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ETSAP & IETS TCP Workshop

Evaluating costs and environmental performance of CO₂ capture for heavy industry application: a comparison between calcium looping and amine scrubbing

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Personal Background



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Personal expertise

- CCUS - CO₂ capture and storage
- CCUS - CO₂ conversion
- Industry decarbonization
- Process modeling
- Techno-economic analysis

Current projects:

GECOS - Group of Energy Conversion Systems:



Our numbers:

- 9 Full professors
- 11 Associate professors
- 21 Researchers
- 34 Ph.D. students

Our Topics:

- Power Cycles
- Renewable energy
- Carbon Capture
- Micro-Grids and multi-energy systems
- Energy system modelling and optimization
- Hydrogen and sustainable fuels



HERCCULES
full CCUS chain demonstration



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Background

CEMENT:

Up to **6-7%** of the global CO₂ emissions come from the **cement** industry

Hard-to-abate industry, approximately **60%** of CO₂ emissions come from the **calcination** of limestone (during the **clinker** production step).

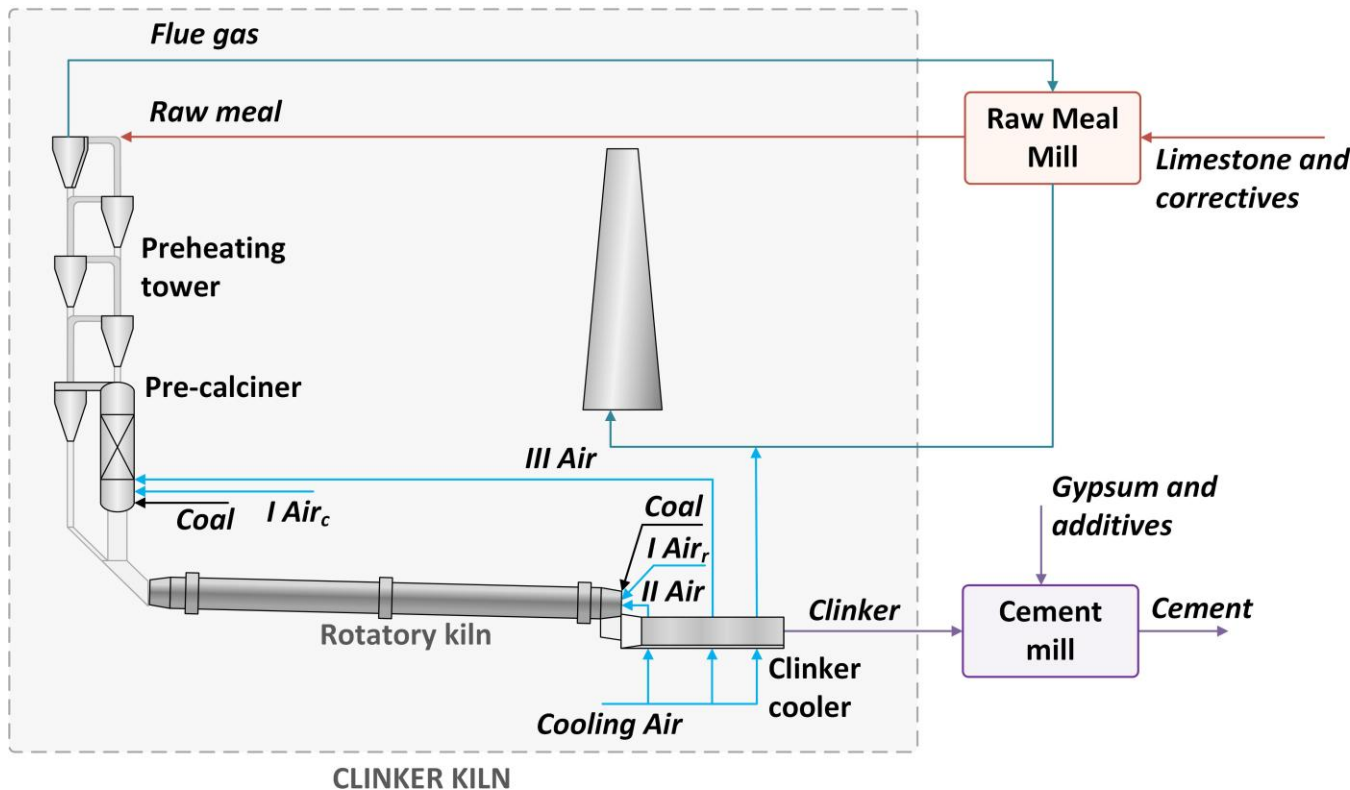
Decarbonization and mitigation techniques include: reduction clinker-to-cement ratio, energy efficiency, fuel shift to alternative fuels, and **Carbon Capture and Storage**.

STEEL:

- Up to **7%** of the global CO₂ emissions come from the **steel** industry
- The traditional and most widespread process is based on the **Blast Furnace (BF)** and **Basic Oxygen Furnace (BOF)**, which use **coal** and **coke** as energy sources and reducing agents.
- Decarbonization and mitigation techniques include: scrap recycling, energy efficiency, electrification and hydrogen, and **Carbon Capture and Storage**.



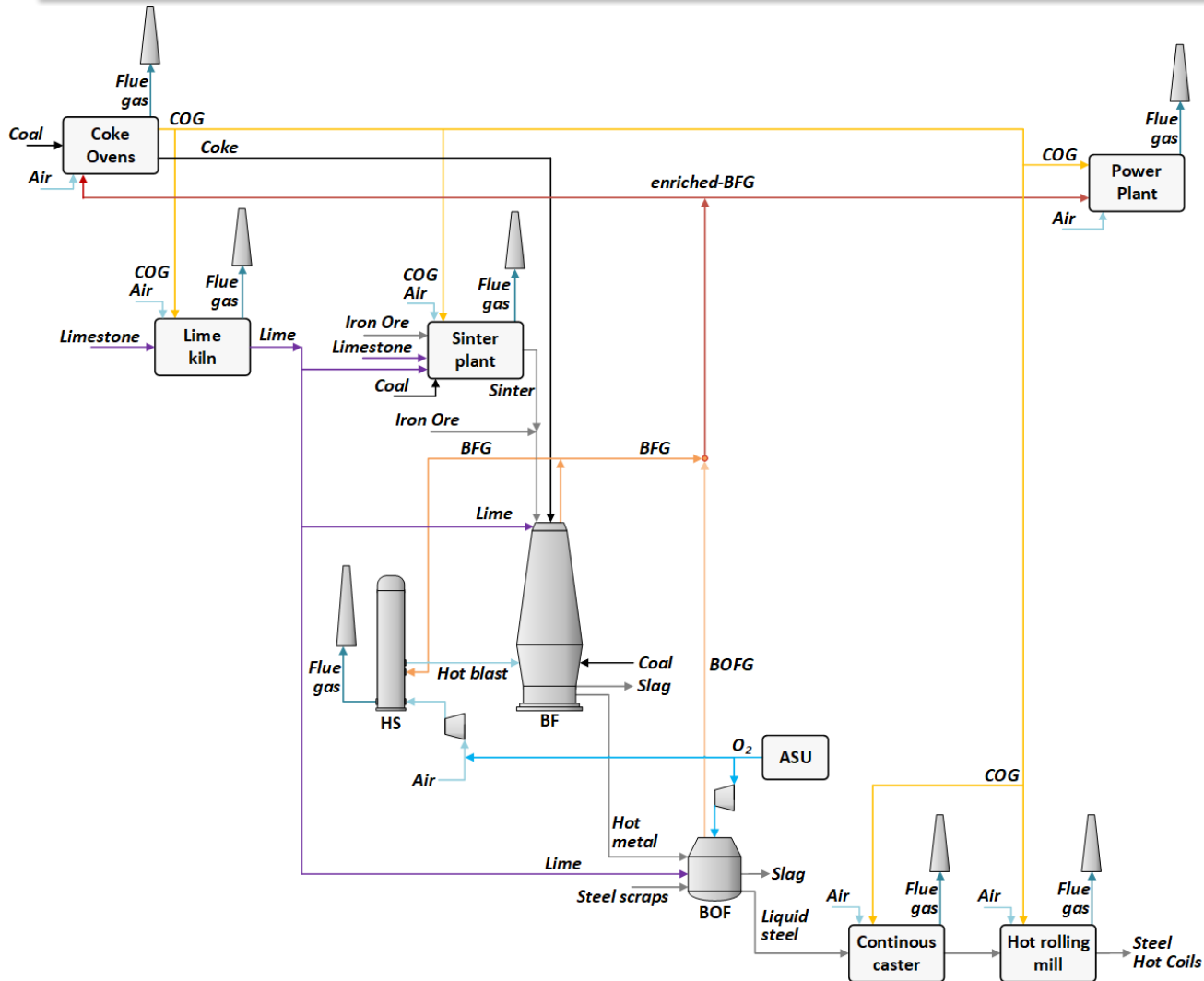
Cement production: reference process



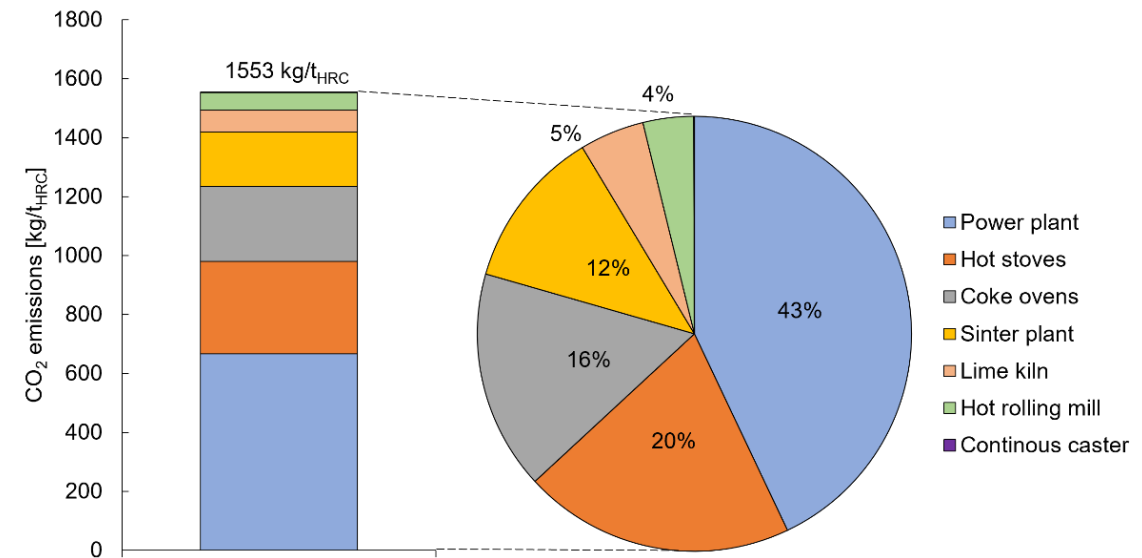
Reference cement plant	
Annual cement production	1.45 Mt/y
Clinker-cement ratio	0.65 -
Coal consumption	2.0 GJ/t _{cem}
Electric consumption	0.3 GJ/t _{cem}
CO ₂ emissions at plant stack	540 kg _{CO2} /t _{cem}

- State-of-the-art plant clinker kiln with a preheating tower, pre-calciner, rotatory kiln, and clinker cooler.
- Raw meal composed mainly of limestone.
- Hot air exiting the clinker cooler is used as combustion air.
- Flue gas at 20-30% concentration in CO₂.

Steel production: reference process

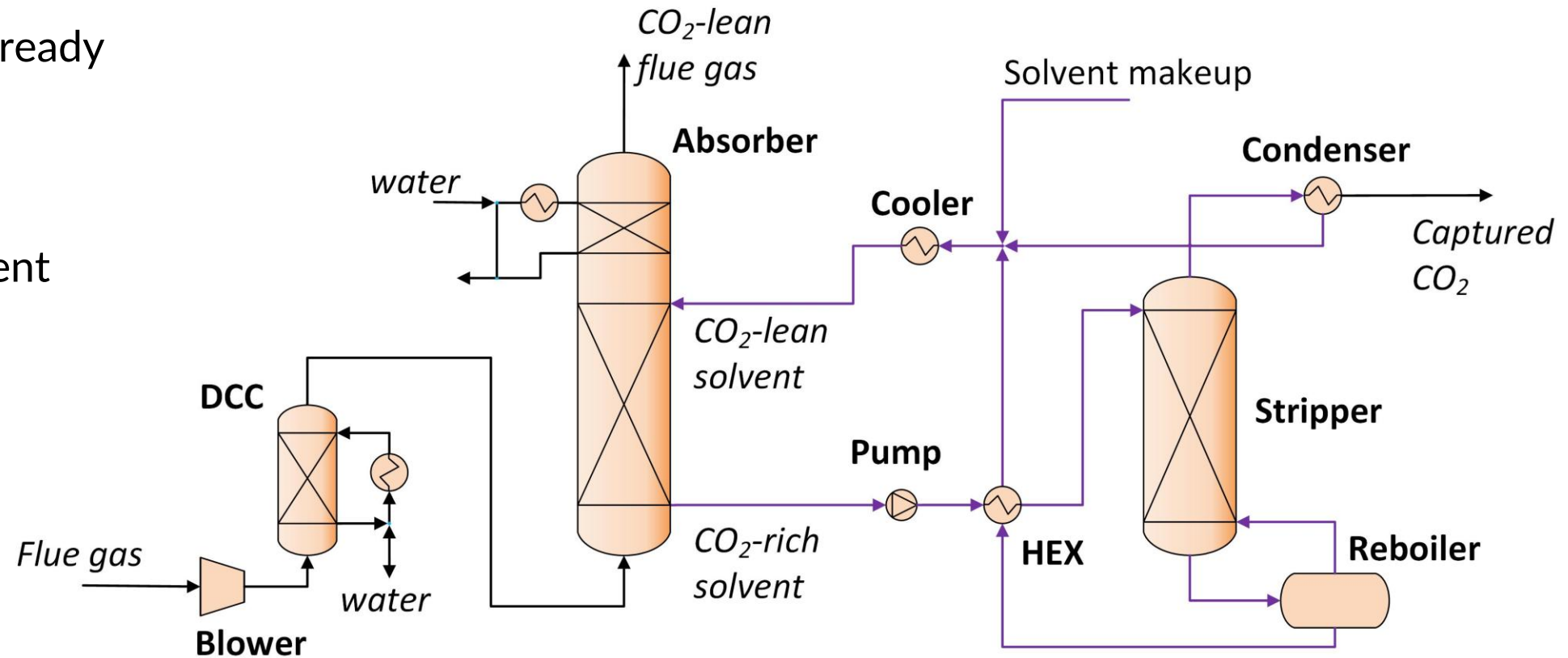


Reference steel plant	
Annual steel production	4.0 Mt _{HRC} /y
Coal consumption	16.7 GJ/t _{HRC}
Electric consumption	0.1 GJ/t _{HRC}
CO ₂ emissions at plant stack	1,553 kg _{CO2} /t _{HRC}



CO₂ capture technologies: Ammine scrubbing

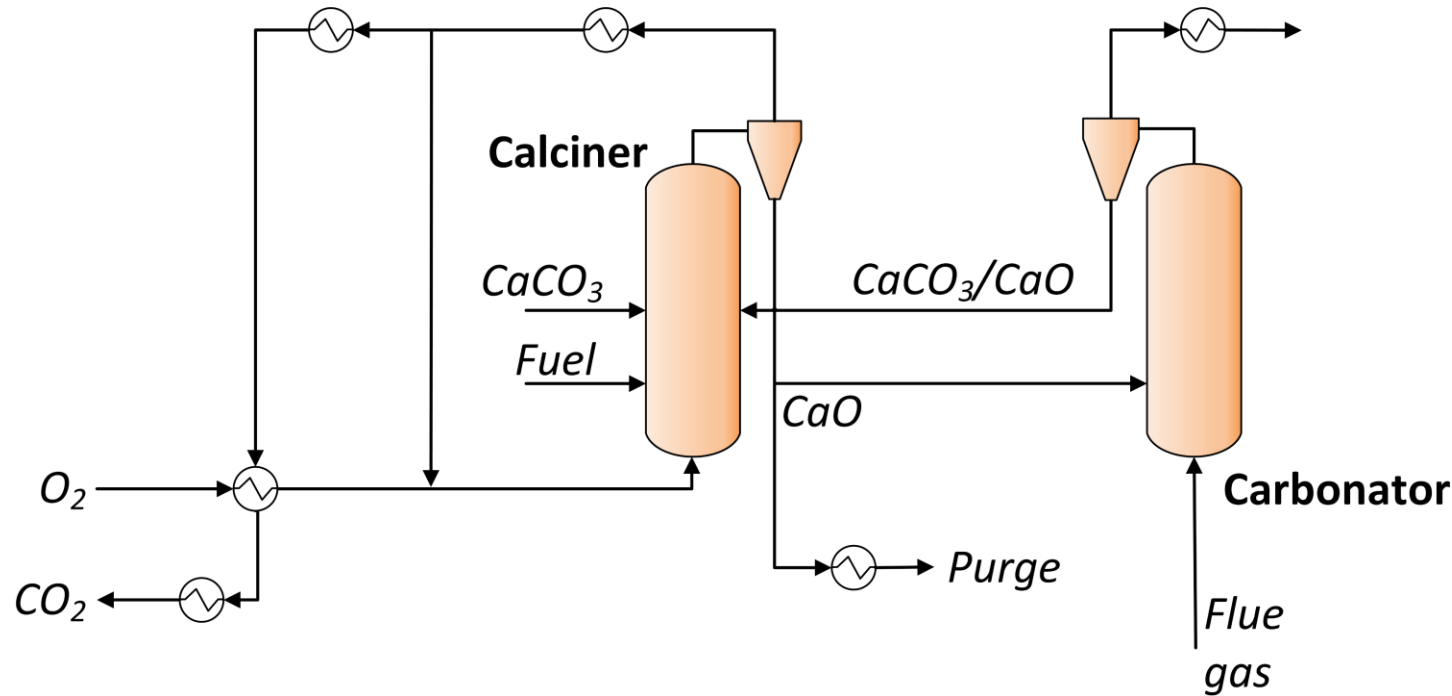
- Technology (MEA) already at commercial scale
- Need steam for solvent regeneration



Main components: Direct contact cooler, Absorber column, Stripper column

Main auxiliaries: Steam generation, CO₂ compression unit

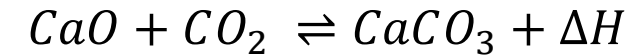
CO₂ capture technologies: calcium looping



Main components: carbonator and calciner

Main auxiliaries: Air Separation Unit (ASU), Rankine unit, Compression and Purification Unit (CPU)

Chemical looping process based on the carbonation/calcination reaction.



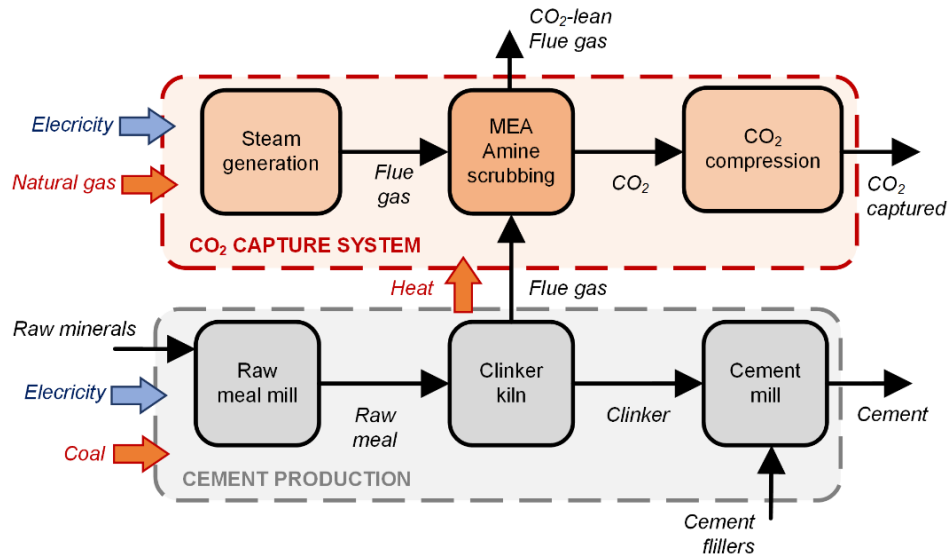
Thermal energy needed for the calcination reaction is supplied through **oxy-combustion**.

It uses a cheap sorbent (CaO) already widely used in industry.

Part of the energy supplied to the calciner can be recovered for steam and electricity production.

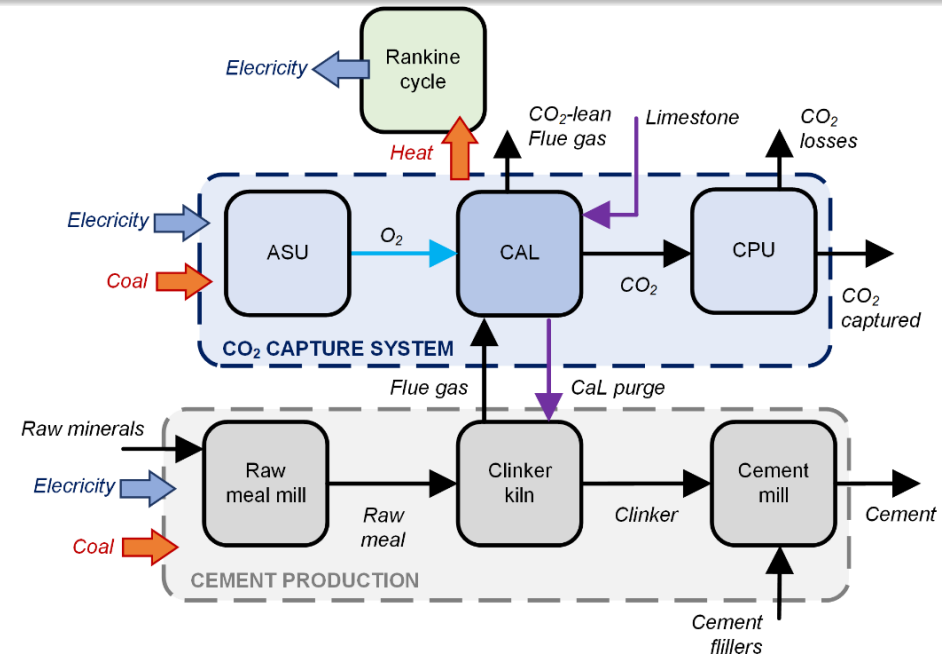
Part of the sorbent need to be continuously purged from the system to maintain high CO₂ capture rates.

CO₂ capture in cement: MEA and CaL



MEA integration:

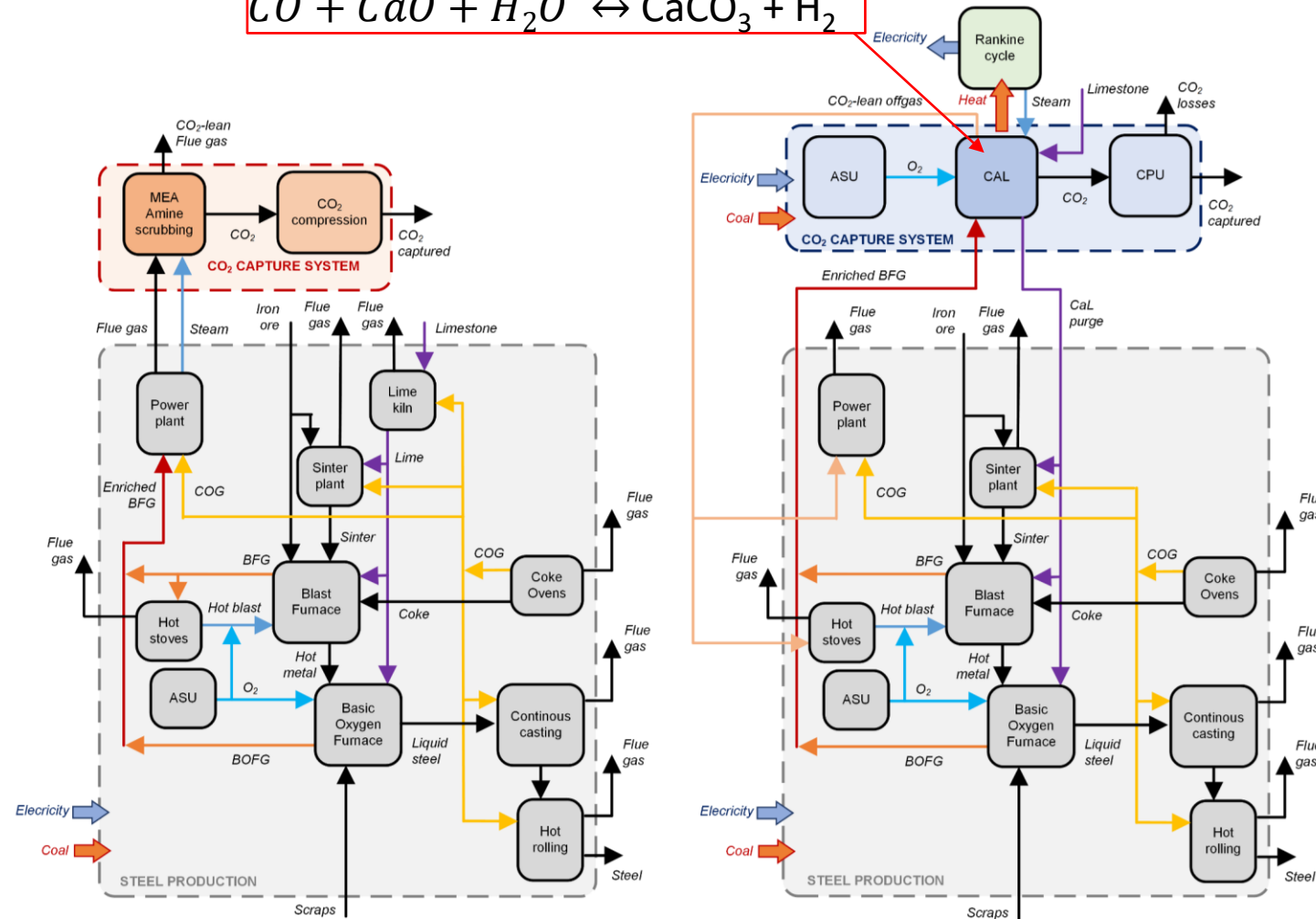
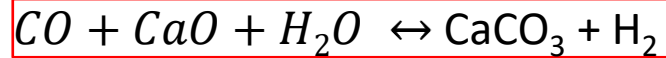
- CO₂ capture from clinker kiln flue gas
- Steam produced from heat recovery and a dedicated CHP fueled with Natural gas



CaL integration:

- CO₂ capture from clinker kiln flue gas
- CaO purge fed to the clinker kiln
- Electricity from the Rankine cycle covers the power demand of the plant, without producing excess electricity.

CO₂ capture in steel: MEA and CaL



MEA integration:

- CO₂ capture from power plant flue gas
- Steam extracted from the power plant steam turbine

CaL integration:

- CO₂ capture from BFG and BOFG
- Steam injection into the carbonator for the **WGS** reaction
- H₂-rich offgas fed to the power plant and hot stoves
- CaO purge replaces 100% of the lime produced from the lime kiln and limestone fed to the furnaces
- Electricity production exceeds the plant site consumption

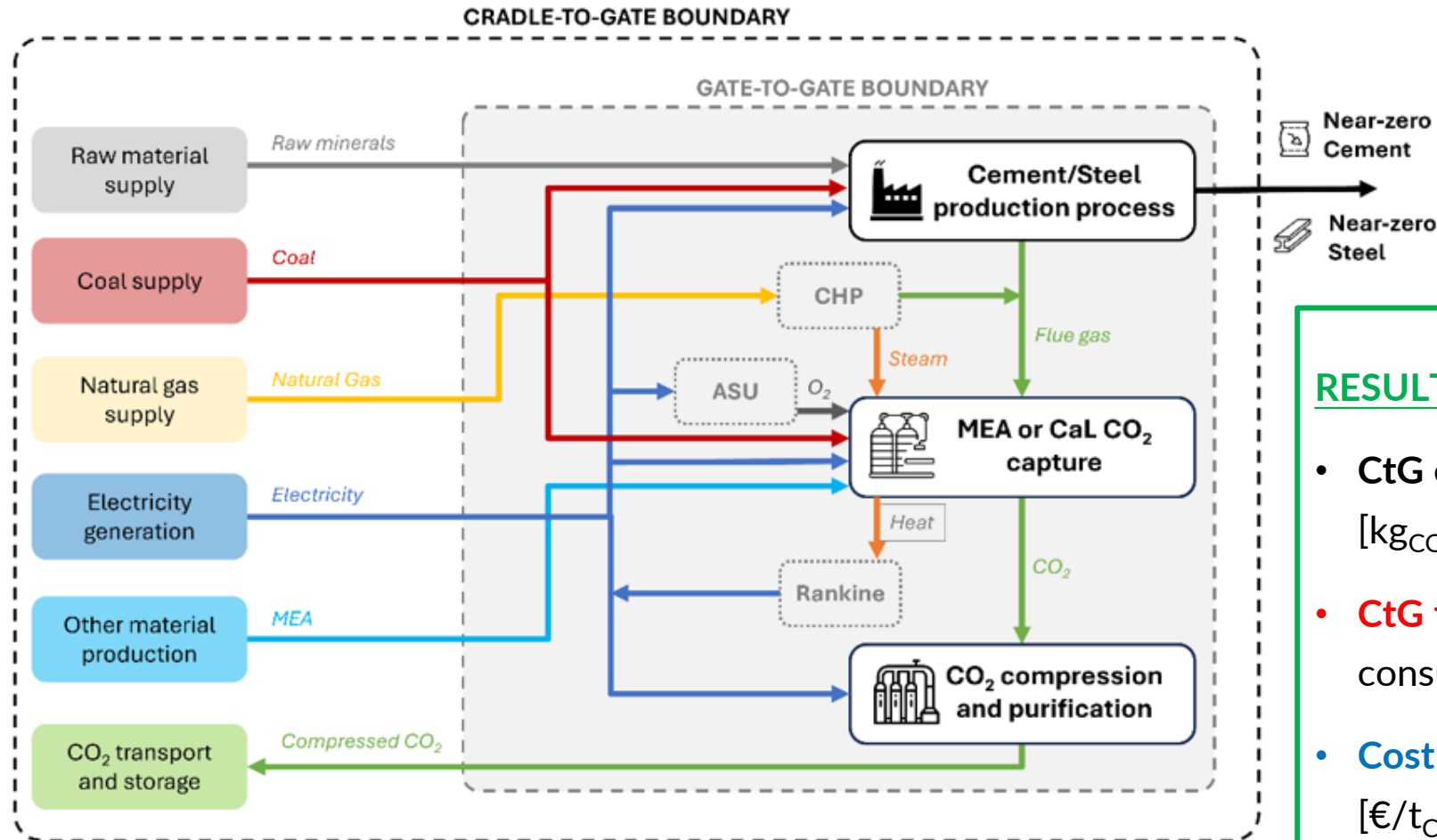
Methods: System boundaries

GtG balance:

Process modeling
of the plant

CtG balance:

- Fossil fuel demand – FFP
- Equivalent CO₂ emissions - GWP

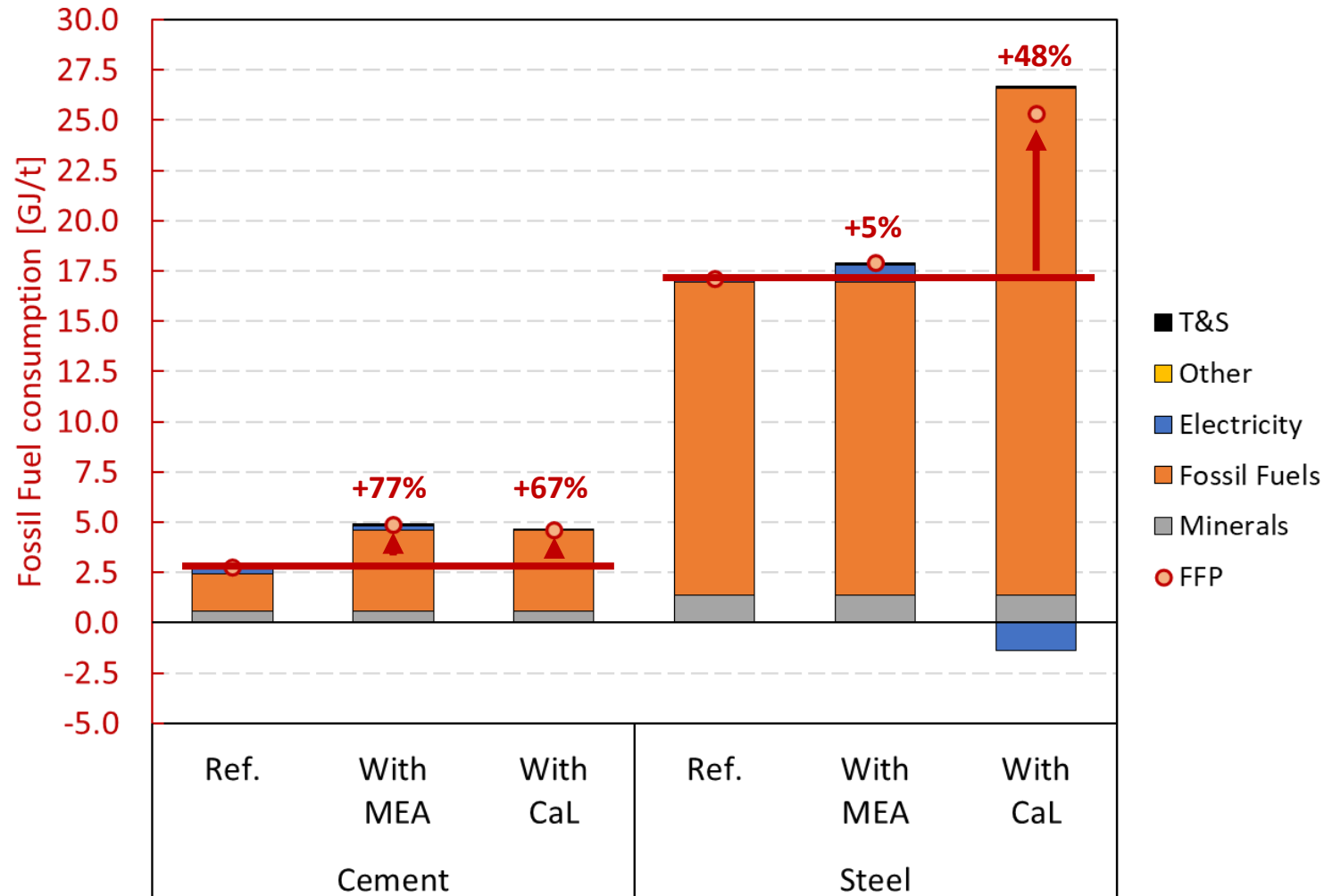


RESULTS:

- CtG eq. CO₂ emissions [kg_{CO2,eq}/t]
- **CtG fossil fuel** consumption [GJ_{LHV}/t]
- **Cost of eq. Avoided CO₂** [€/t_{CO2}]

Environmental performance: Energy consumptions

Fossil Fuel Potential (FFP)



MEA steam consumption **3.3 GJ/t_{CO2}**

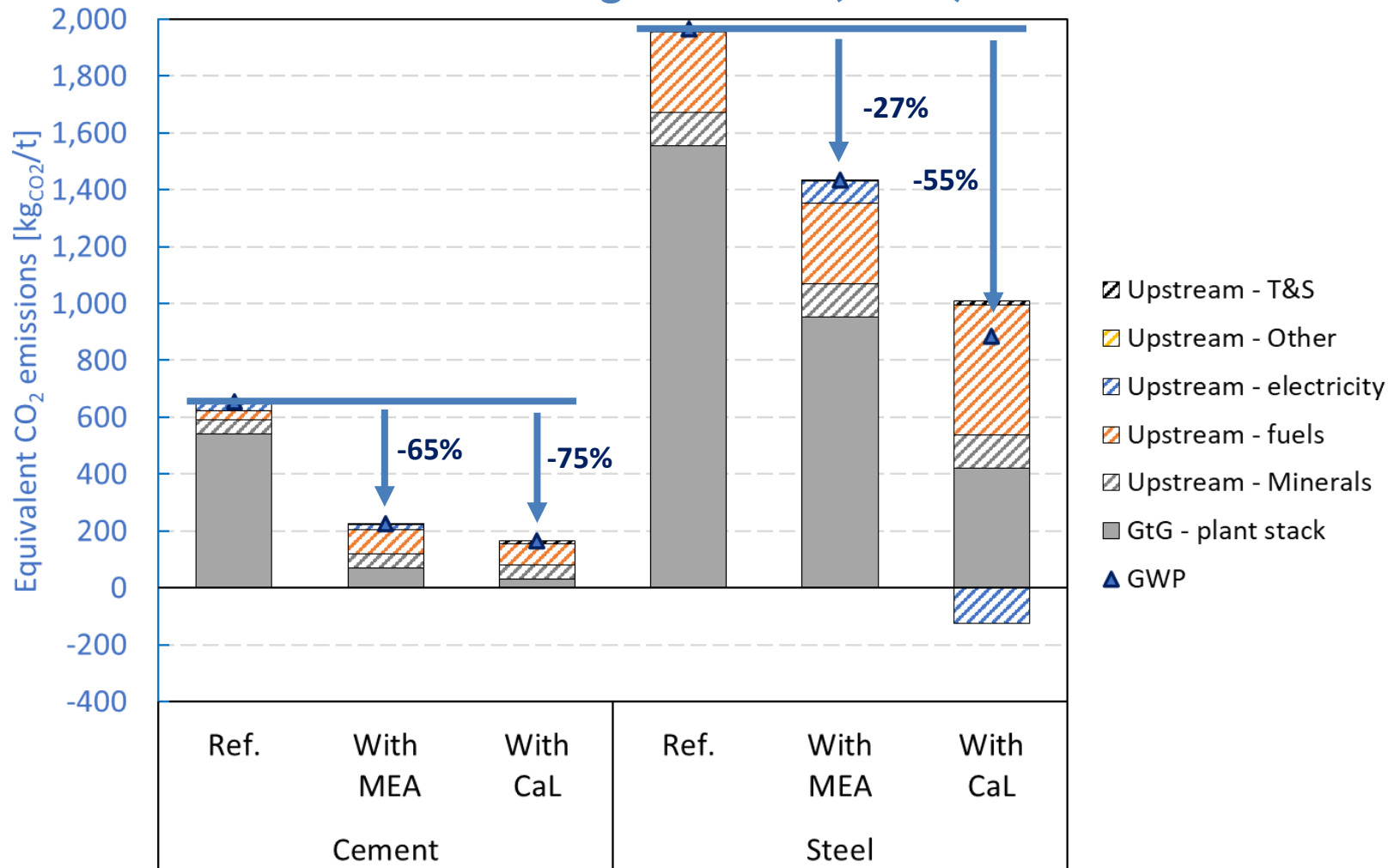
- Additional natural gas consumption in cement
- Additional electricity consumption in steel

CaL coal consumption **4.2-4.8 GJ/t_{CO2}**

- Electricity savings from heat recovery
- Energy savings in the clinker kiln and steel mill due to the reuse of the CaO purge in the production process.

Environmental performance: CO₂ emissions

Global Warming Potential (GWP)



Reduction in the emissions at the plant stack:

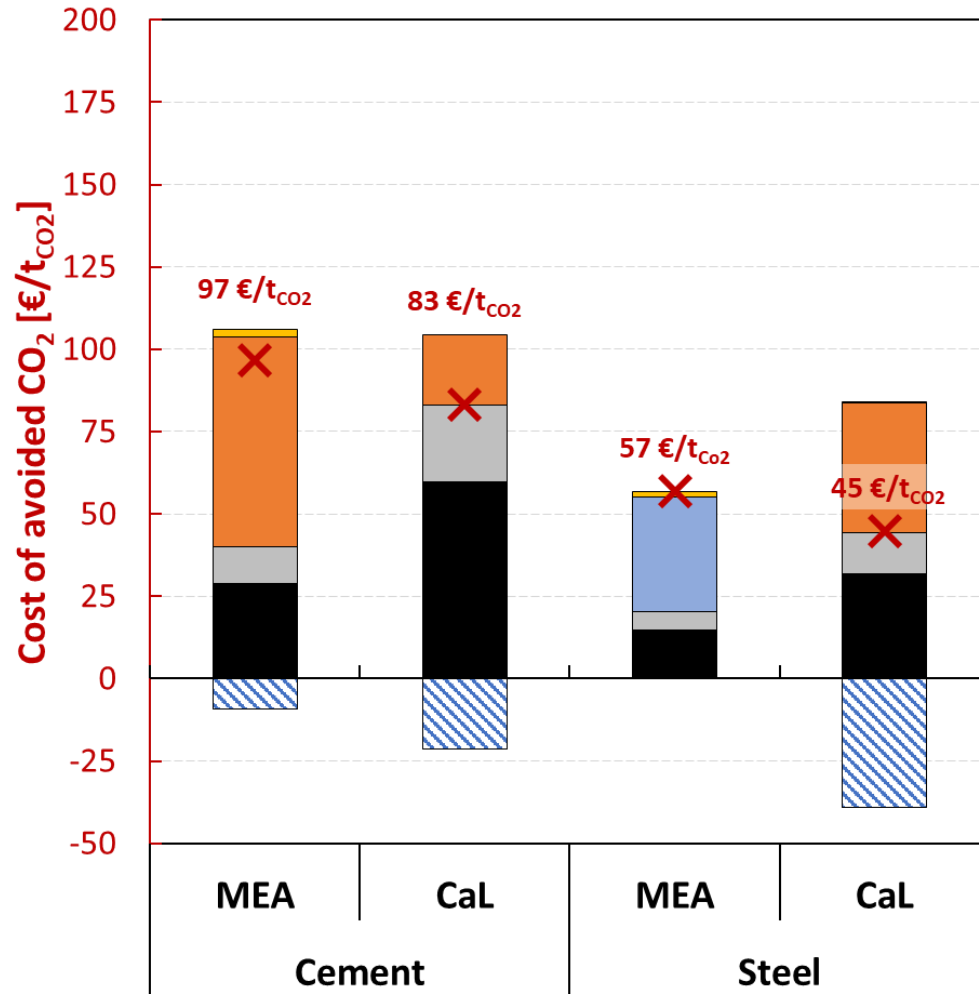
- **Cement:** -79%/-97% (MEA/CaL)
- **Steel:** -39%/-73% (MEA/CaL)

Increase in electricity upstream emissions for MEA integration in the steel plant (EU grid mix).

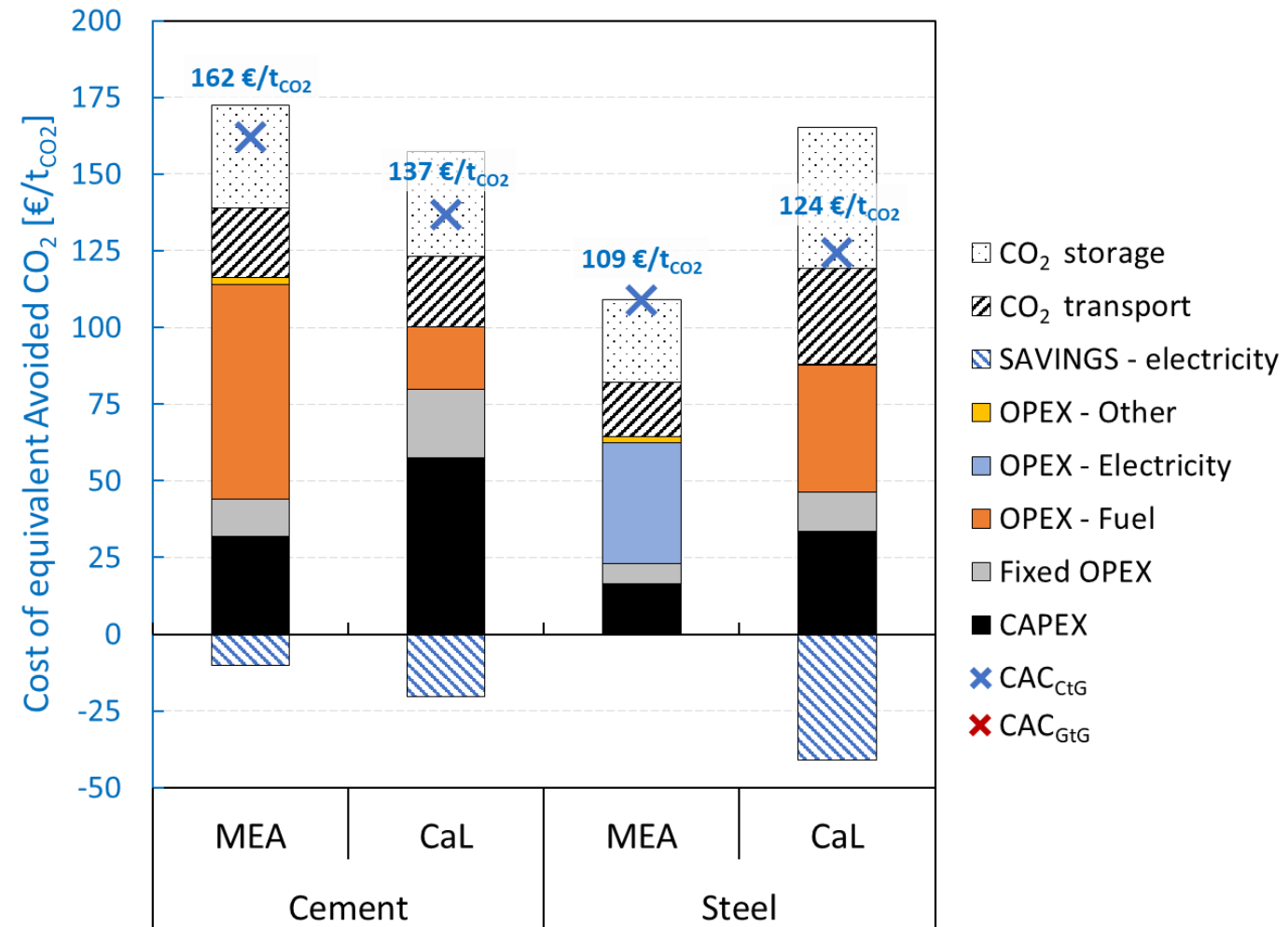
Increased upstream emissions for coal and natural gas

Costs per CO₂ avoided

Gate-to-gate balance, without transport and storage



Cradle-to-gate balance, with transport and storage



Conclusions

- Both **MEA** and **CaL** are suitable carbon capture technologies to **substantially reduce CO₂ emissions** from cement and steel plants.
- Depending on the considered CO₂ capture technology and system boundaries, the amount of CO₂ captured, CO₂ avoided, and equivalent CO₂ avoided may substantially differ.
- The estimated environmental performance (**emissions reductions**) and costs (**cost per avoided CO₂**) are strongly **influenced by the system boundaries** considered in the analysis (gate-to-gate or cradle-to-gate).
- CaL**-integrated plants show **better environmental performance**, in terms of both gate-to-gate and cradle-to-gate CO₂ emissions reductions, **at competitive costs** compared to MEA-based solutions.

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Read Online



Thank you for your attention!

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References

- Ferrario et al., 2026 – “Assessing CO₂ capture in cement and steel: a comparison between calcium looping and amine scrubbing”, *ACS Energy&Fuels*, DOI: [10.1021/acs.energyfuels.6c01682](https://doi.org/10.1021/acs.energyfuels.6c01682)
- Ferrario et al., 2025 – “Achieving net-zero cement through carbon capture and fuel switching”, *Chemical Engineering Journal*, DOI: [10.1016/j.cej.2025.168230](https://doi.org/10.1016/j.cej.2025.168230)