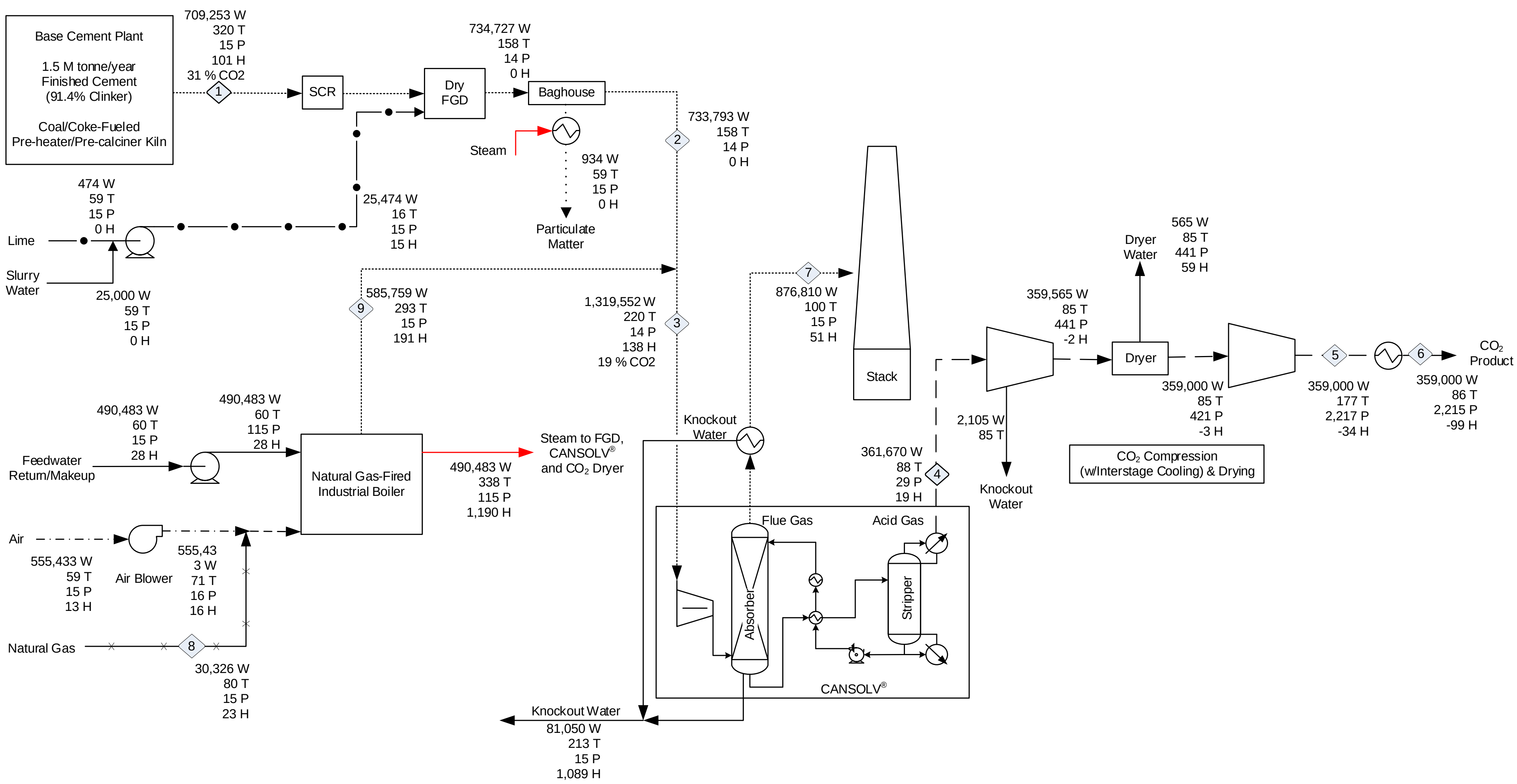
Cost and Performance Results

Flue Gas Desulfurization (FGD) + Selective Catalytic Reduction (SCR) Sensitivity Summary

- An analysis of the effects of capture stream contaminants (e.g., NO_x, SO_x, particulate matter [PM]) is included for cases CM95-B, CM95-B1, CM95-B3, and CM95-B4.
- The CO_2 emissions stream from the kiln was treated for removal of SO_x and NO_x as well as for the resulting PM created in the FGD process.
  - A dry FGD process was employed, utilizing lime as a reactant to remove SO_2 from the kiln off-gas, such that the combined stream SO_2 content was at or below the quoted capture system inlet maximum of 37 ppm_v SO_2 [6].
    - The resulting SO_X emissions are below the regulatory limit of 0.4 $lb/ton_{clinker}$ in all cases [7]; with the polishing scrubber in the capture system (~97% removal efficiency), SO_x emissions are essentially zero for all cases.
  - A polishing baghouse was included for PM removal such that the resulting PM emissions from the process meet the annual regulatory limit of 0.07 $lb/ton_{clinker}$ [7].
  - SCR was applied to the kiln off-gas stream for NO_x removal such that the combined stream NO_x content entering the capture system was at or below the quoted capture system inlet maximum of 2 ppm_v NO_x, assuming 5% NO_2 and the balance being NO [6].
    - The resulting NO_x emissions are below the regulatory limit of 1.5 $lb/ton_{clinker}$ in all cases [7].

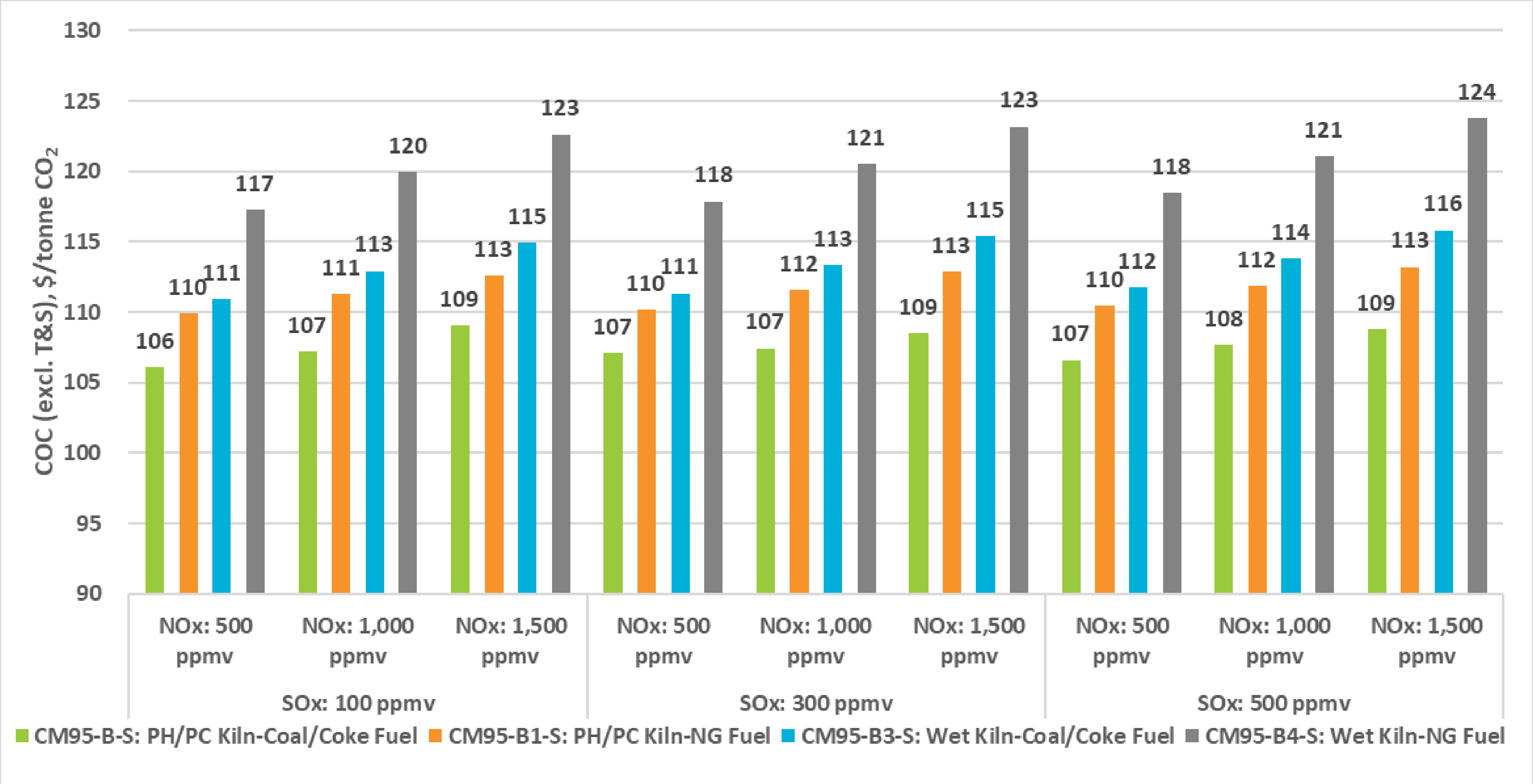
Cost and Performance Results

FGD + SCR Sensitivity Cases (Represented by CM95-B-S300-N1000)



Cost and Performance Results

FGD + SCR Sensitivity Summary (continued)



Note: All monetary values Real, Nov. 2022 USD

Cost and Performance Results

Air In-Leakage Scenario Analysis Summary

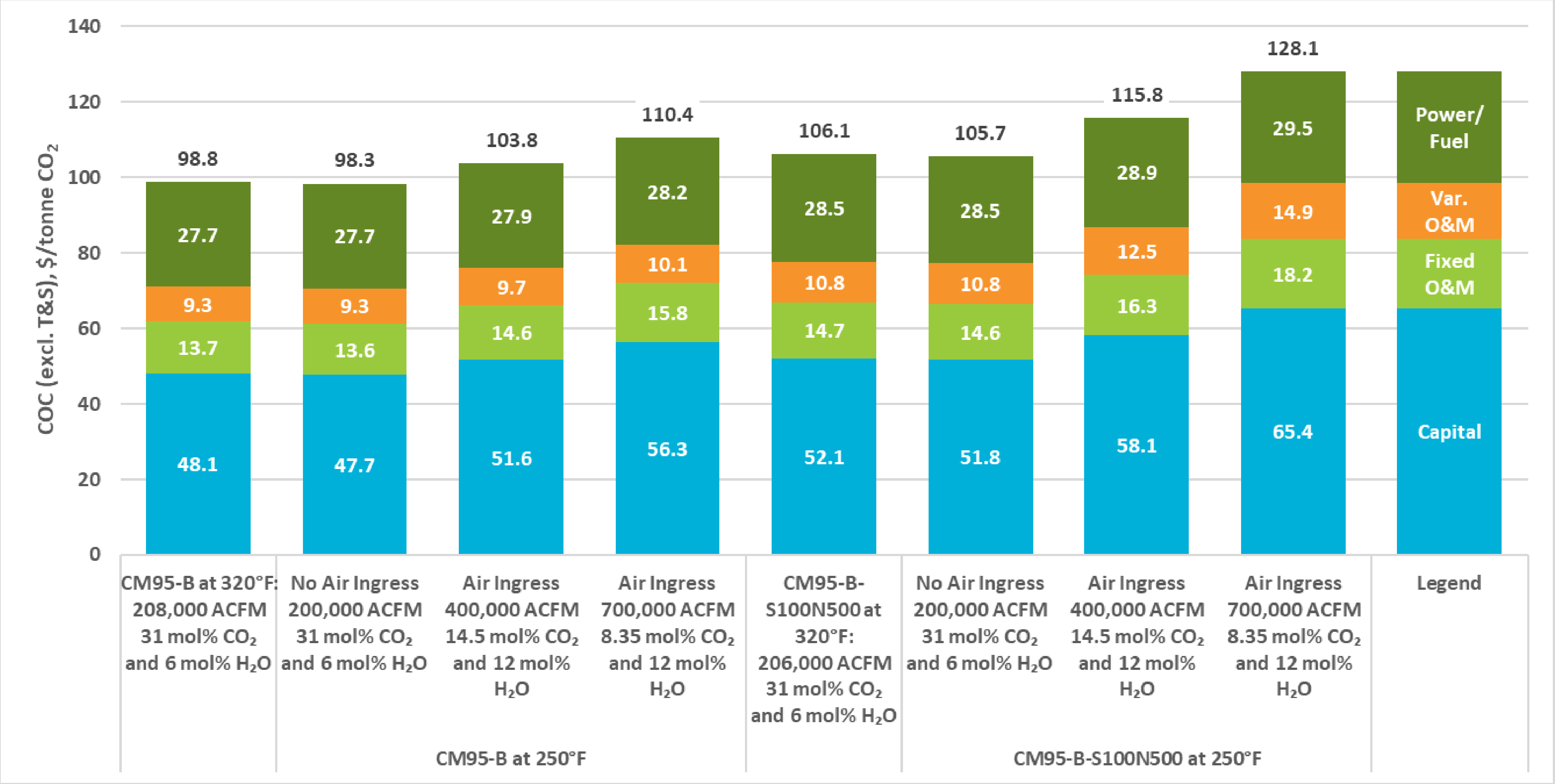
- The kiln off-gas in a cement plant is often used for heating and drying the raw mill in the first steps of the cement production process. As a result, the moisture content and volumetric flowrate of the stream to be treated increase as air leaks into the stream when passing through raw mill units and water is absorbed from the raw mill.
- To show deviations from base case cost and performance for various air in-leakage scenarios, base case CM95-B was manipulated to produce the following design cases; the same three scenarios were evaluated for case CM95-B-S100N500 to show impacts to a case that includes FGD and SCR:
  1. Kiln off-gas at 250 °F with base case composition and flowrate.
  2. Kiln off-gas at 250 °F with 12 mol% H_2O and air added to the kiln off-gas to bring the total gas flow to 400,000 ACFM.
  3. Kiln off-gas at 250 °F with 12 mol% H_2O and air added to the kiln off-gas to bring the total gas flow to 700,000 ACFM.

Base Case Number	CM95-B				CM95-B-S100N500			
		Entering Capture System at 250°F				Entering Capture System at 250°F		
Air In-leakage Scenario	Base Case 320°F	Base Case	400,000 ACFM	700,000 ACFM	Base Case 320°F	Precooled Base Case	Precooled 400,000 ACFM	Precooled 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	8.35	31.1		14.6	8.35
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

Conclusions

- Increasing levels of SO_x, NO_x, and PM in the kiln emissions stream incur cost premiums associated with capital and O&M costs required to abate those contaminants and avoid detriment to the solvent system.
  - A 7.4–18.8% increase in COC over the respective base case (i.e., analogous cases without additional SO_x/NO_x/PM abatement).
    - The capital cost increase associated with the addition of FGD and SCR was 8.4–13.7% relative to their respective base cases, suggesting that additional capital costs provide the most impact to the COC for cases with more advanced SO_x and NO_x control.
- False air and moisture ingress into the kiln emissions stream can result in a notable increase to the COC due to the higher capital costs required to accommodate larger gas volumes at the capture system inlet.
  - Capture costs can increase by as much as 11.7% for cases without FGD and SCR and 20.7% for cases with SCR and FGD.
  - PCA contributors indicate that false air ingress and the presence of SO_x and NO_x in the emissions stream is the most likely scenario for plants in the current domestic fleet.

Questions/ Comments

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https://www.osti.gov/biblio/1970135

References

1. A. Hasanbeigi, "Global Cement Industry's GHG Emissions," May 17, 2021, Global Efficiency Intelligence. [Online] Available: https://www.globalefficiencyintel.com/new-blog/2021/global-cement-industry-ghg-emissions. [Accessed 12 October 2021].
2. National Minerals Information Center, "Cement Statistics and Information." [Online]. Available: https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf. [Accessed 3 September 2021].
3. NETL, "Quality Guidelines for Energy System Studies: Carbon Dioxide Transport and Storage Costs in NETL Studies," U.S. DOE/NETL, Pittsburgh, 2019.
4. GCCA, "Getting the Numbers Right Project," 2019.
5. PCA, "Environmental Product Declaration: Portland Cement," March 12, 2021, Portland Cement Association. [Online] Available: https://mitsubishicement.com/wp-content/uploads/pca_epds_2021.pdf. [Accessed 24 November 2021]
6. NETL, "Quality Guidelines for Energy System Studies: Capital Cost Scaling Methodology," U.S. DOE/NETL, Pittsburgh, 2019.
7. National Emission Standards for Hazardous Air Pollutants From the Portland Cement Manufacturing Industry, 40 C.F.R. § 63 (1999). https://www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-63/subpart-LLL.

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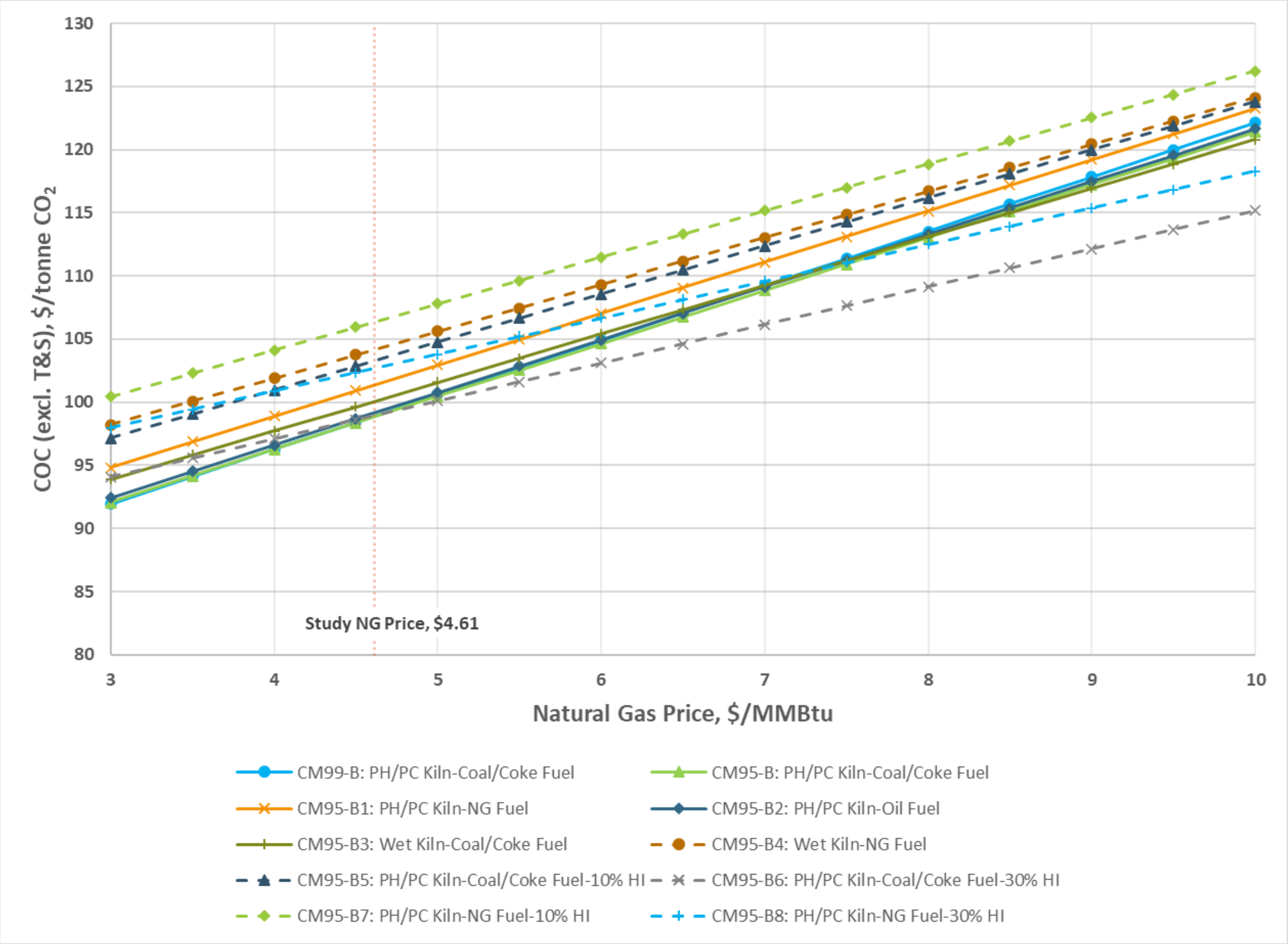
Supplemental Slides

Sensitivity Analyses

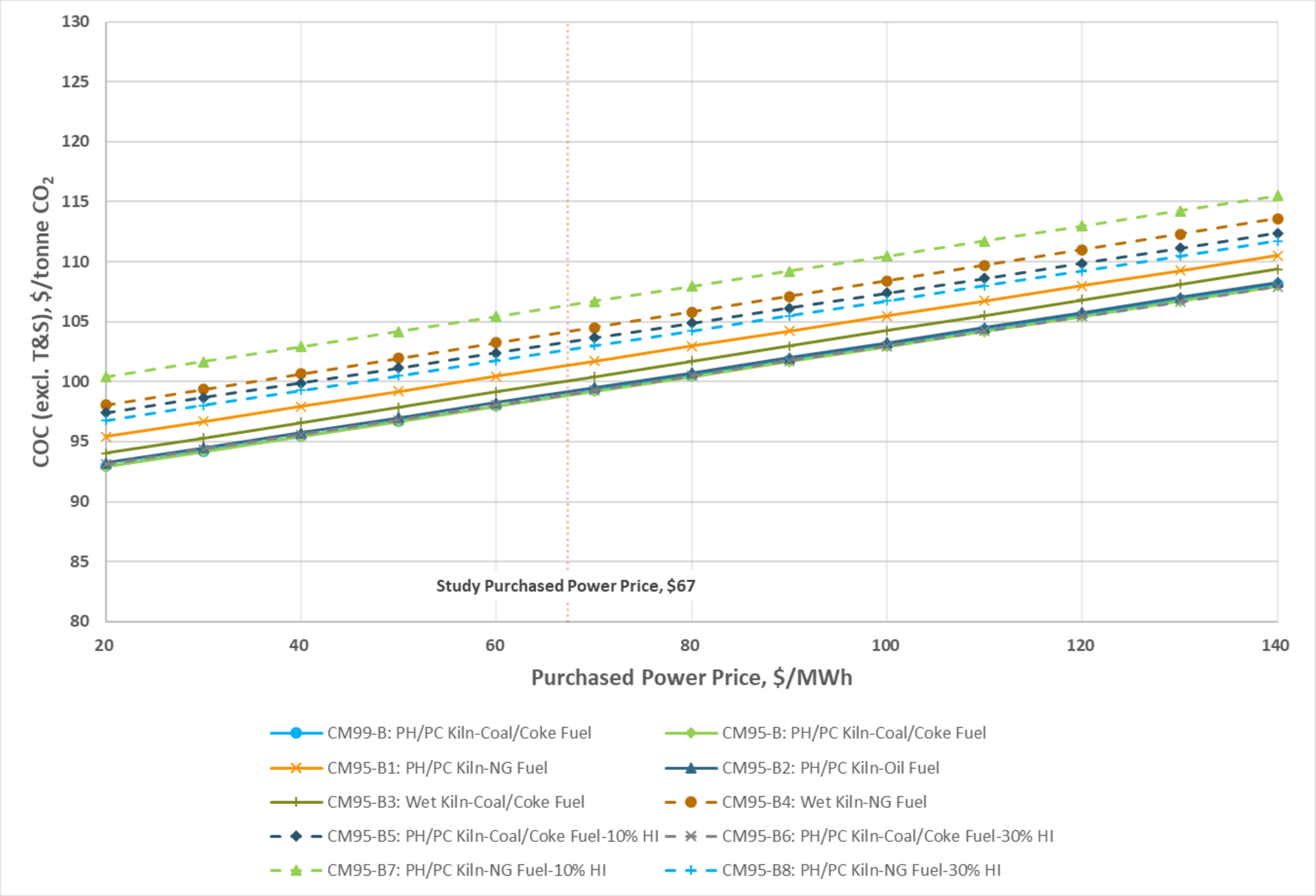
Natural Gas Price



Note: All monetary values Real, Nov. 2022 USD

Sensitivity Analyses

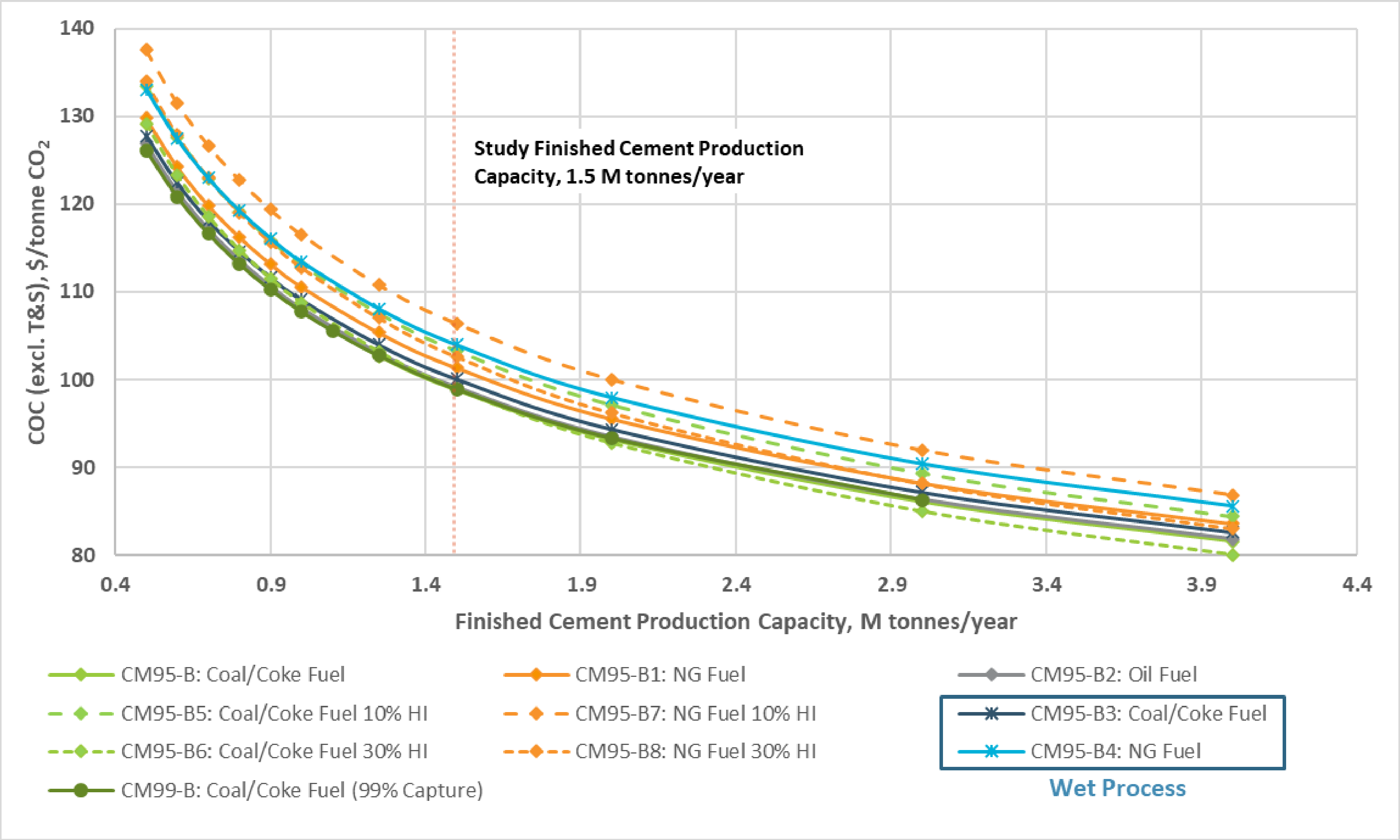
Purchased Power Price



Note: All monetary values Real, Nov. 2022 USD

Sensitivity Analyses

Finished Cement Production Capacity (CO_2 Generated) for Base Cases



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