

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



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Director of Research
MIT Energy Initiative



Guiyan Zang

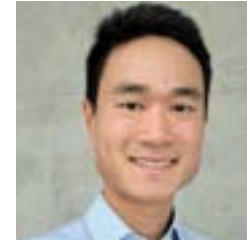
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Haoxiang (Hundey) Lai

Previous Postdoc
MIT Energy Initiative



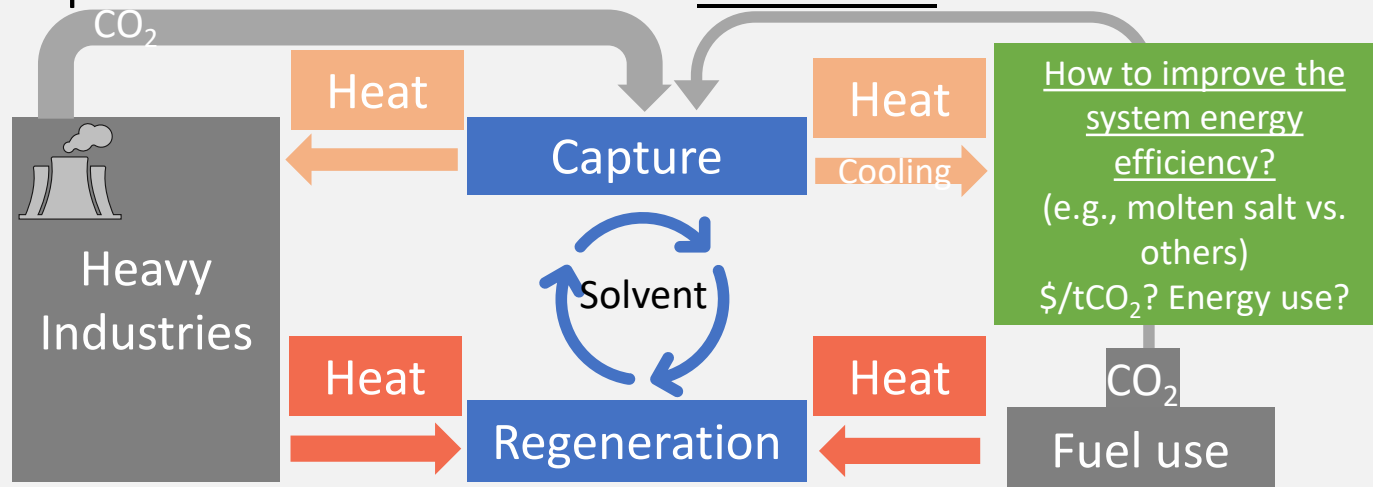
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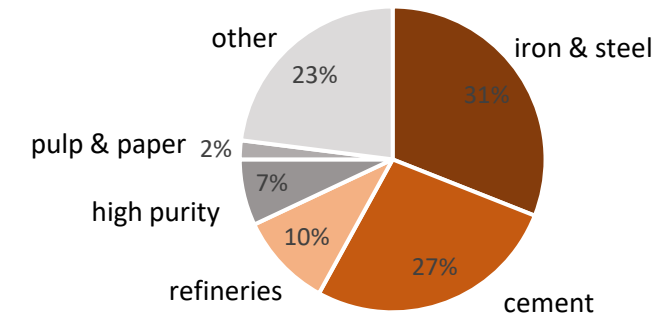
Motivation and objectives

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 CO₂ capture techs 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: 550-775 °C



Share of industrial GHG emissions



Objectives

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

In progress industries and technologies

- MEA (Monoethanolamine)
- CC (CO₂ Capture)

☐ Industries

- Cement, steel

☐ Carbon capture technologies

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

☐ In progress combination

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

Cement + carbon capture (Molten salt, MEA)

Capture CO₂ from Cement Plant

- Cement plants decarbonization using Molten Salt (MS) & MEA carbon capture

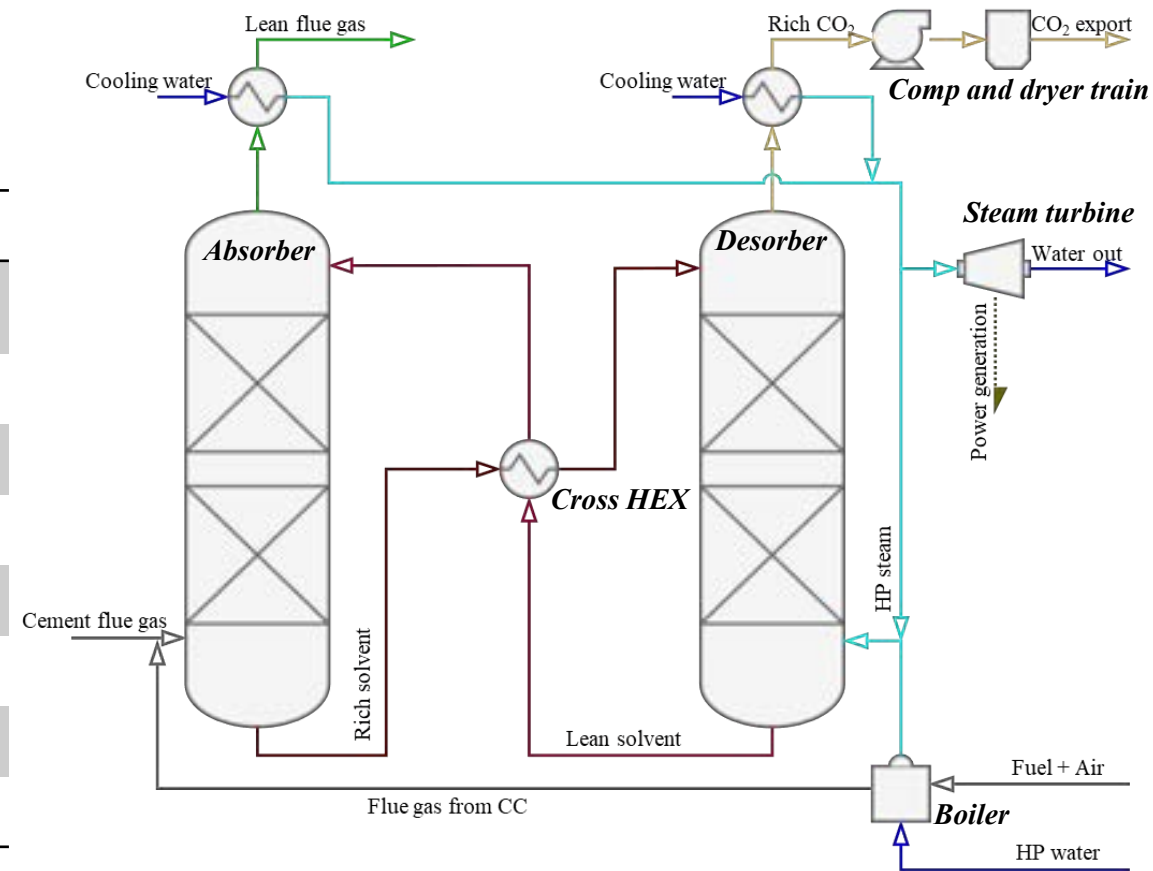
Aspen Plus & HYSYS Model

Capturing CO₂ from Cement plant flue gas

Process Evaluation	MS ¹⁾	MEA ²⁾
Clinker Production, M tonnes/yr	2.06	
Cement CO ₂ Emissions, M tonnes/yr	1.41	
CO ₂ Capture Rate, %	95	
Molecular formula	(Li _{1.5} Na _{1.5})BO ₃	C ₂ H ₇ NO
Heat of reaction, kJ/molCO ₂	212±13	95±25
Temperature, °C	500—800	40—120
Working capacity, molCO ₂ /L	12	1—2
Kinetics, mins for full uptake	Fast (~1)	Moderate (~10)

* Molten salt input information from Mantel Capture Co.

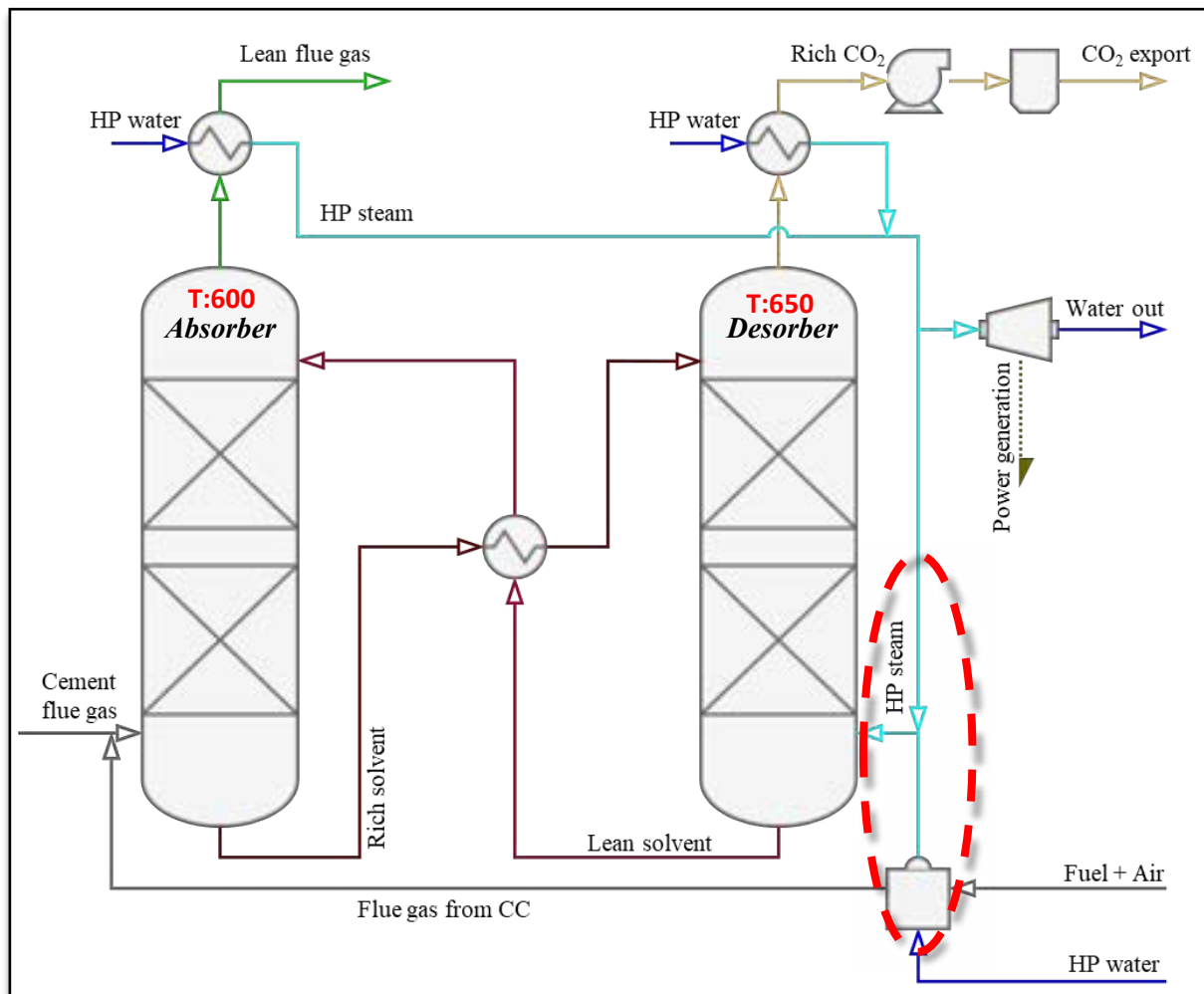
- MEA (Monoethanolamine)
- MS (Molten Salt)



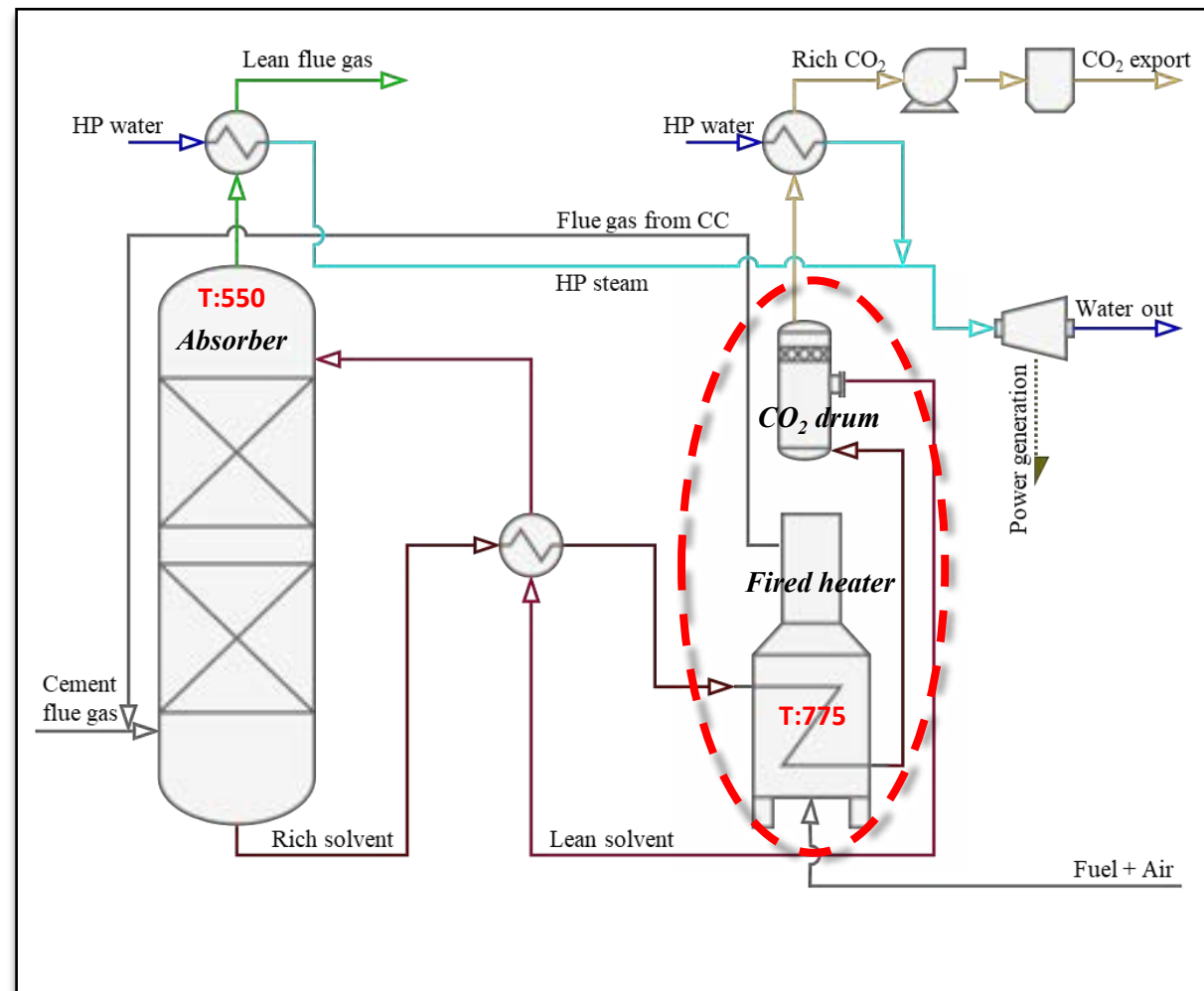
- Two column basis (Absorber and Desorber), Temperature swing**
- Regeneration needs additional heat
- Waste heat can be recovered to generate steam and power (byproduct)

Two types of MS regeneration

Steam Stripping (SS)

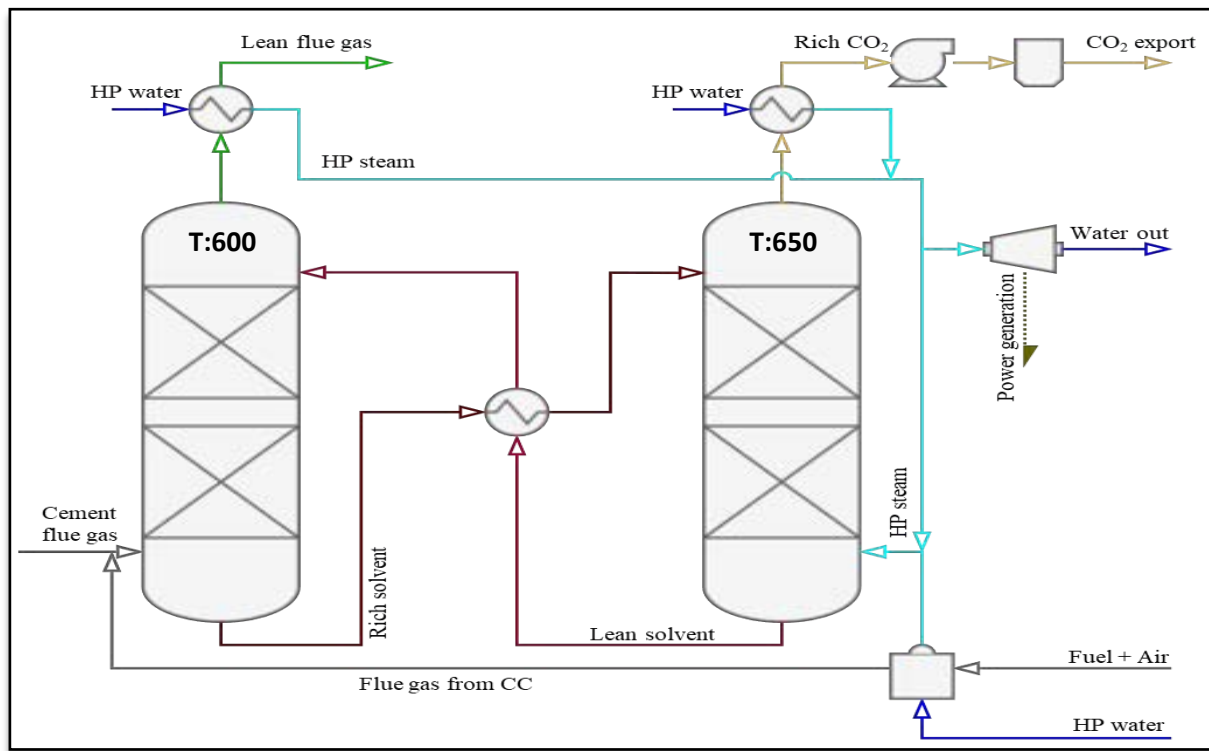


Thermal Regeneration (TR)



Two types of MS regeneration

Steam Stripping (SS)

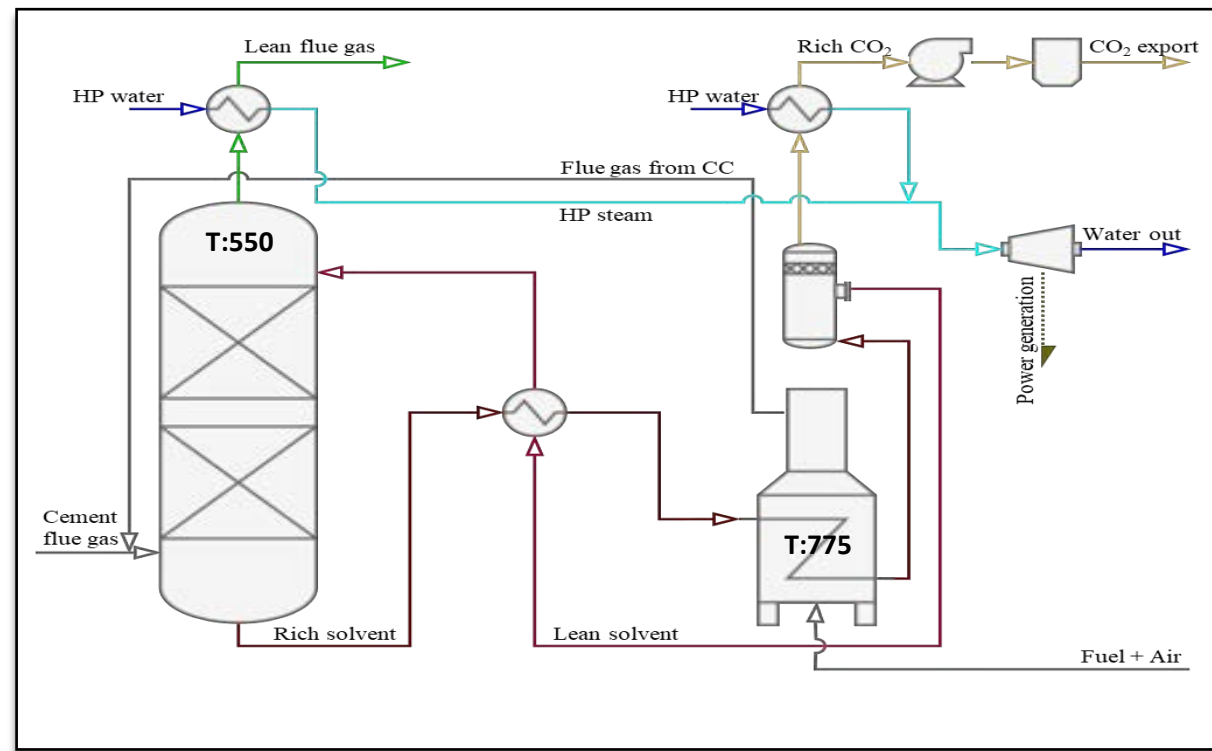


Steam-to-carbon ratio: 8, **Wet** rich CO₂

Operates at **600—650** °C

Generate electricity

Thermal Regeneration (TR)



No need for steam boiler, **Dry** rich CO₂

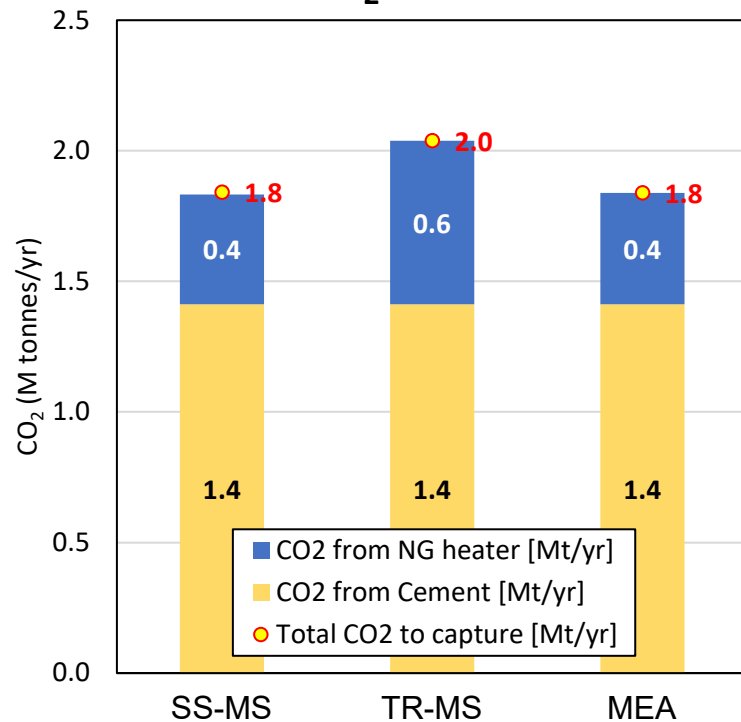
Operates at **550—775** °C

Generate **more** electricity

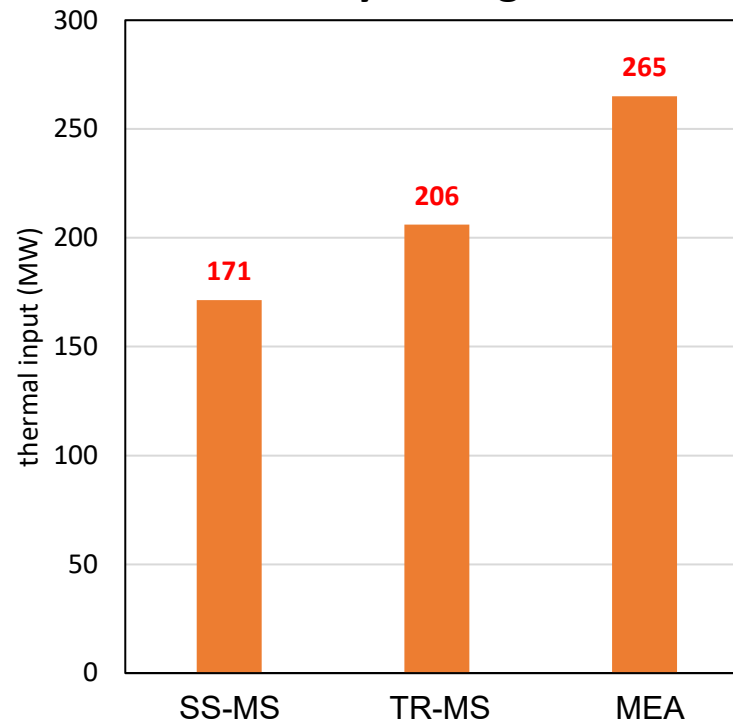
Operating Performance

- SS(Steam Stripping)
- TR(Thermal Regeneration)
- MS(Molten salt)
- MEA(Monoethanolamine)

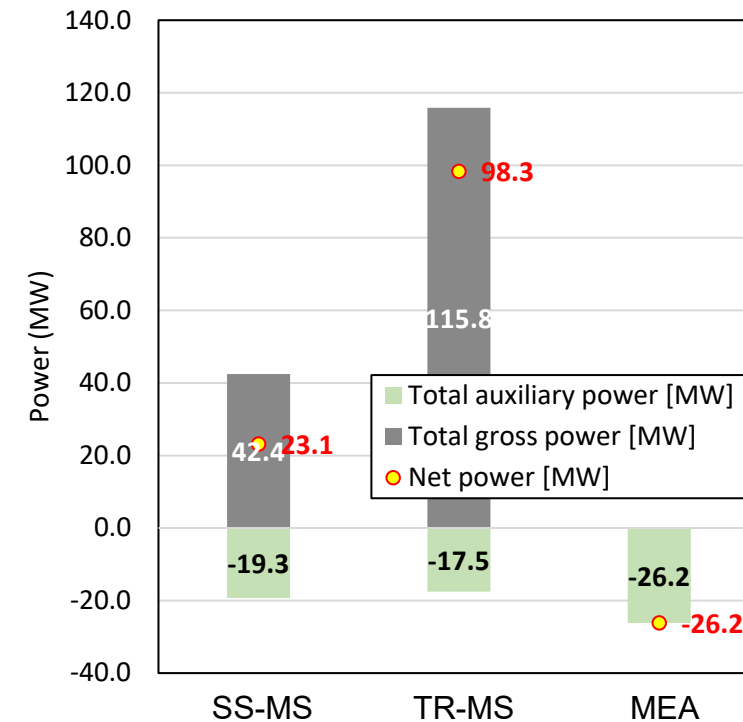
CO₂ amount



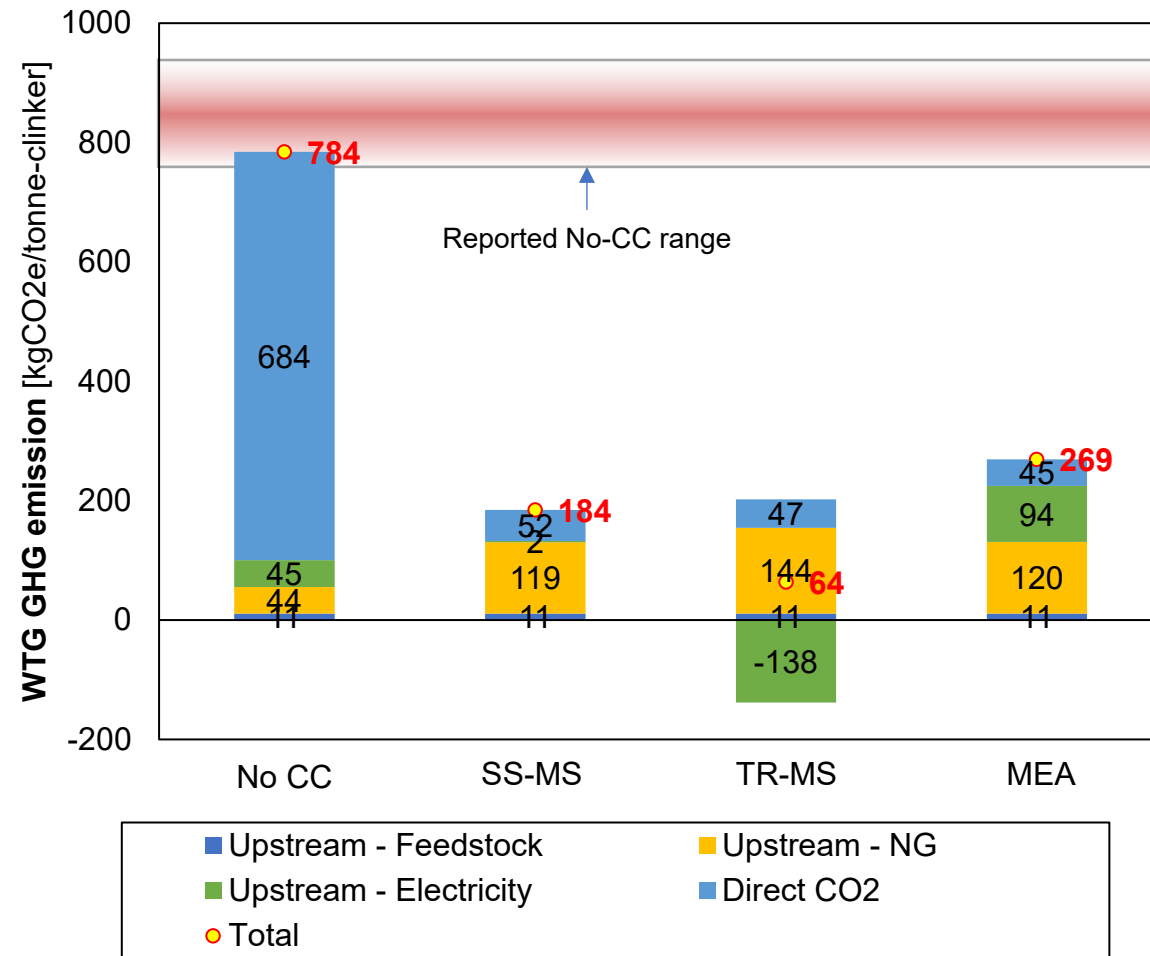
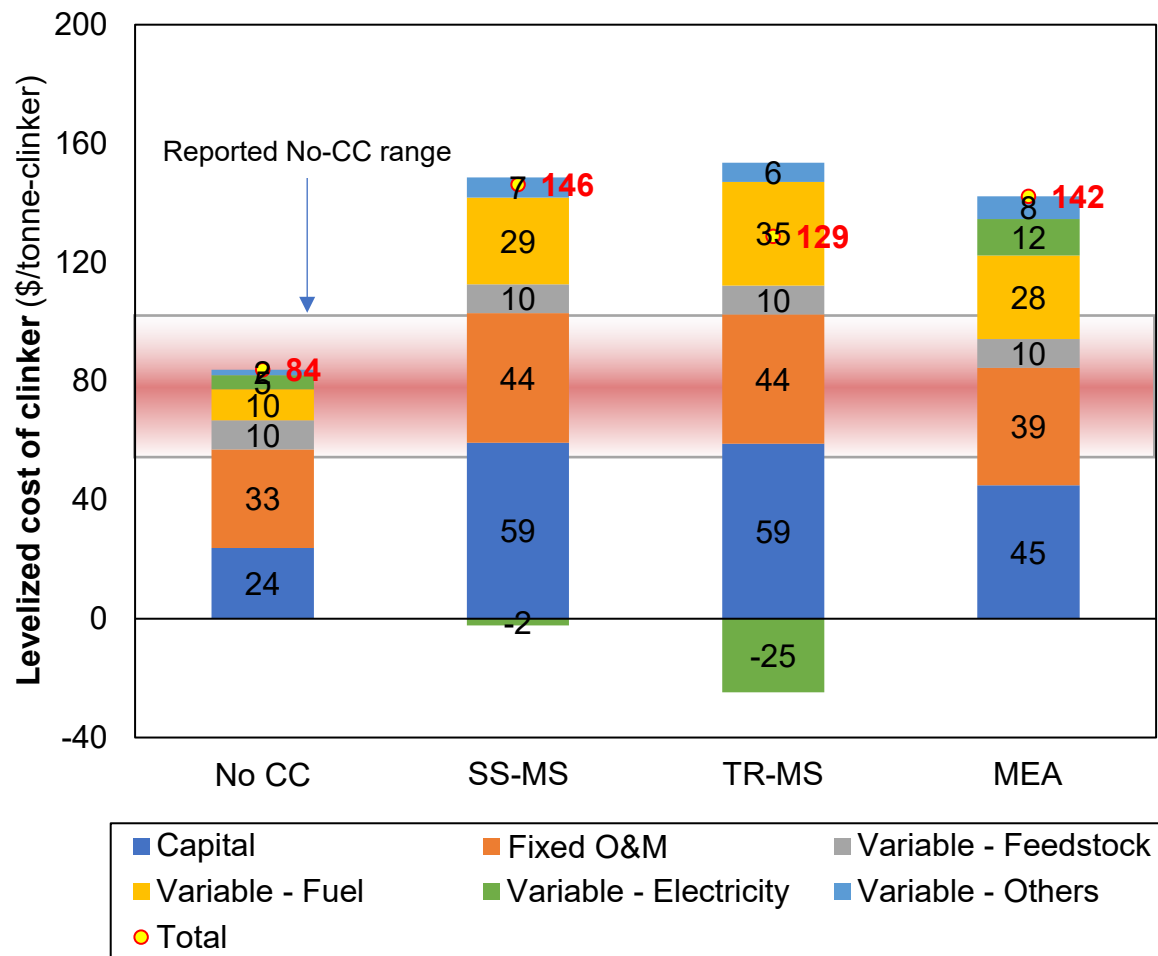
Heat duty for regeneration



Power balance



Cost and GHG results



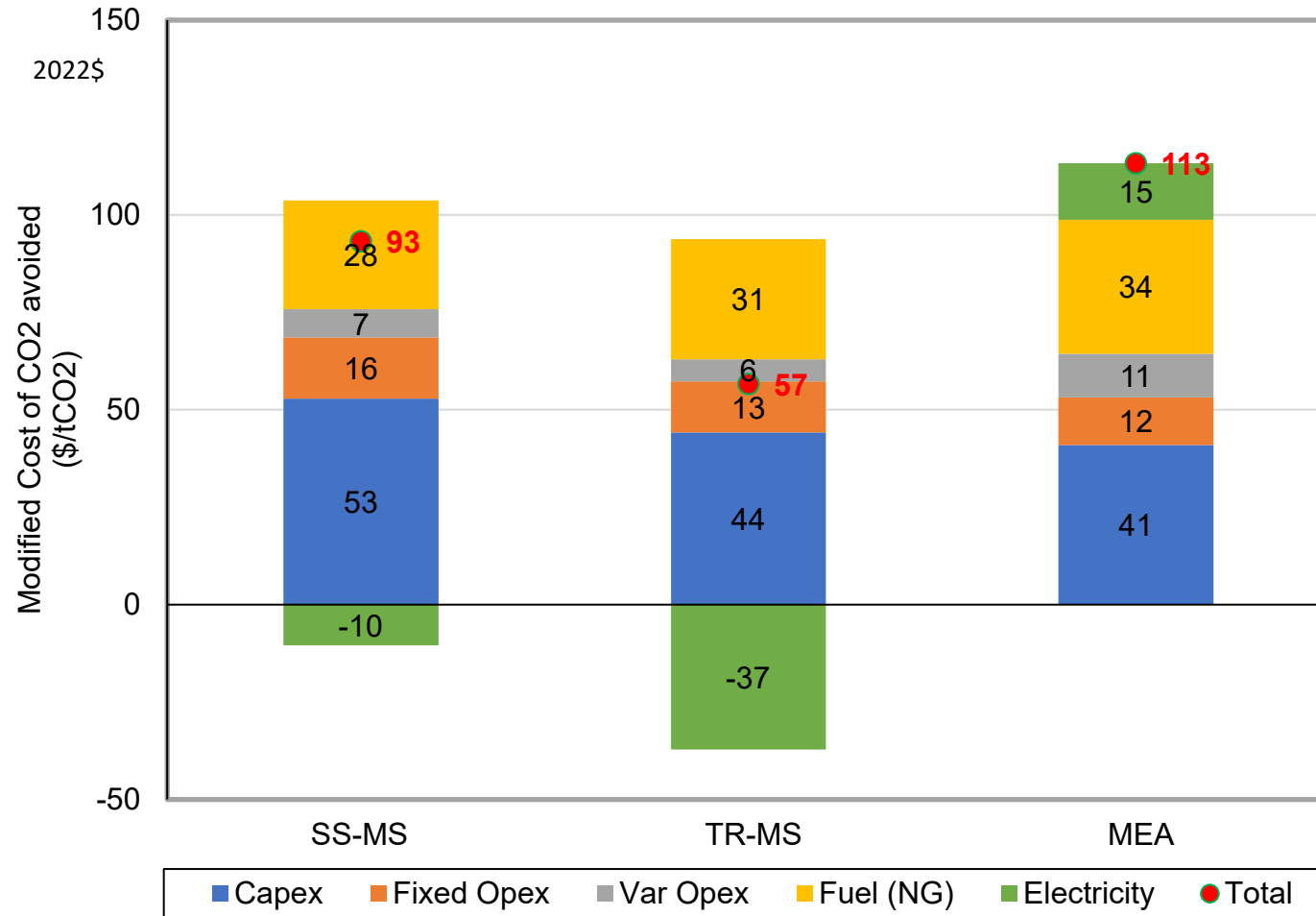
Assumptions (U.S. 2022 average):

- NG: \$4.6/mmbtu, 14.2 kgCO₂e/mmbtu
- Grid electricity: \$67.3/MWh, 439 kgCO₂e/MWh

Cost of CO₂ avoided (mCOA)

$$\text{Modified COA} = \frac{\text{COC}}{\text{CO}_2 \text{ captured}} - \text{CO}_2 \text{ from additional NG use} - \text{Upstream CO}_2 \text{ of NG and electricity}$$

COA



- **Molten Salt (MS)** capture technology appears to be comparable with the Amine capture technology under the same TEA assumptions
- **High temperature operation**
 - high quality of waste heat
 - high amount of gross power generation

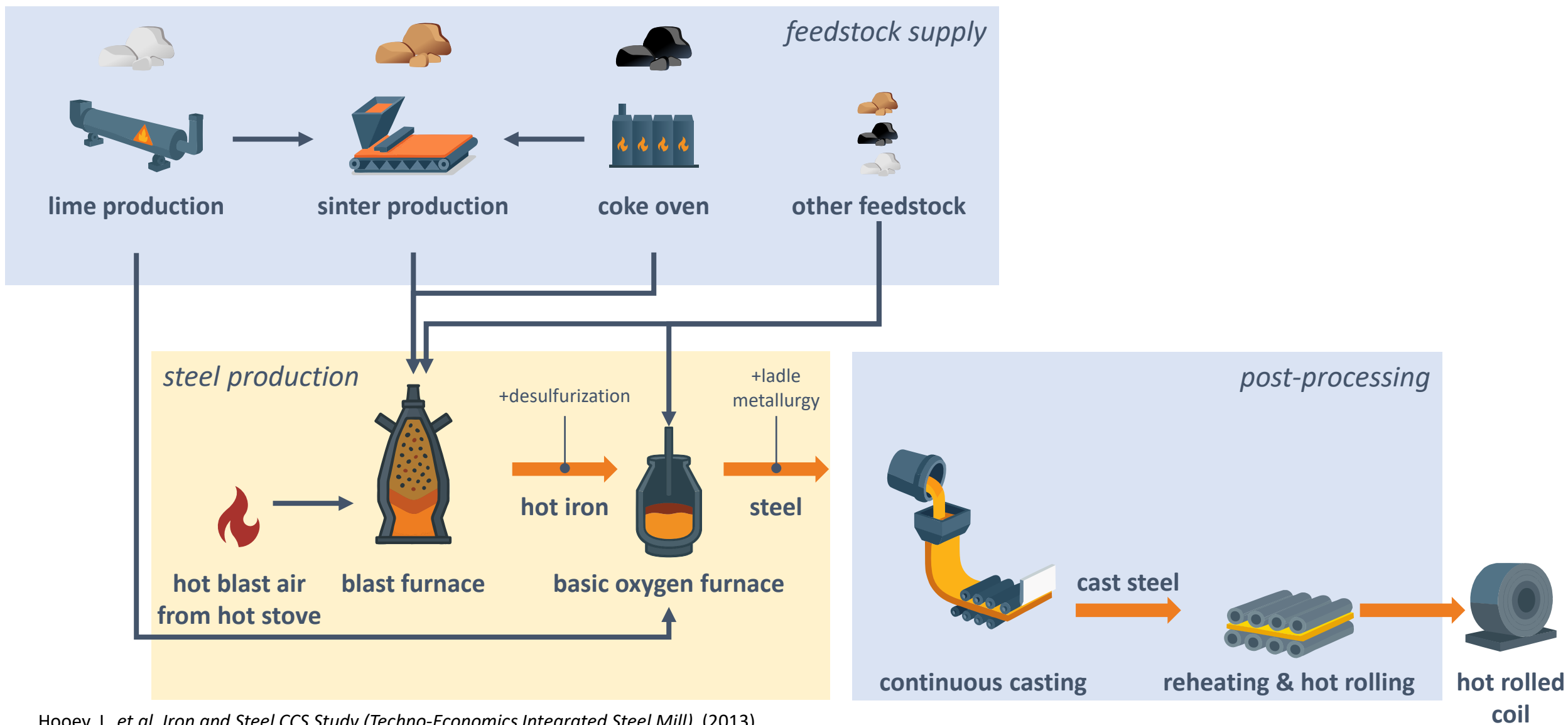
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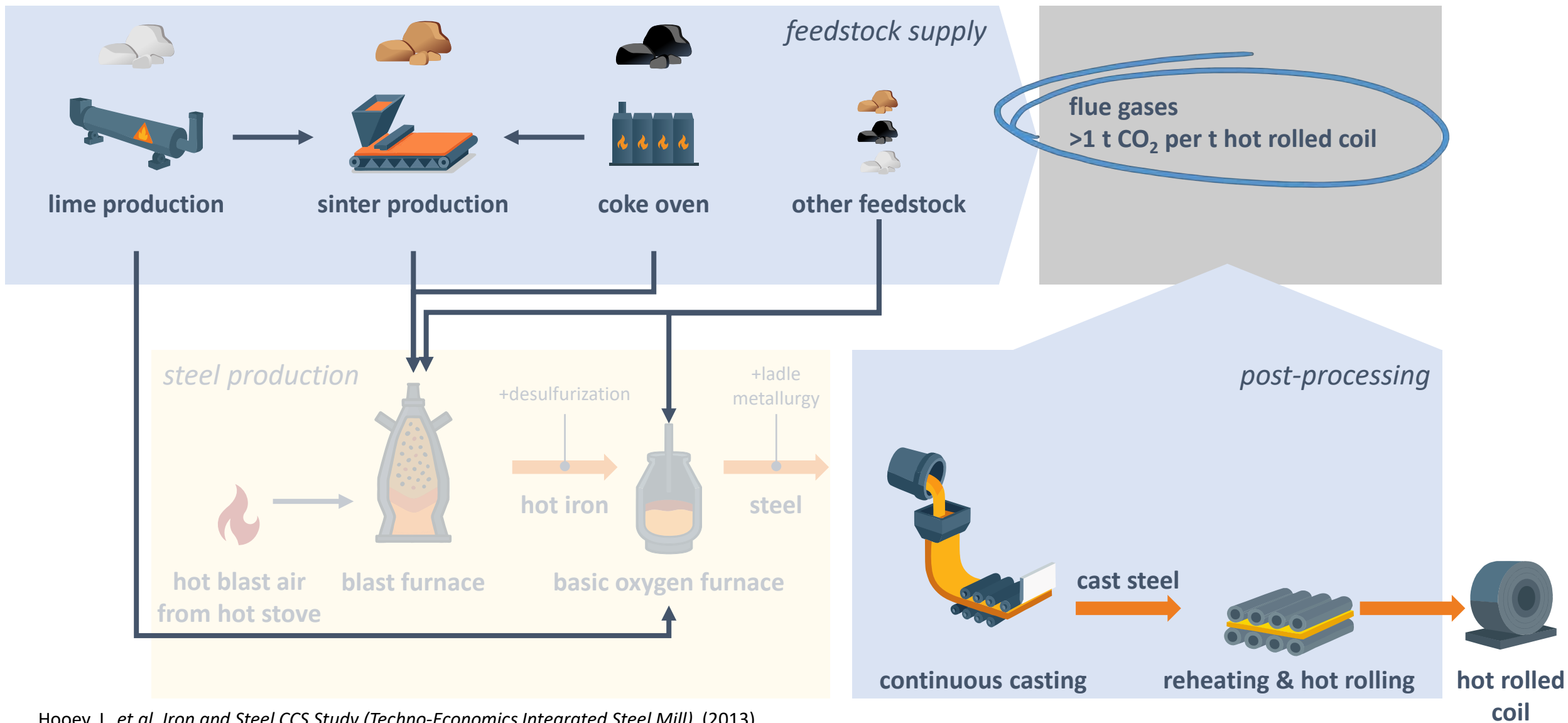
Steel plant

BF-BOF: Emissions originate from various sources



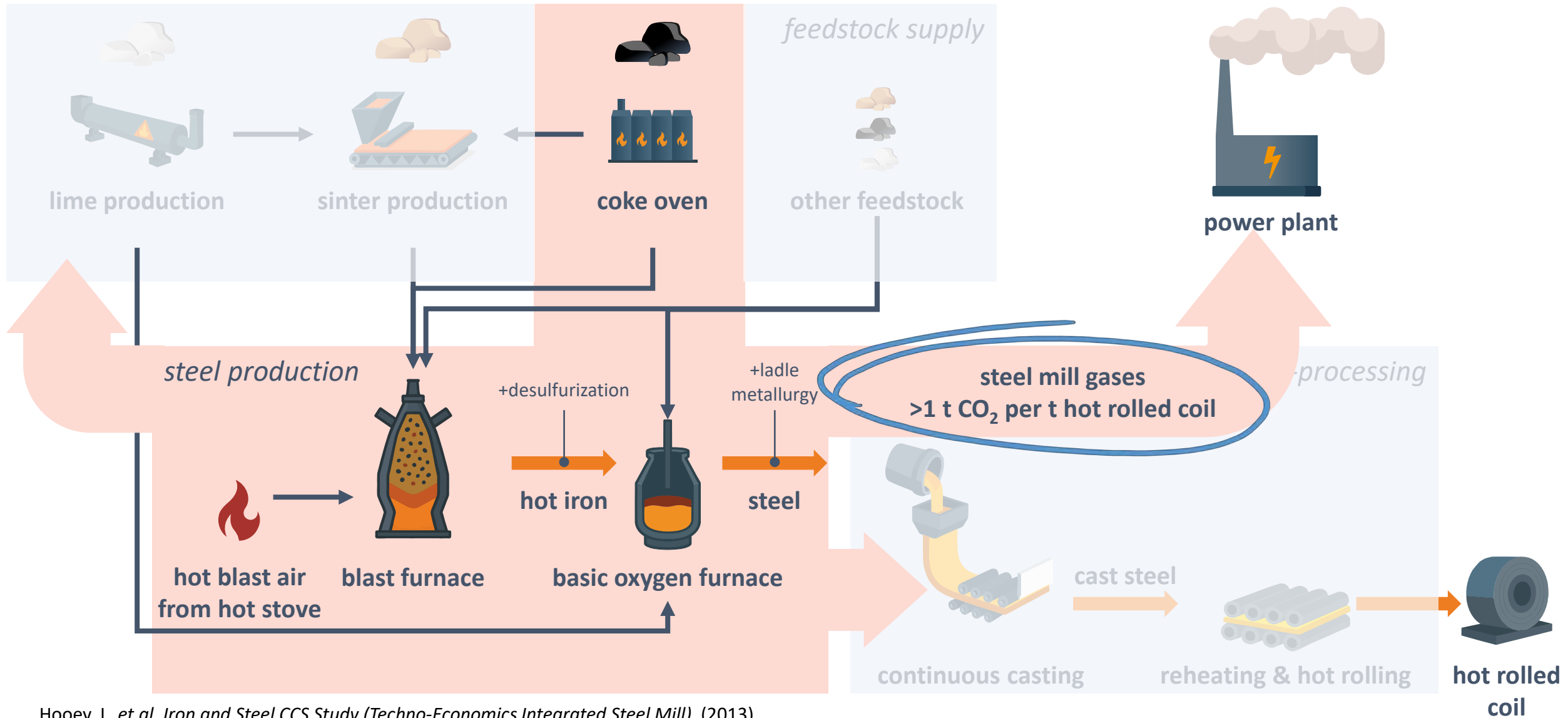
Hooey, L. et al. *Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill)*. (2013).

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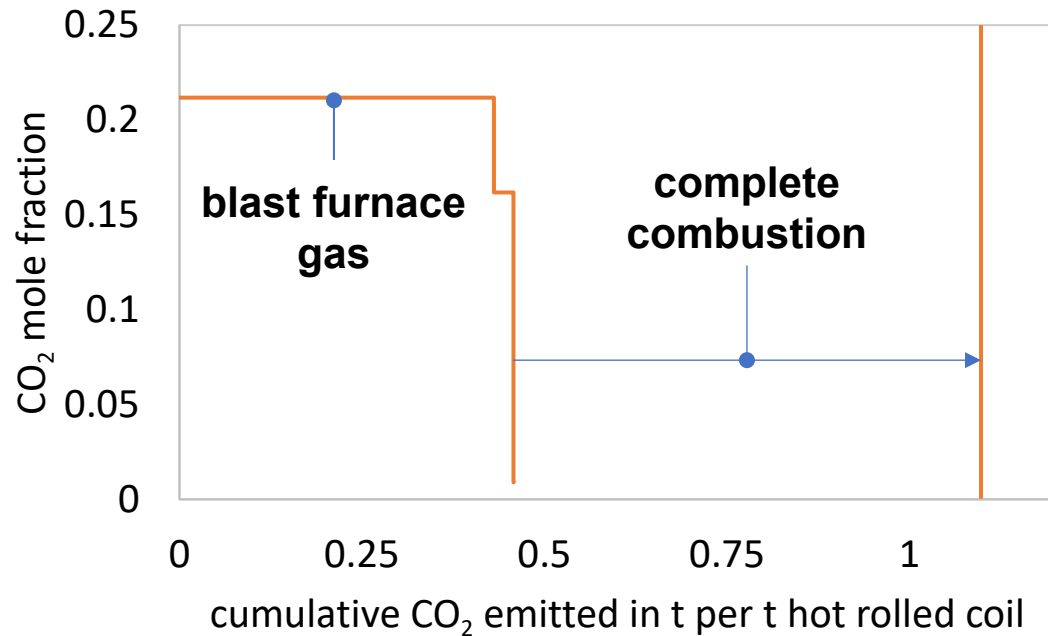
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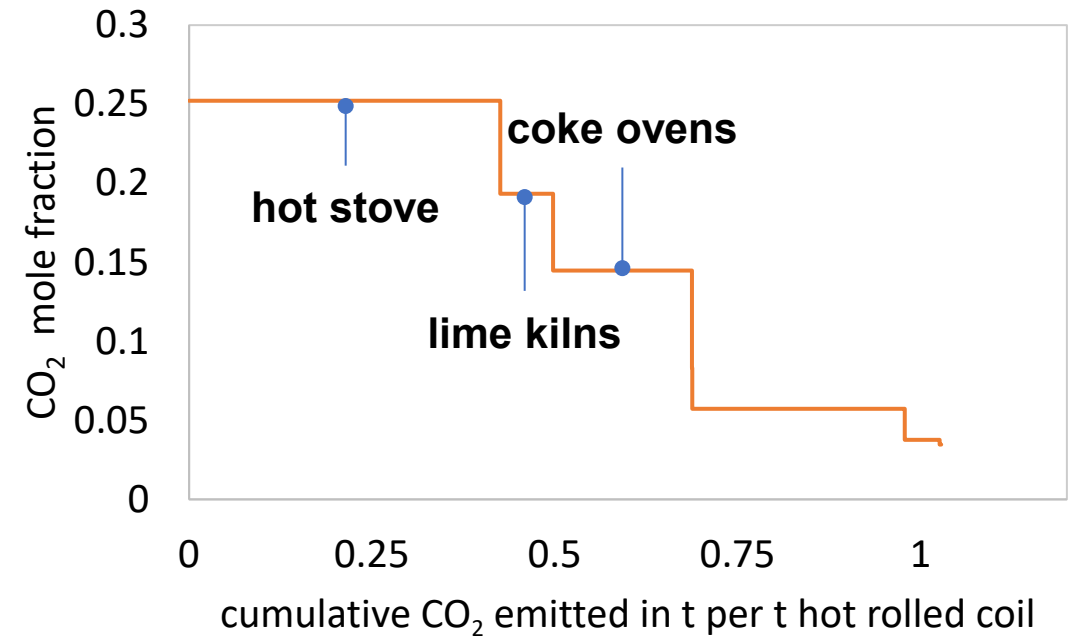
Hooey, L. et al. *Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill)*. (2013).

BF-BOF: Where to capture?

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

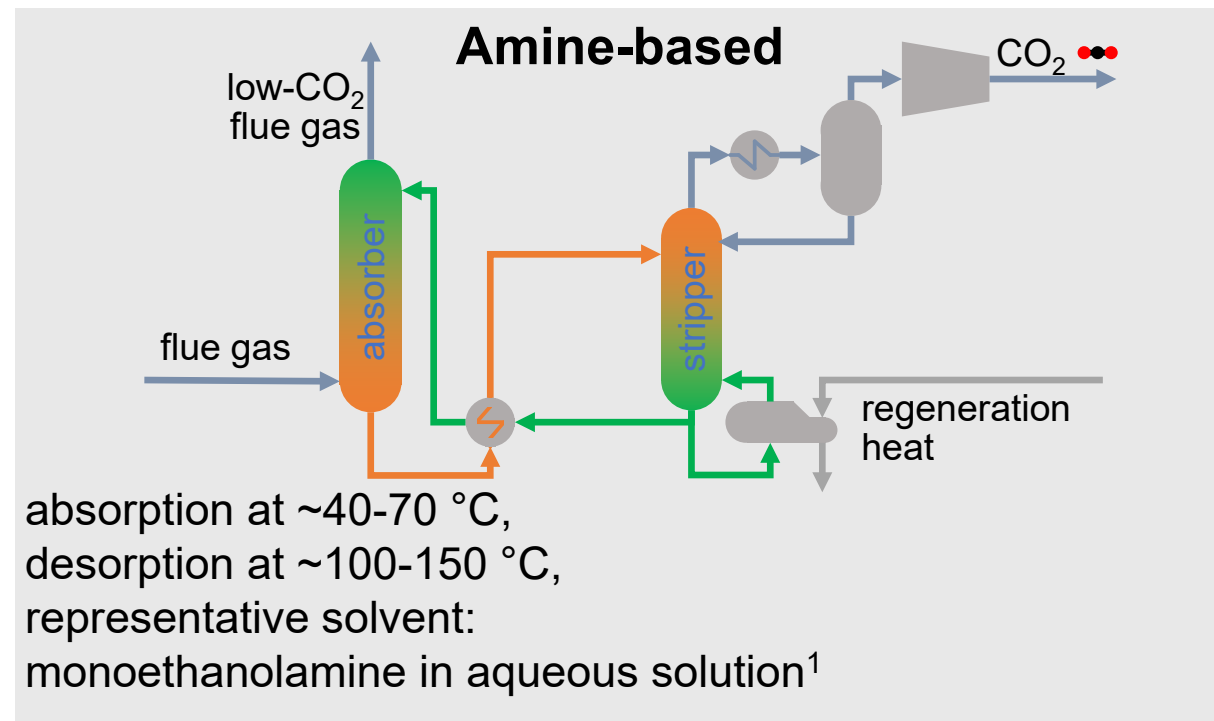


flue gases
from feedstock supply / post-processing



Hooey, L. et al. *Iron and Steel CCS Study (Techno-Economics Integrated Steel Mill)*. (2013).

Capture technologies



1

size the capture plant (Aspen Plus)

2

determine electricity and natural gas consumption, as well as amount of carbon dioxide captured

3

estimate component cost based on [3-4]

4

cost of carbon avoided cost based on [5]

¹ Rochelle, G. T. Thermal degradation of amines for CO₂ capture. *Current Opinion in Chemical Engineering* 1, 183–190 (2012).

² Halliday, C. et al. Bench-Scale Demonstration of Molten Alkali Metal Borates for High-Temperature CO₂ Capture. *Ind. Eng. Chem. Res.* 59, 8937–8945 (2020).

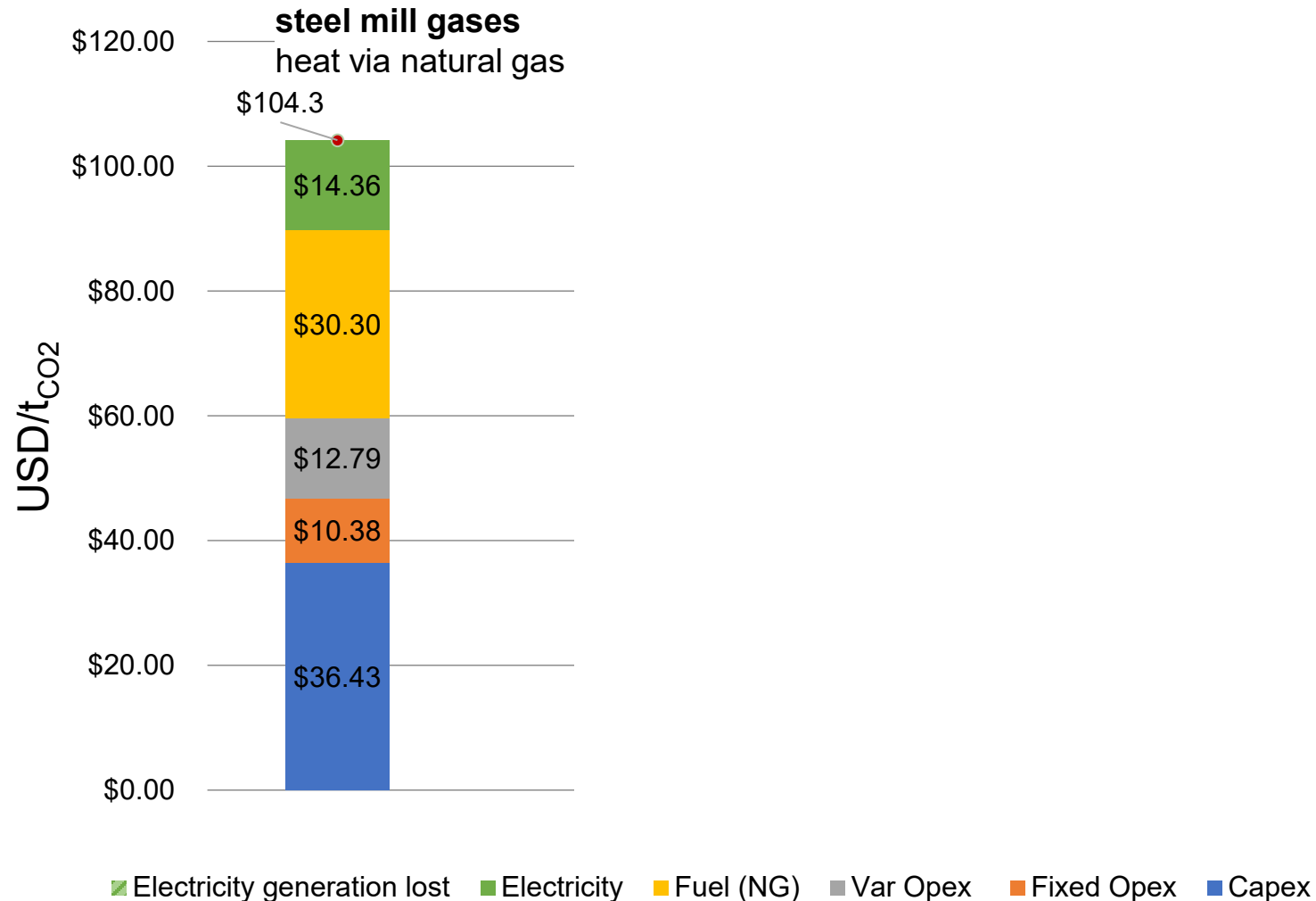
³ Seider, W. D. et al. *Product and Process Design Principles: Synthesis, Analysis, and Evaluation*. (John Wiley & Sons Inc., New York, 2017).

⁴ Electric Power Research Institute & Elliott, W. *Front-End Engineering Design (FEED) Study for a Carbon Capture Plant Retrofit to a Natural Gas-Fired Gas Turbine Combined Cycle Power* (2021).

⁵ Hughes, S. & Zoelle, A. *Cost of Capturing CO₂ from Industrial Sources*. National Energy Technology Laboratory. (2023).

cost of CO₂ avoided

$$\frac{\text{Cost}_{\text{capture}} - \text{Cost}_{\text{base}}}{\text{CO}_2 \text{ captured} - \text{CO}_2 \text{ from additional NG} - \text{upstream emissions of NG and electricity}}$$

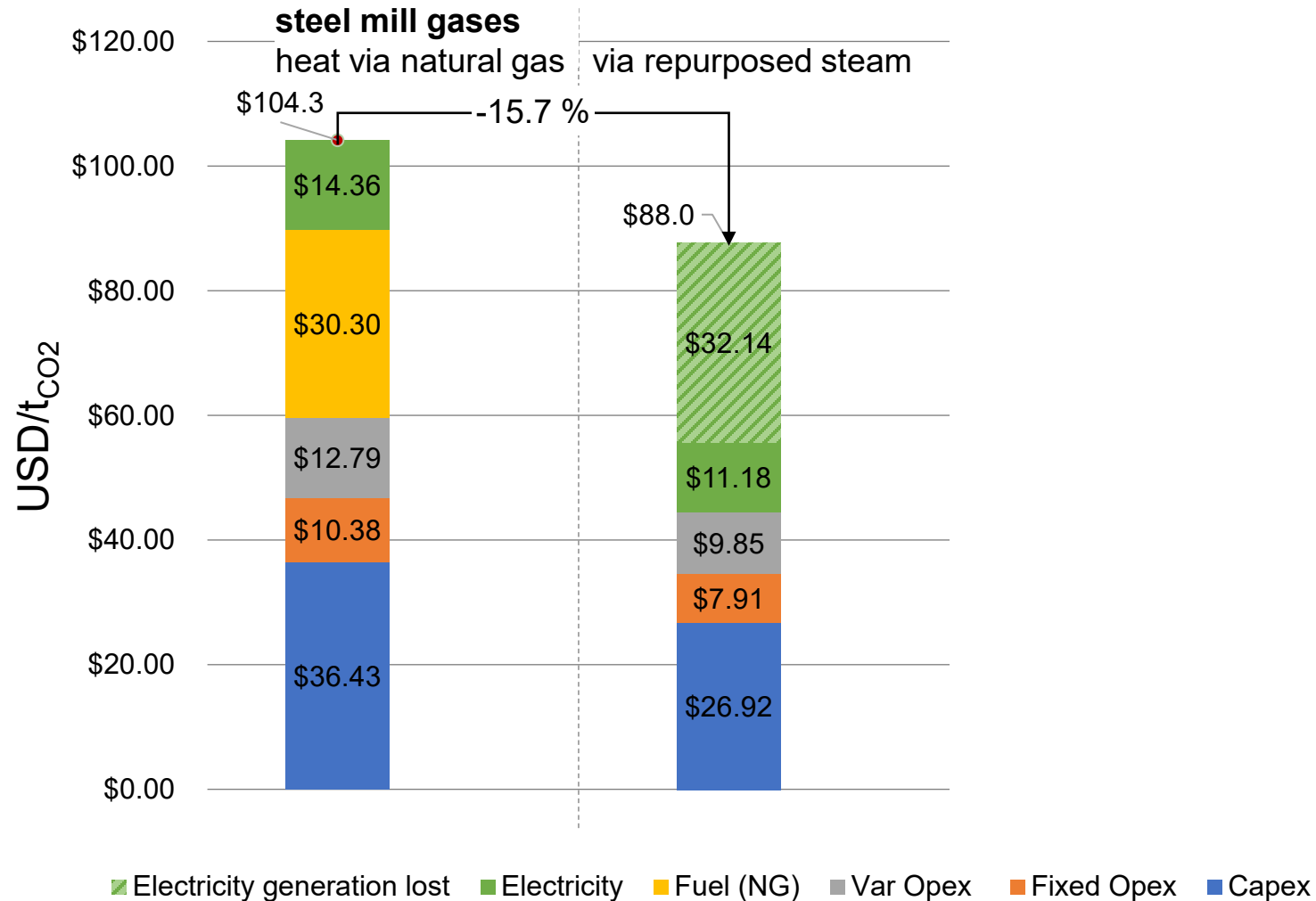


Main assumptions:

- BEC based on [1-2], TEA methodology based on [2]
- NG: \$4.6/MMBtu, 14.2 kgCO₂e/ MMBtu
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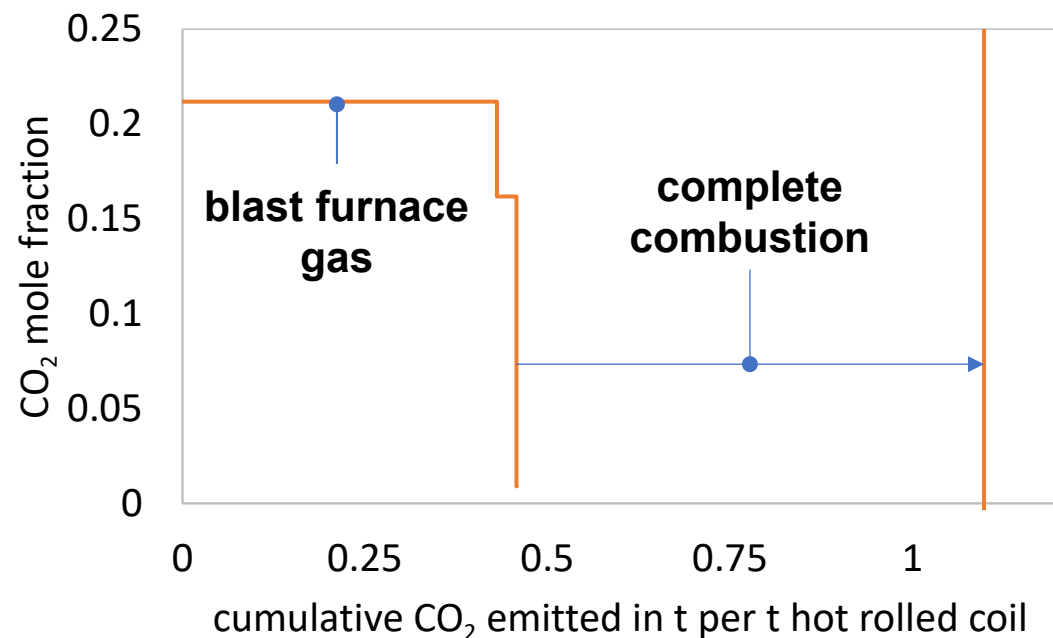


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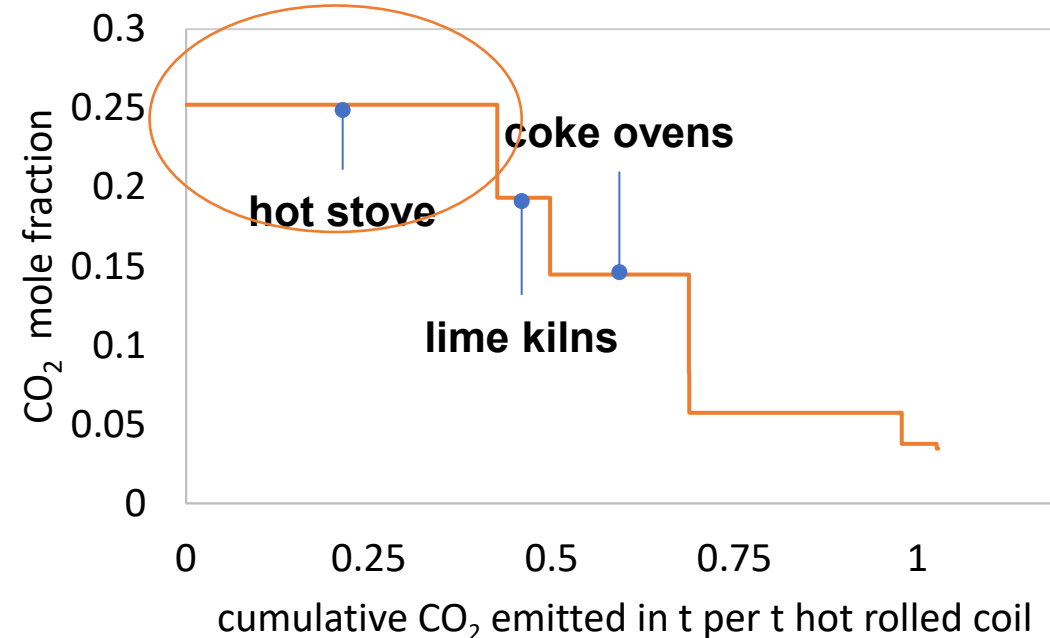
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BF-BOF: Where to capture?

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

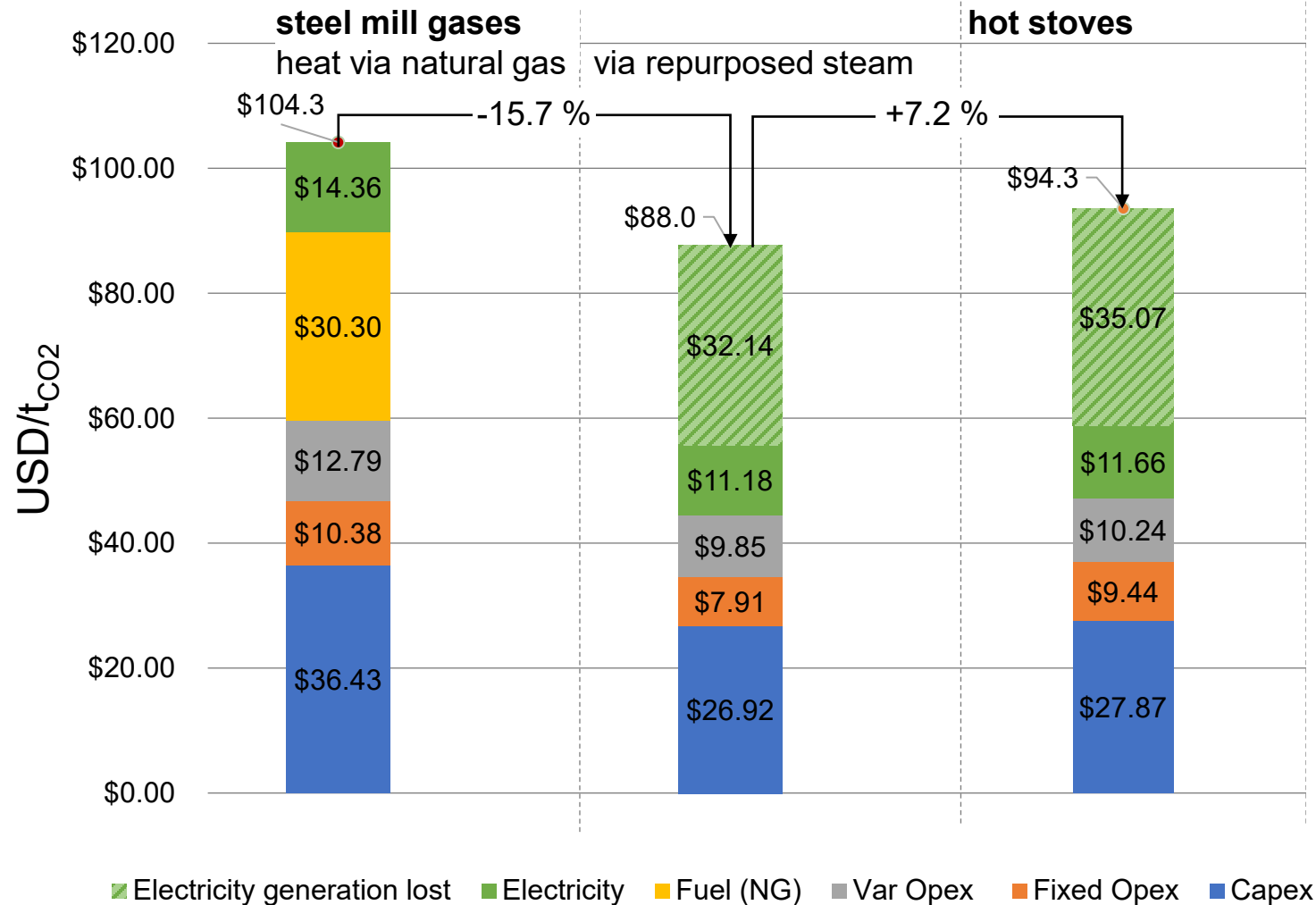


flue gases
from feedstock supply / post-processing



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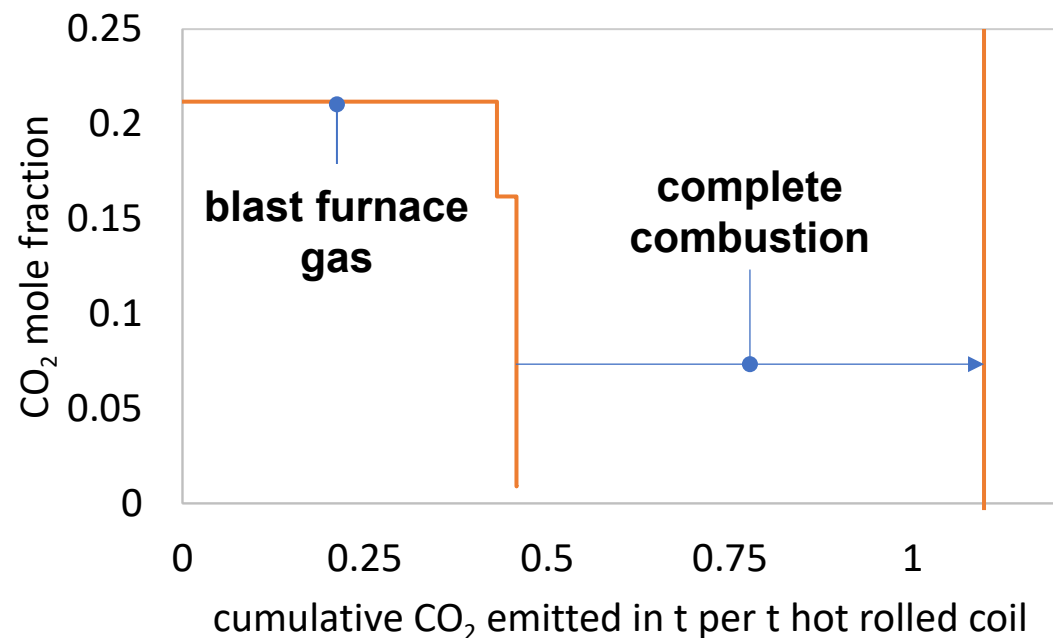


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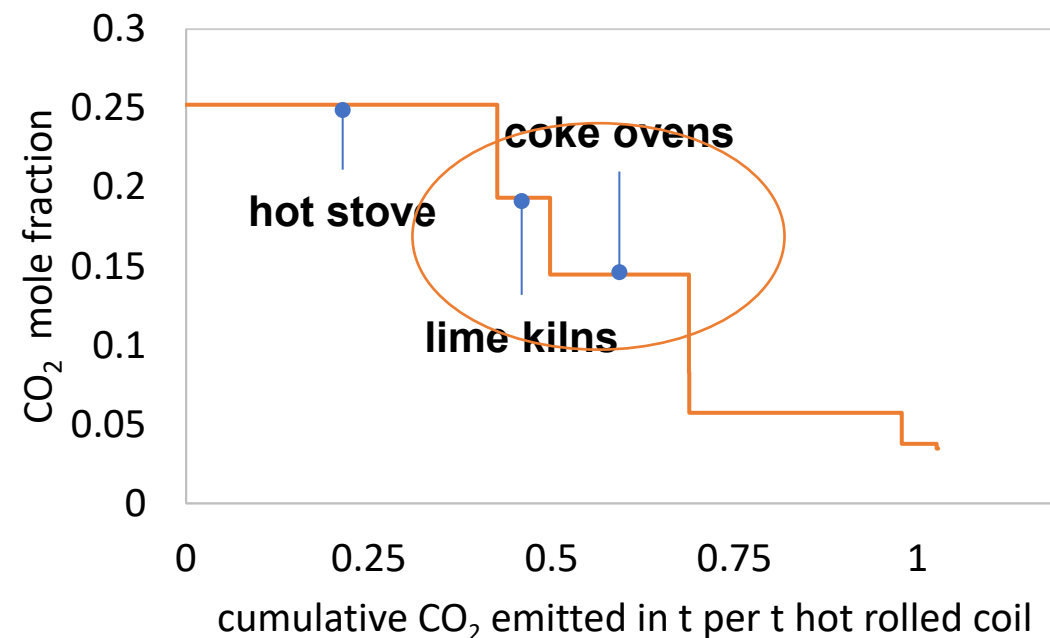
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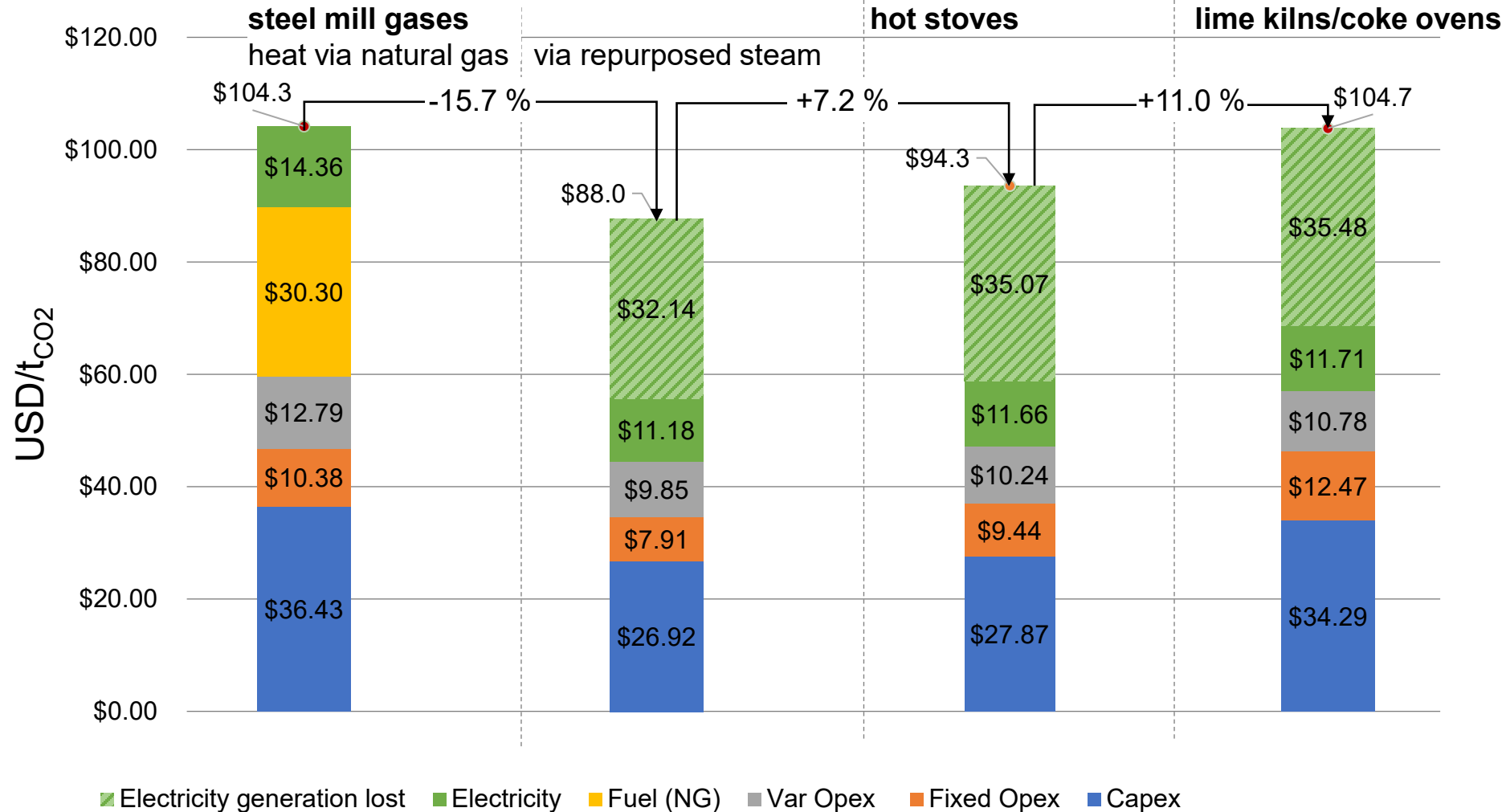


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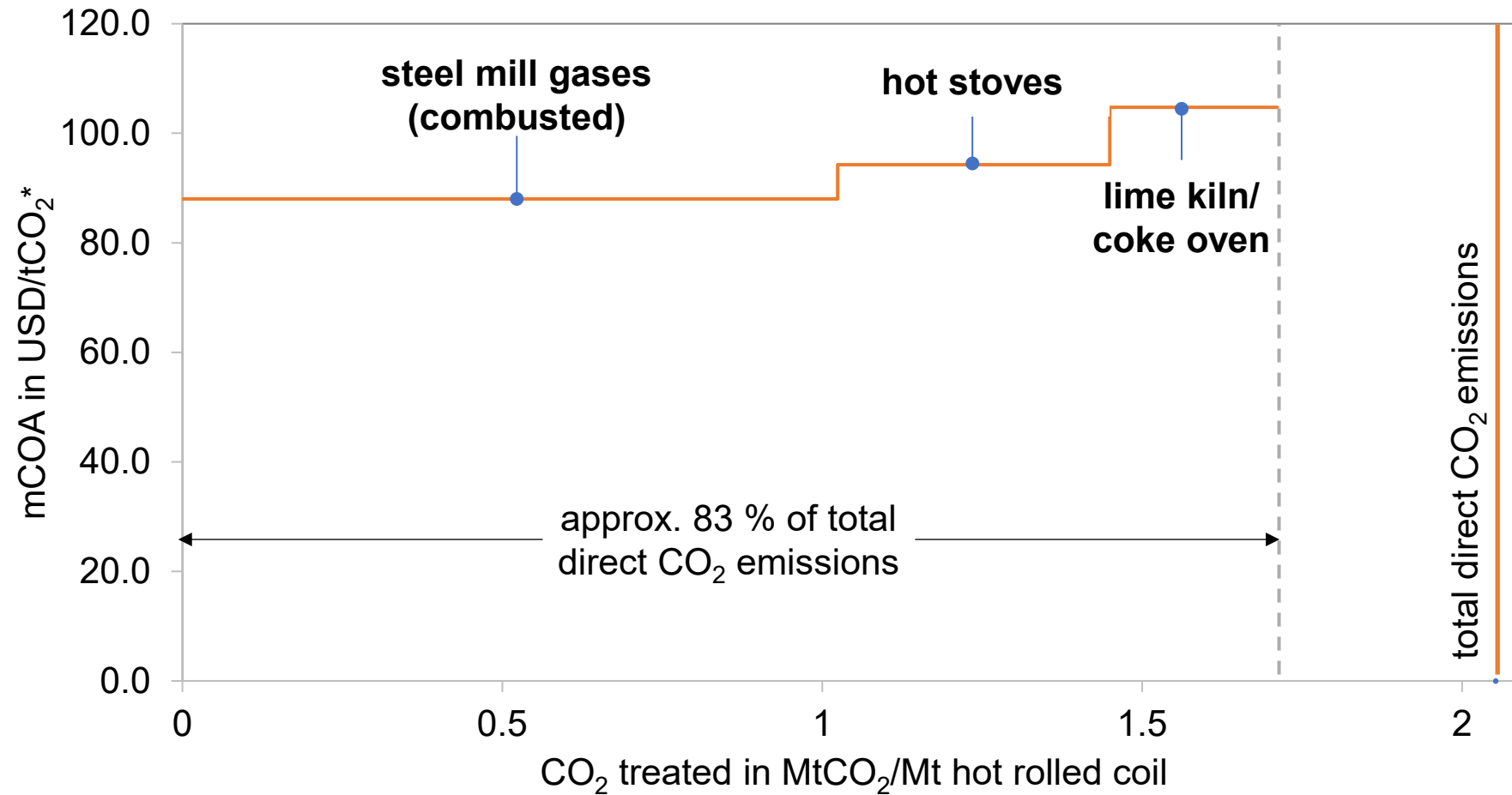


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The cost increases with the degree of CO₂ emissions avoided

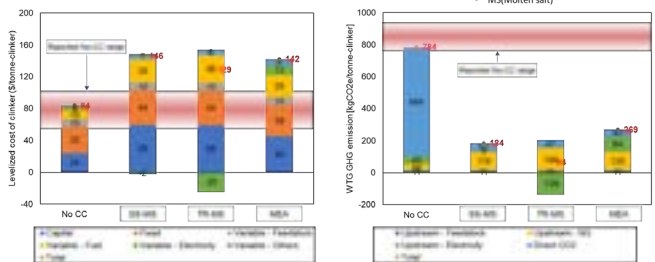
PRELIMINARY



*assuming heat from repurposed steam

Summary and future work

Cost and GHG results



Assumptions (U.S. 2022 average):
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 • Grid electricity: \$67.3/MWh, 439 kgCO₂/MWh

Summary

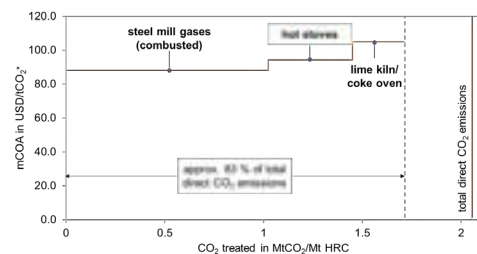
Cement:

- Molten salt results in lower capture cost than the amine-based capture under the same TEA assumptions
- Cost savings are driven by high-temperature waste heat production, which allows for power generation

Steel:

- Flue gases are distributed and vary in CO₂ concentration
- Cost is lowest, when targeting large flue gas sources using locally available heat sources.
- Cost of carbon avoided increases with the degree of CO₂ avoided

The cost increases with the degree of CO₂ emissions avoided



*assuming heat from repurposed steam

cost of CO₂ avoided

$$\frac{\text{Cost}_{\text{capture}} - \text{Cost}_{\text{base}}}{\text{CO}_2 \text{ captured} - \text{CO}_2 \text{ from additional NG} - \text{upstream emissions of NG and electricity}}$$

CO₂ captured – CO₂ from additional NG – upstream emissions of NG and electricity

