

Future Energy Systems Center

Cost-Performance Analysis and Benchmarking of CO₂ Capture Systems for Hard-to-Abate Industries

Project Updates
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Project Team

Principal Investigators



Alan Hatton

Ralph Landau Professor of Chemical
Engineering Practice
MIT Department of Chemical Engineering



Betar Gallant

Class of '22 Career Development Professor,
MIT Department of Mechanical Engineering



Randall Field

Director of Research
MIT Energy Initiative



Guiyan Zang

Research Scientist
MIT Energy Initiative

Postdocs



Woojae Shin

Postdoc
MIT Energy Initiative



David Shu

Postdoc
MIT Energy Initiative



Haoxiang (Hundey) Lai

Postdoc
MIT Energy Initiative



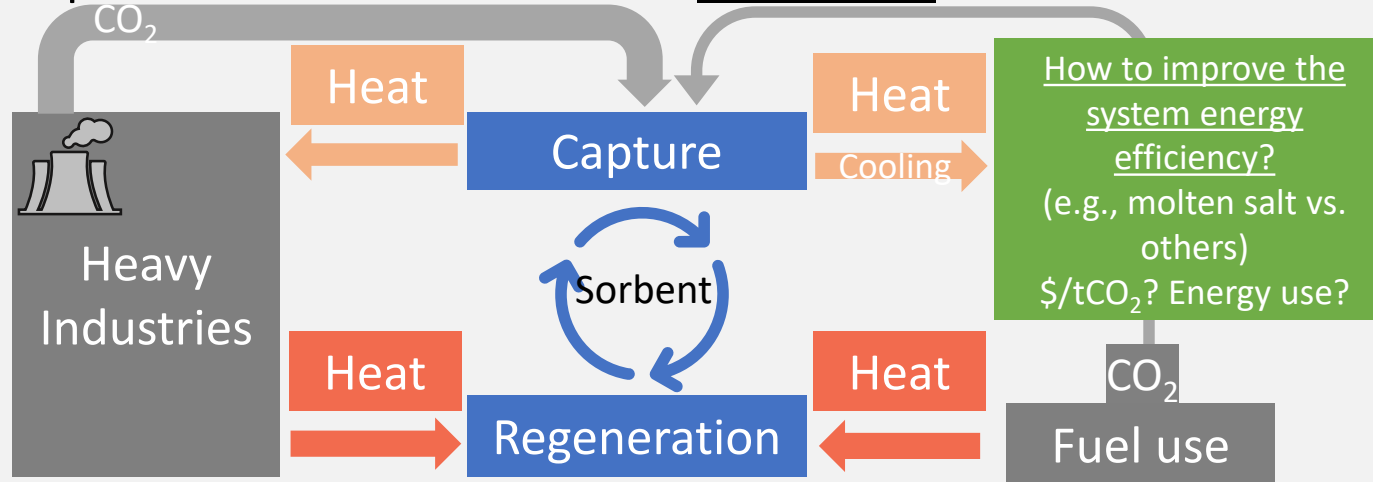
Bosong Lin

Previous Postdoc
MIT Energy Initiative

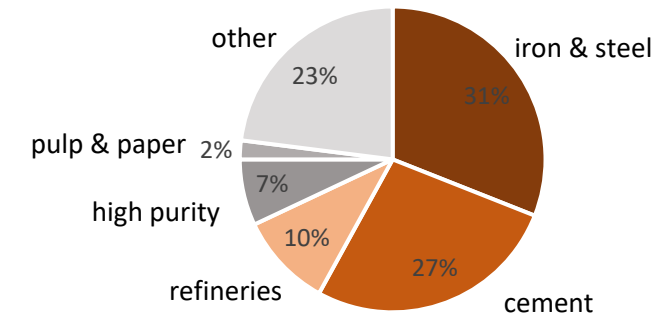
Motivation and objectives

Motivation

- ~25% of CO₂ emissions are from hard-to-abate industries: cement, iron/steel, ethylene, hydrogen, and others, with variable emissions characteristics: concentration (CO₂ %), temperature (~300 - ~1500 °C), flow rate, etc.
- The most mature processes are based on temperature-swing separation with amines and are optimized for ~40-120 °C. Cost and system efficiency are major challenges.
- Capture based on molten salts: 600-650 °C



Share of industrial GHG emissions



Objectives

1. Determine the emissions, efficiency, and cost impacts of temperature-matched capture.
2. Develop a universal framework to cross-compare across different emissions types and capture technologies.
3. Use model outputs to identify applications with largest potential (efficiency/emissions savings x scale of industry) to guide future technology development.

Targeted industries and technologies

☐ Industries

- Cement, steel, chemical, power

☐ Carbon capture technologies

- Molten salt, solvent based (MEA), adsorbent based (calcium looping), others (cryogenic)

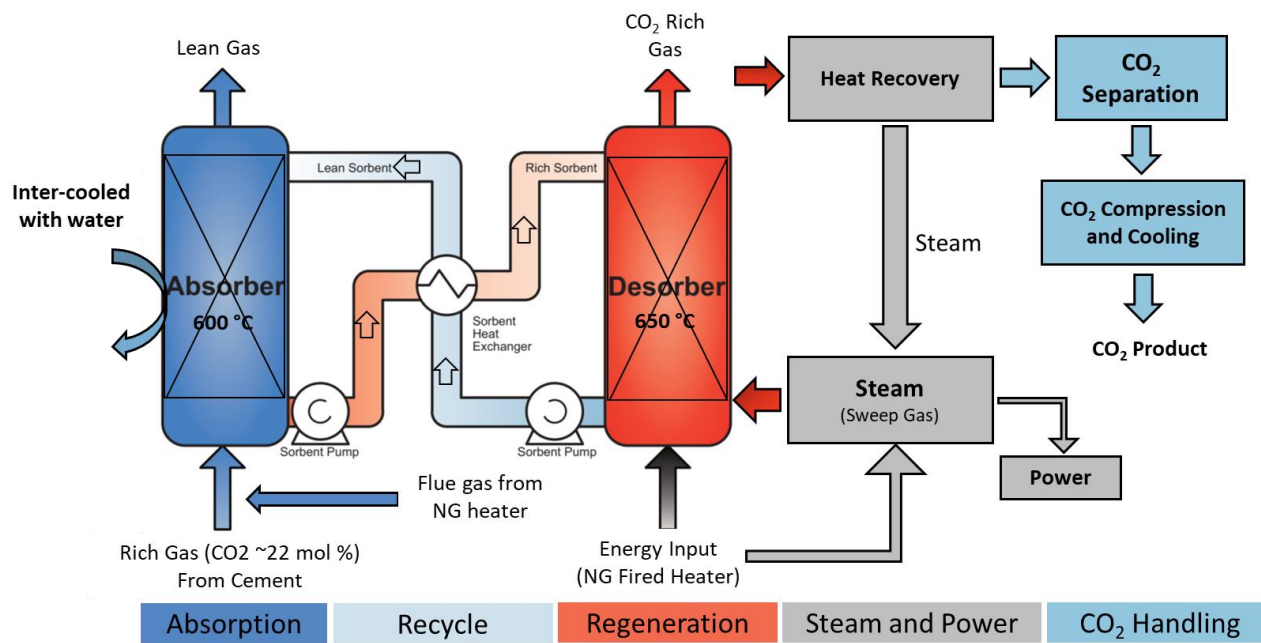
☐ In progress

- Cement + CC (molten salt, MEA)
- Steel

Cement + carbon capture (Molten salt, MEA)

Capture CO₂ from Cement Plant

- Case study: Cement plants decarbonization using Molten Salt carbon capture



- “Temperature-Swing” carbon capture
- Desorption needs high-quality heat by NG fired heater
- Steam is used as a sweep gas for desorption
- High-quality heat can be recovered to generate steam and power (byproduct)

Aspen HYSYS Model

Base case: Capturing CO₂ from Cement plant flue gas
[1.78 M tonnes/yr cement production]

Process Evaluation		Note
CO ₂ Emissions, M tonnes/yr	1.61	75% from Cement, 25% NG fired heater
CO ₂ Capture Rate, %	95	/
NG HHV Thermal Input, MW _t	224	1.35 kWh _t /kgCO ₂
Total Gross Power, MW _e	35	0.21 kWh _e /kgCO ₂
Net Power, MW _e	19	0.11 kWh _e /kgCO ₂
Total Auxiliary Power, MW _e	16	0.098 kWh _e /kgCO ₂
Pumps, MW _e	4	0.025 kWh _e /kgCO ₂
Compression, MW _e	12	0.073 kWh _e /kgCO ₂

The simulation results were based on molten salt data from Mantel Capture Co.

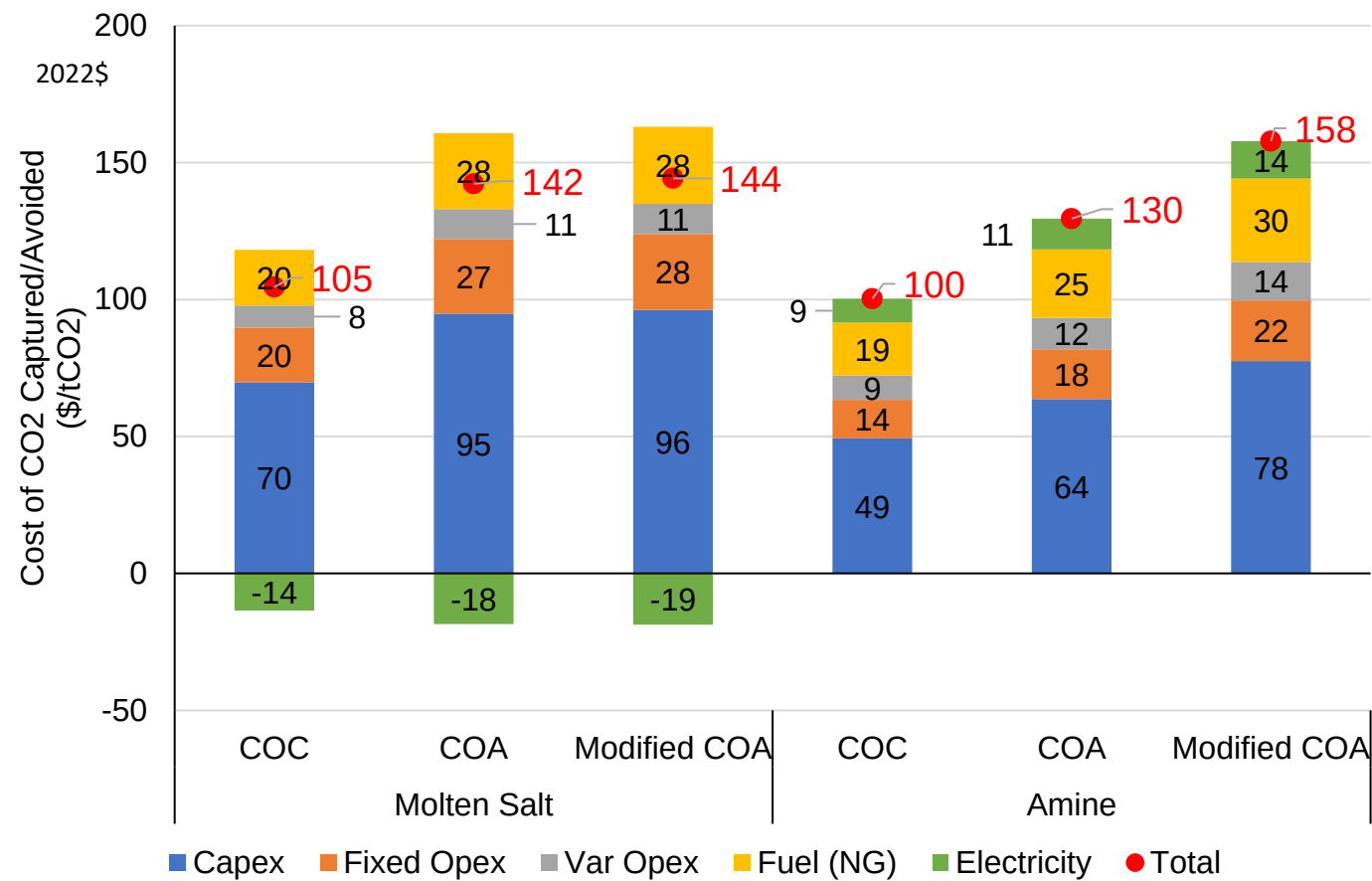
TEA Results

COC: Cost of CO₂ Capture

COA: Cost of CO₂ avoided

Modified COA: well-to-gate system boundary

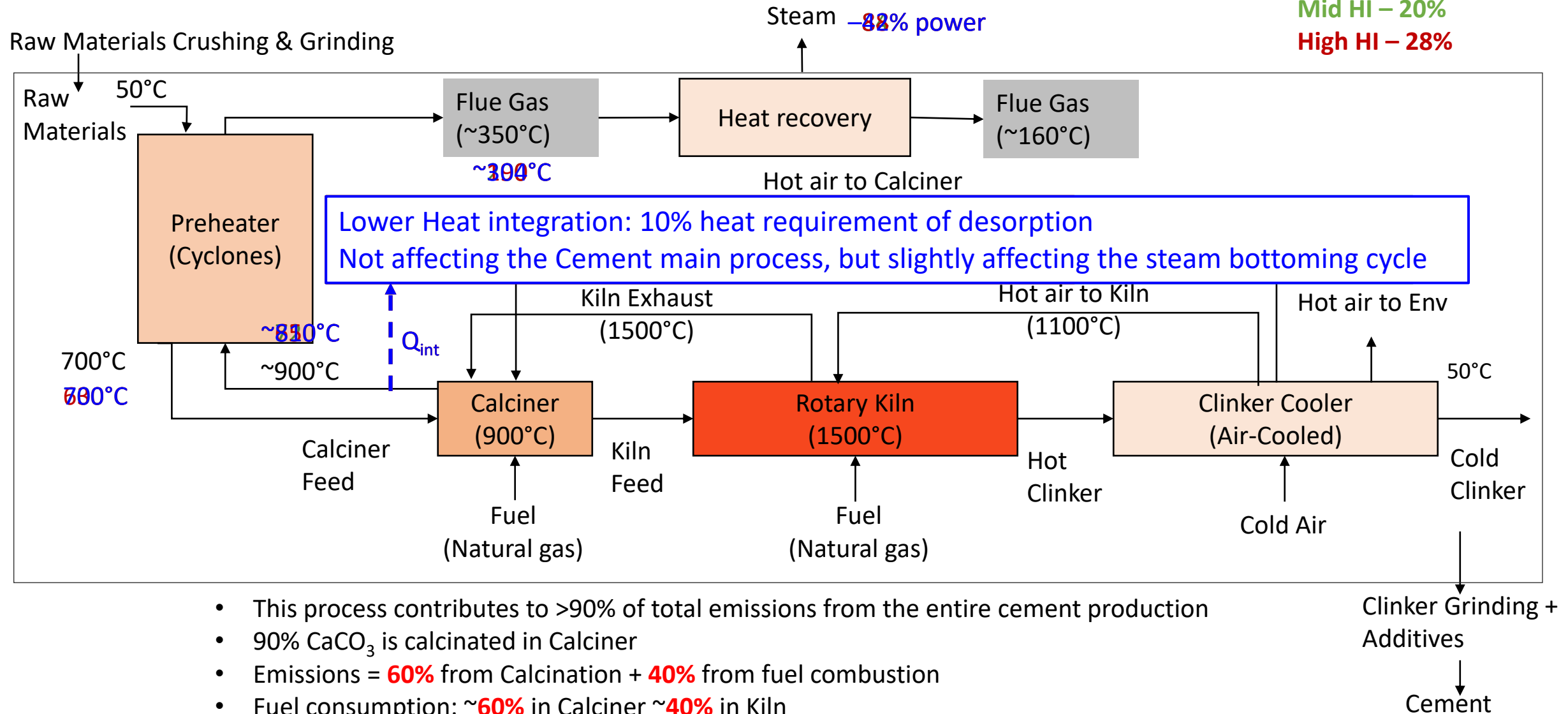
Molten Salt capture technology appears to be comparable with the Amine capture technology under the same TEA assumptions



$$\text{COC} = \frac{\text{Cost}_{\text{capture case}} - \text{Cost}_{\text{base}}}{\text{CO}_2 \text{ captured}} \quad \text{COA} = \text{CO}_2 \text{ from additional NG use} \quad \text{Modified COA} = \text{Upstream CO}_2 \text{ of NG and electricity}$$

Heat Integration (HI) with Cement Plant

Low HI – 10%
Mid HI – 20%
High HI – 28%

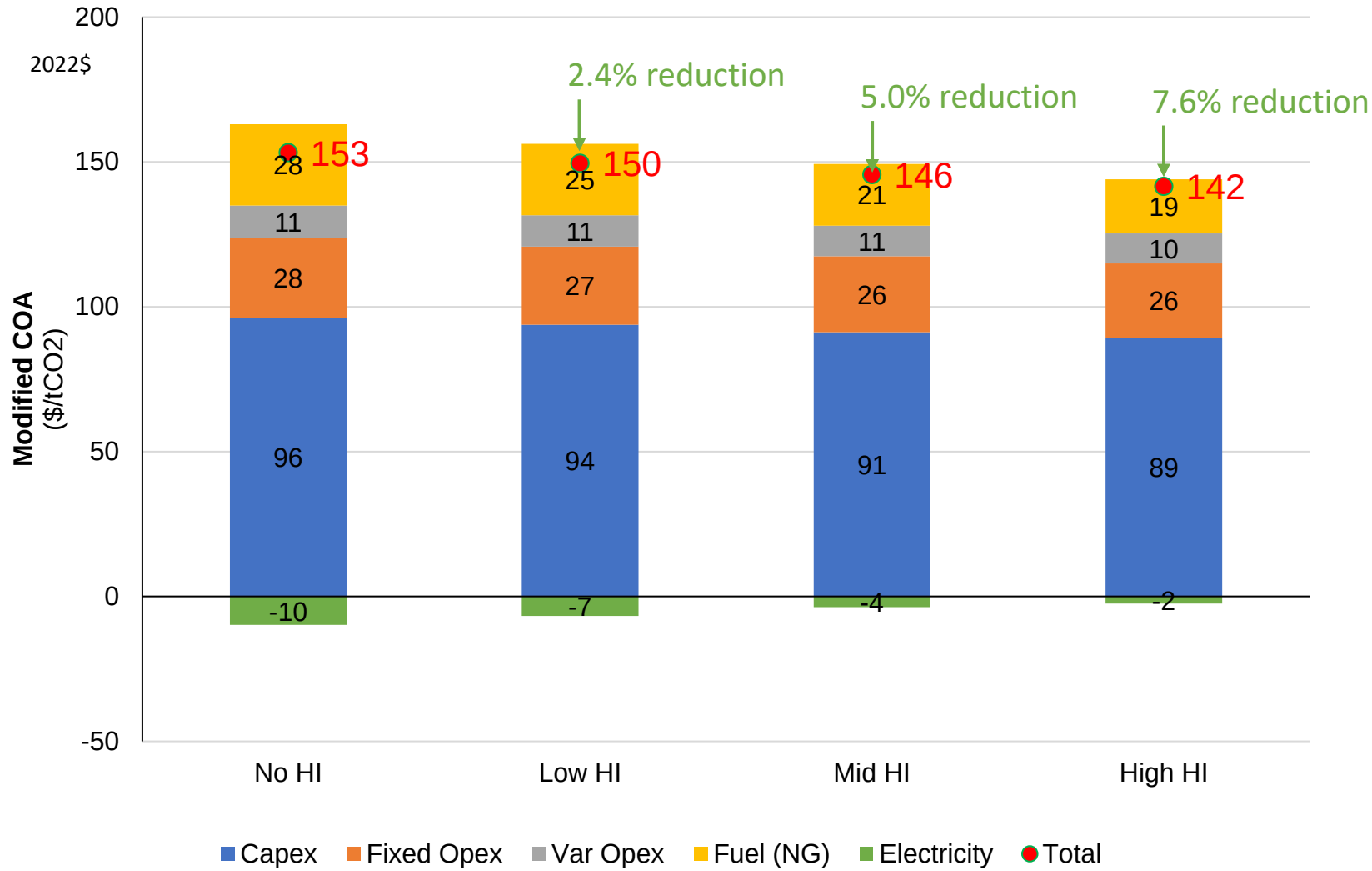


Reference: Atsonios et al. 2015. Fuel

Benhelal et al, 2012. Energy Science and Technology

Nwaoha et al. 2018. International Journal of Greenhouse Gas Control

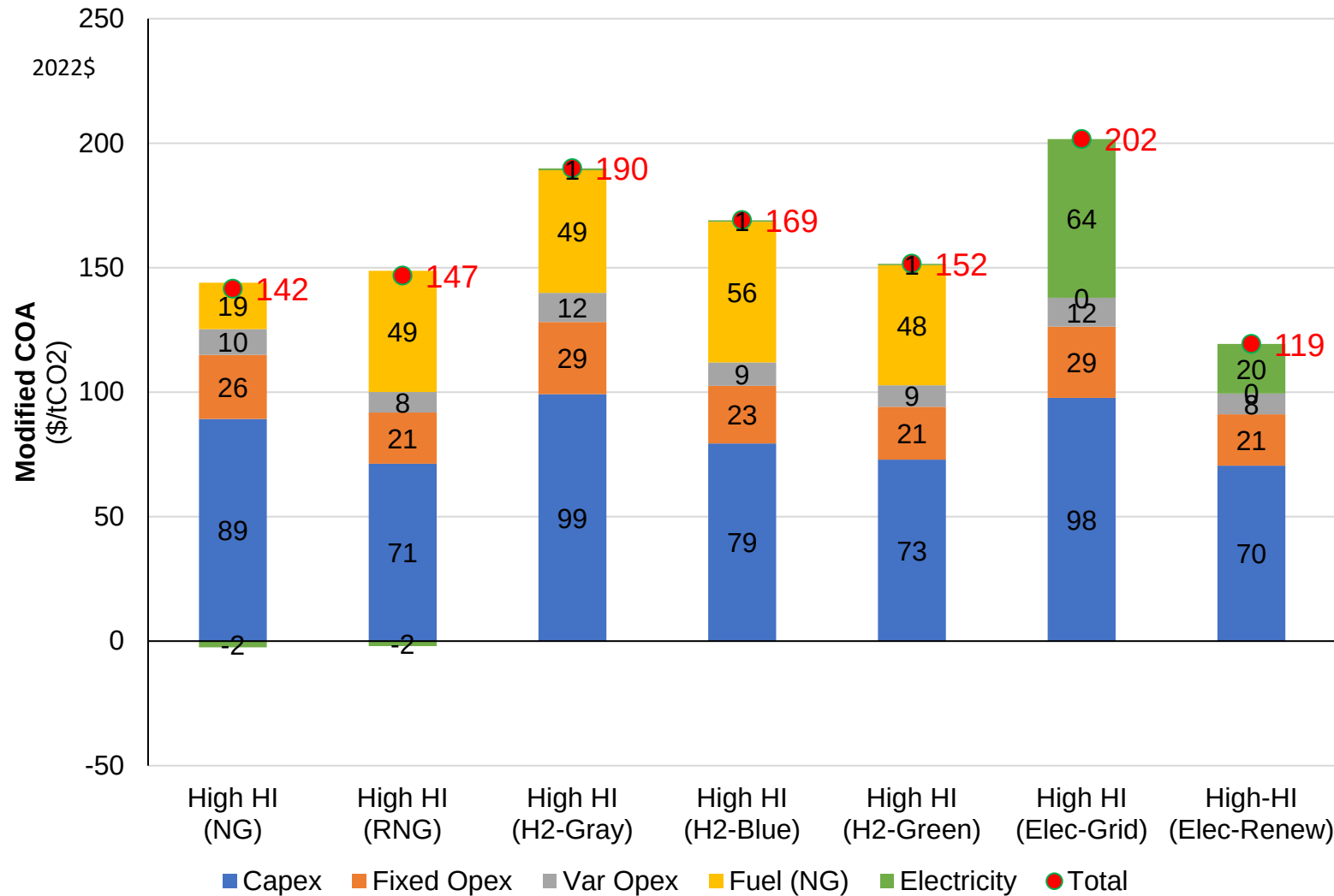
Effects of Heat Integration (Molten Salt)



Assumptions:

- Heat integration (HI): taking heat from the calciner outlet flue gas stream
- TEA for the Molten salt capture system only, not including changes in the Cement plant
- Account for power loss in the Cement plant (as extra auxiliary load in the capture process)
- Low and Mid HI doesn't affect the Cement main process, but High HI affect

Effects of Fuel Switching (Molten Salt)



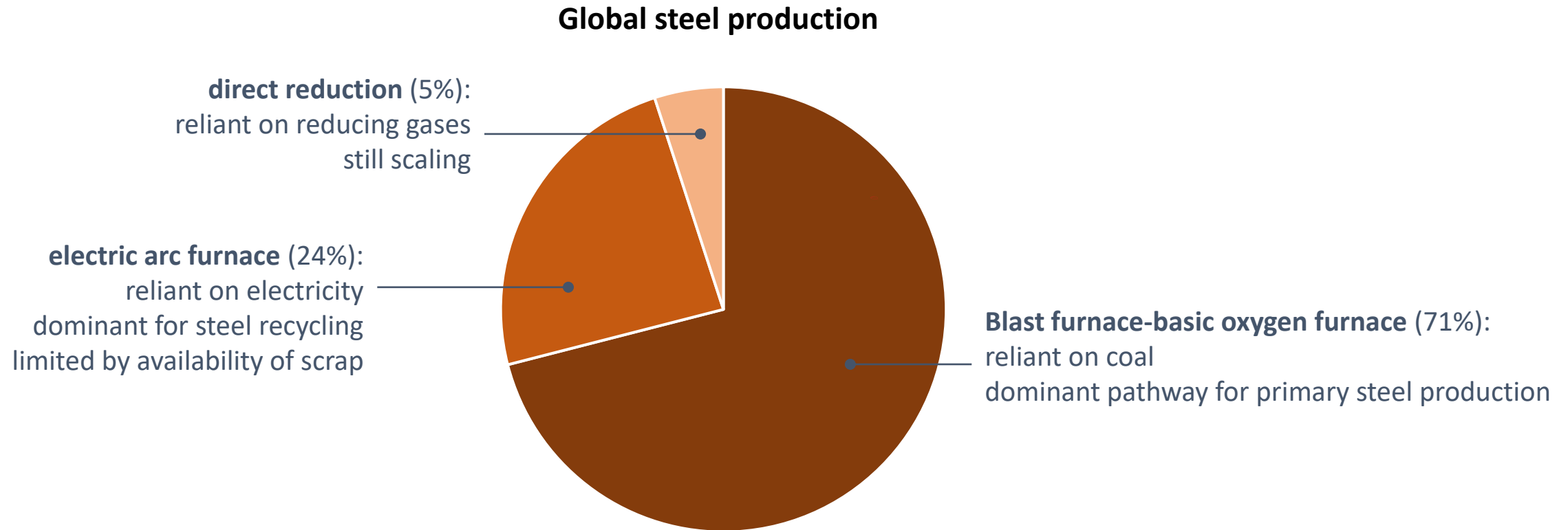
Assumptions:

- Fuel switching: changing fuel for heat-up the desorber (for endothermic rxn)
- High HI
- NG: \$4.6/mmbtu, 14.2 kgCO₂e/mmbtu
- RNG: \$15.0/mmbtu, 10.2^{a)} kgCO₂e/mmbtu
- H₂(Gray): \$1.5/kgH₂, 11.0 kgCO₂e/kgH₂
- H₂(Blue): \$2.75^{b)}/kgH₂, 3.4 kgCO₂e/kgH₂
- H₂(Green): \$5^{c)}/kgH₂, 0.0 kgCO₂e/kgH₂
- Grid electricity: \$67.3/MWh, 439 kgCO₂e/MWh
- Renewable E: \$29.1^{d)}/MWh, 0 kgCO₂e/MWh

- a) Assume landfill gas and no GHG accounting for combustion
 b) Apply \$0.6/kgH₂ additional credit assuming Tier 4(45V credit)
 c) Apply \$3.0/kgH₂ additional credit assuming Tier 1(45V credit)
 d) LCOE of onshore wind. Transmission cost not included.

Steel plant

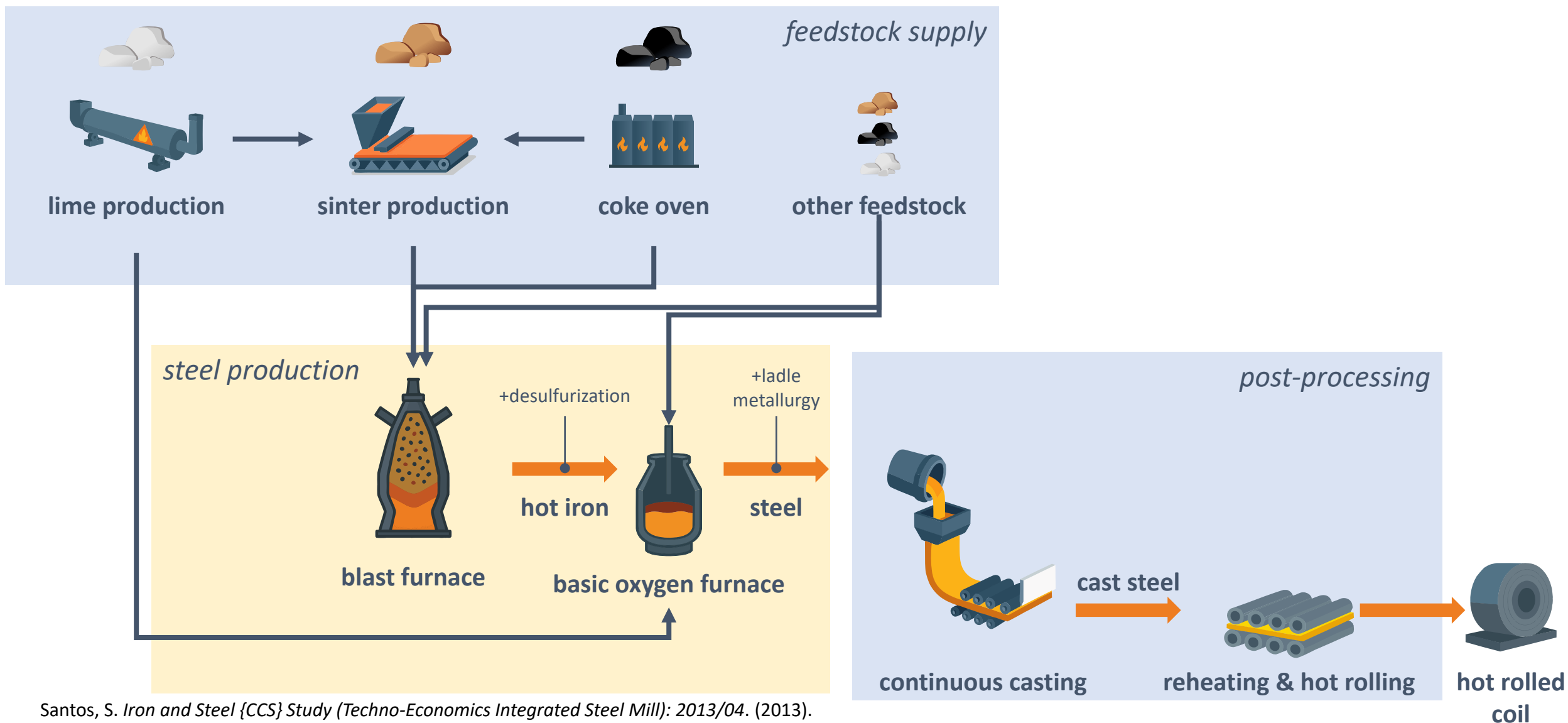
Steel industry: BF-BOF pathway dominates today



Decarbonizing steel must target capital-intensive legacy infrastructure while scaling new processes.

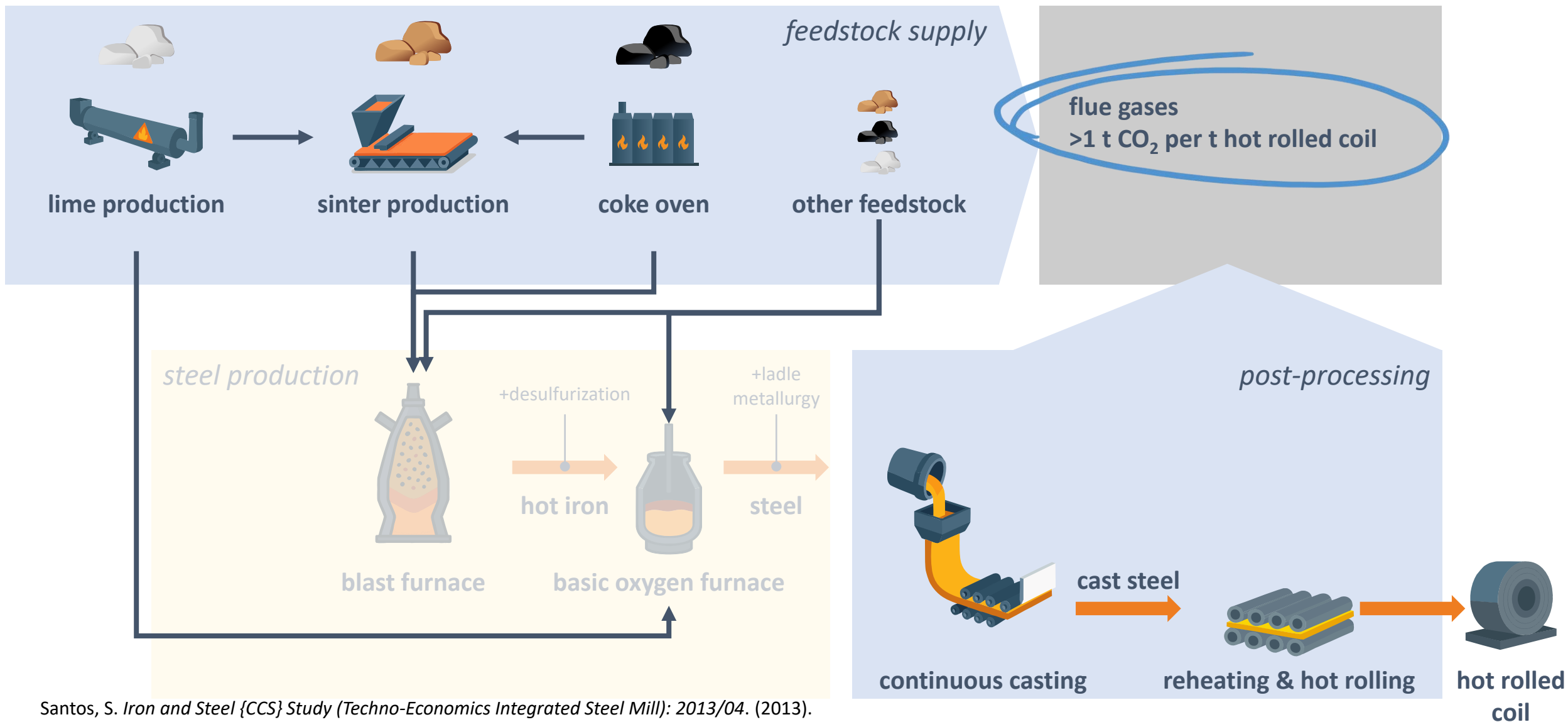
Fan, Z. & Friedmann, S. J. Low-carbon production of iron and steel: Technology options, economic assessment, and policy. *Joule* 5, 829–862 (2021).

BF-BOF: Emissions originate from various sources



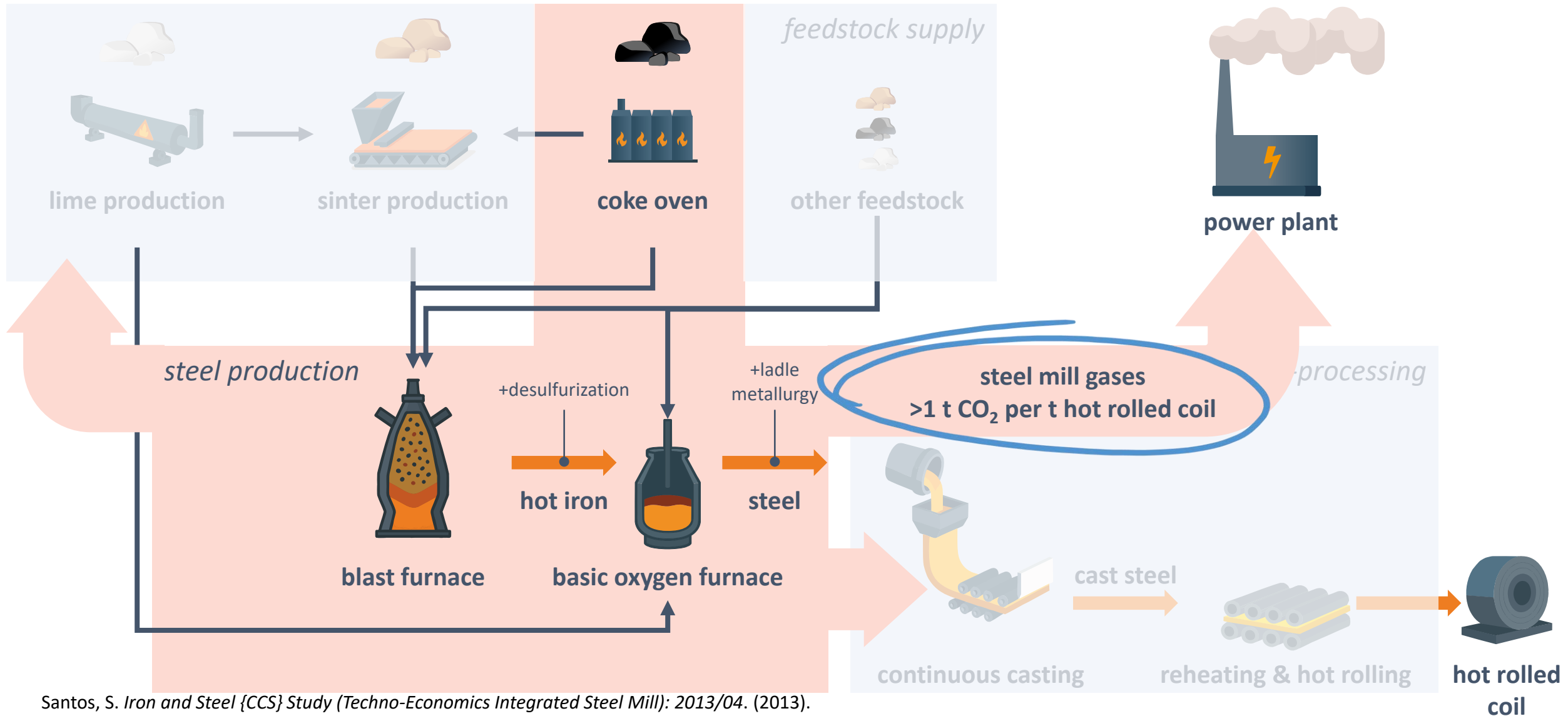
Santos, S. Iron and Steel {CCS} Study (Techno-Economics Integrated Steel Mill): 2013/04. (2013).

BF-BOF: Emissions originate from various sources



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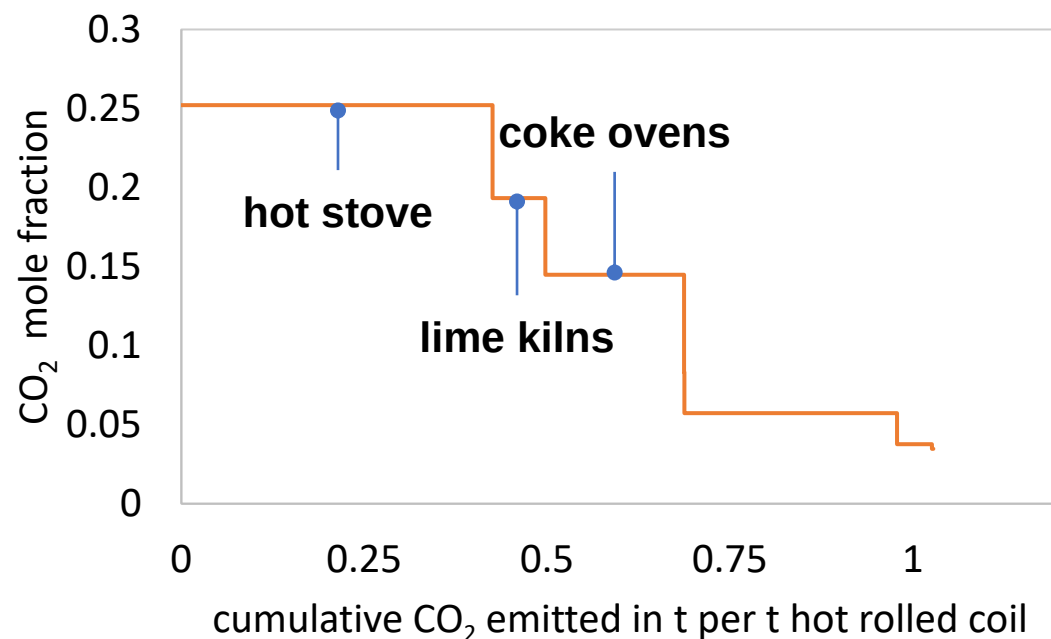
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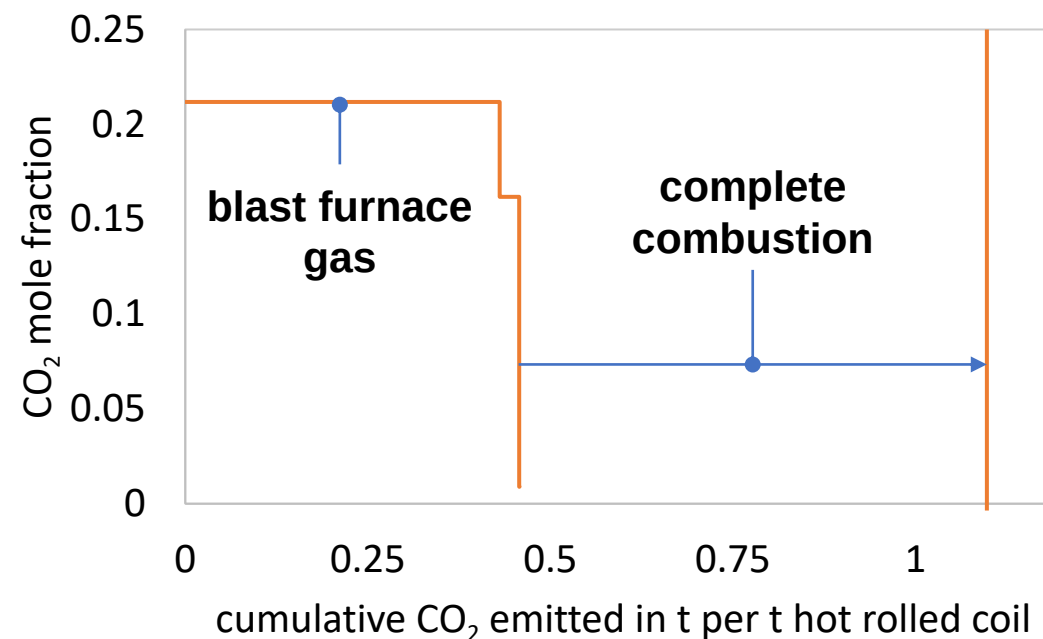
BF-BOF: Where to capture?

flue gases
from feedstock supply / post-processing



capture from flue gases
starting with highest concentration source

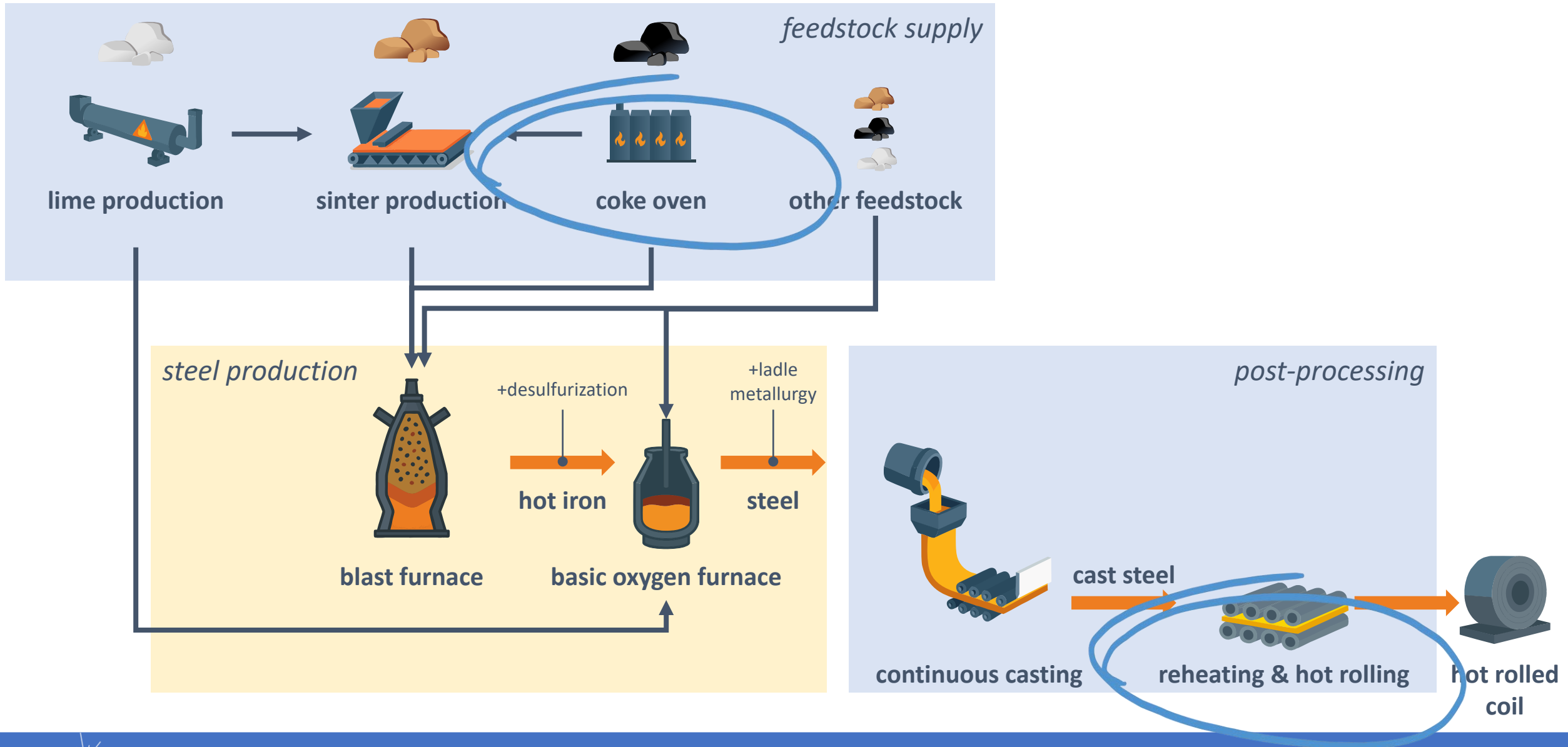
steel mill gases
from blast furnace/basic oxygen furnace/coke oven



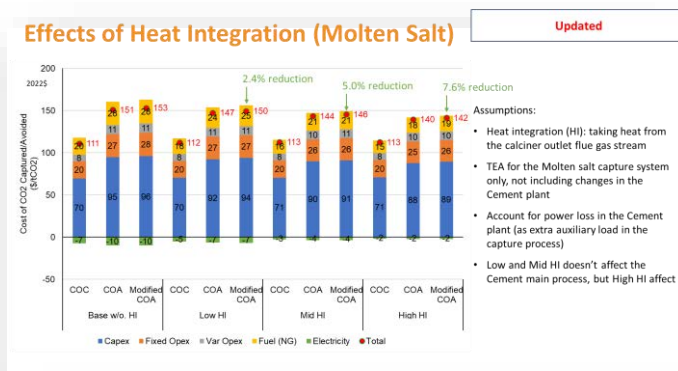
capture from steel mill gases

- prior to combustion
- post combustion
- after water-gas shift reaction

Waste heat integration may reduce energy demand

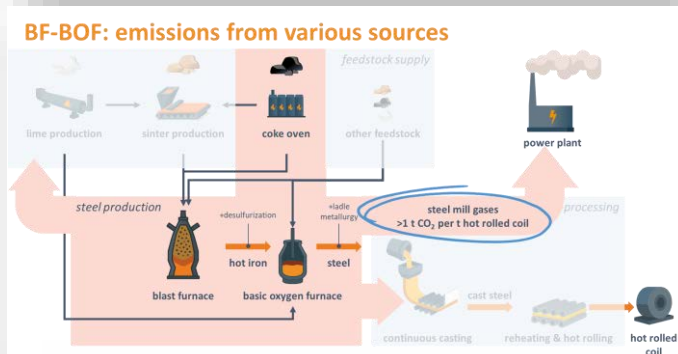


Summary and future work



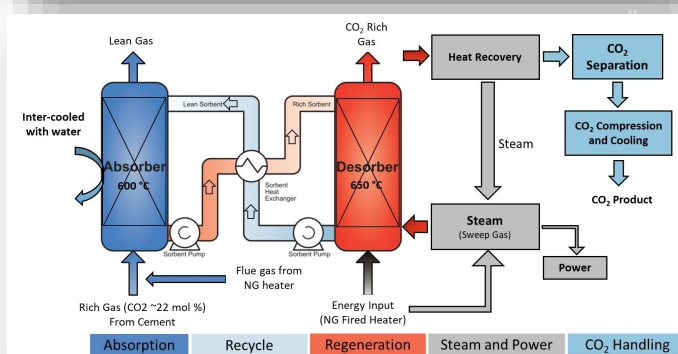
Summary cement

- Molten Salt shows slight lower capture cost than the Amine-based capture technology under the same TEA assumptions
- Heat integration reduce overall systems' energy consumption and costs
- Fuel switching to non-fossil gas reduce CO₂ emission and resultant CO₂ capturing CAPEX, but current clean fuel price is high



Future work

- Extension to other industries (e.g. steel process)
- Include additional CCS technologies (e.g. calcium looping)

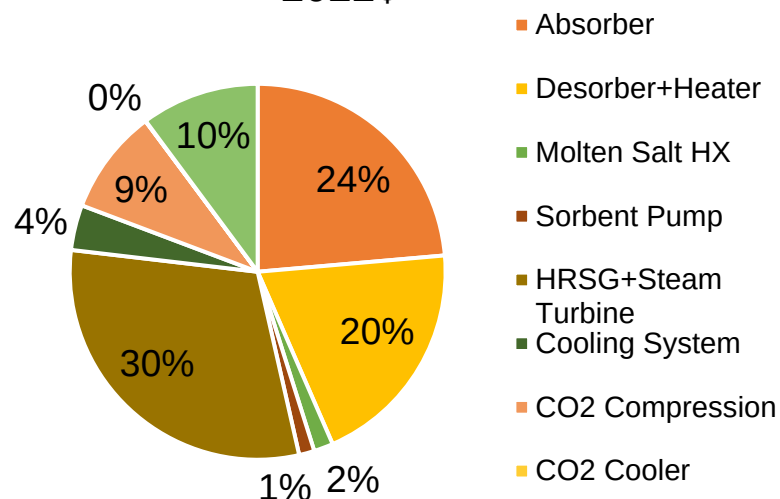


Q&A and Project Discussions

Backup Slides

Techno-Economic Analysis

TPC (\$758 MM)
2022\$



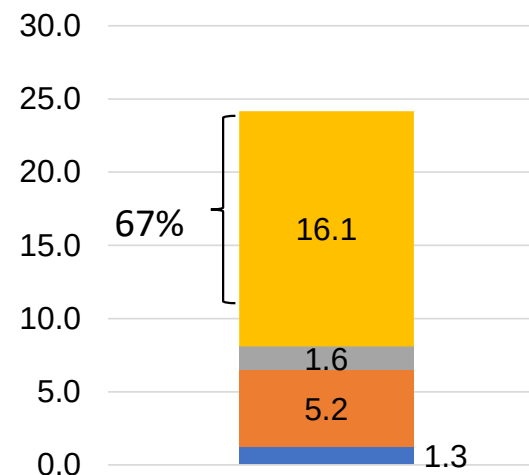
Major Drivers

- Capture System (Absorber+Desorber w/ Heater): 24+20 = 44%
- HRSG+Steam Turbine: 30%

Key Takeaways

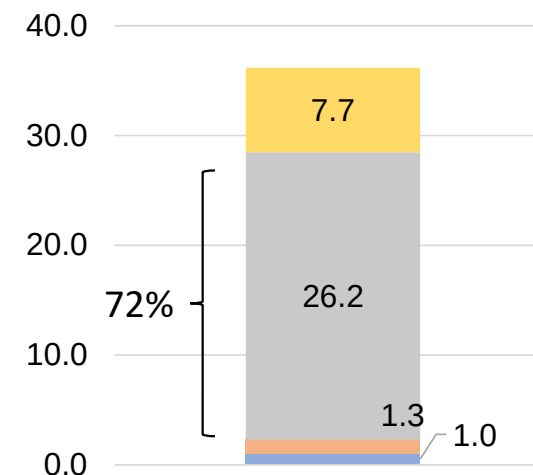
- TPC for molten salt capture system: \$758 MM (\$470/tCO₂/year)
- The system is **capital-intensive**, approximately equivalent to 1/3 of TPC for a 770-MW NGCC power plant (\$2,300 MM).
- The use of HRSG + Steam Turbine to improve overall energy efficiency

Fixed Operating Costs
(\$24 MM)



- Property Taxes and Insurance
- Admin and Support Labor
- Maintenance Labor
- Operating Labor

Variable Operating Costs
(\$36 MM)



- Maintenance Material
- NG Use
- Water
- Sorbent Replacement

- Fixed OPEX: \$24 MM/year
Main driver: Property Taxes and Insurance (2% of TPC), followed by Maintenance Labor (0.65% of TPC)
- Variable OPEX: ~\$36 MM/year
Main driver: NG Consumption, followed by Regular Maintenance Material (0.96% of TPC) and Sorbent Replacement Cost