PARTIAL CAPTURE – AN OPPORTUNITY TO DECARBONIZE PRIMARY STEELMAKING

A TECHNO-ECONOMIC ASSESSMENT OF AMINE ABSORPTION OF CARBON DIOXIDE AT AN INTEGRATED STEEL MILL

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A Challenge: CO₂ emissions from industry

Challenge
- CO₂ arises from the production process, not only from heating
  - Steel: C as reducing agent
  - Cement: CO₂ from calcination

CCS as opportunity
- Carbon capture and storage (CCS) is one of the few mitigation options
- Industry provides large point sources with high CO₂ concentrations

Data for 2014: *Energy Technology Perspectives 2017, IEA*
Carbon capture and storage

CO₂ source

CO₂ capture: **Amine absorption**, membranes, adsorption

Electricity

Heat

CO₂ transport: ship or pipeline

CO₂ storage in geologic formations: aquifers, depleted oil fields

Technology readiness level (TRL)

TRL 9: commercial

TRL 7: demonstration

CCS – a cost problem?

Status of large-scale CCUS units
18 in operation ~ 40 Mt CO₂ p.a.
5 under construction
20 in development

Required to meet 2C
Thousands of units

Challenges:
• Legal & Regulatory
• Public acceptance
• Policies & Financing
• Cost

Large scale Carbon Capture Utilization and Storage (CCUS) facilities > 400 kt p.a. (in operation); commissioned after 1990

Global CCS Institute. The Global Status of CCS: 2018
Aims

…to support a rapid and sustainable transition of carbon-intensive industries to function in a carbon-constrained society.

i. Contribute to the cost-effective design of amine absorption cycles for partial CO$_2$ capture from industrial processes

ii. Evaluate how cost, energy need, and capture rates are related for CCS in integrated steel mills

iii. Assess the near-term implementation of partial capture in integrated steel mills

iv. Construct a perspective of partial capture in synergy with and in transition to other mitigation options for steel industry
Partial capture - a CCS concept

Idea: only a fraction of the accessible CO$_2$ is captured for storage.

This fraction is determined by

- Economic factors (cost reduction)
- Policy requirements (capture what is required)

Partial capture compared to full capture:

- Lower absolute energy need
- Lower absolute investment cost
- May beat economy of scale (€/t CO$_2$) for:
  - Plants with multiple stacks
  - Plants with excess/low cost heat
  - Plants that can vary their product portfolio flexibly to meet market conditions
Primary steelmaking

Carbon is used as reducing agent

primary steelmaking widely applied in 21st century, because of:

i. Globally rising steel demand
ii. Long blast-furnace lifetimes ~40-60 yrs
iii. Purity demands for high quality steel

→ Primary steelmaking has to be decarbonized
Scope of work

**Paper I**

Design of amine absorption cycles for partial capture

**Paper II**

Partial capture from steel-mill off-gases with excess heat at *constant* load

**Paper III**

Capture rate from CO$_2$ sources

Techno-economic assessment of partial capture from steel mill off-gases

**Paper A**

Dynamic performance of partial capture from a steel-mill off-gas at varying load of excess heat and gas flow
Overview on methods

**Paper I**
Absorption cycle design
- techno-economic evaluation

**Paper II**
Capture from steel mill off-gases with excess heat

**Paper III**
Techno-economic evaluation of partial CO₂ capture from steel mill off-gases

**Paper A**
Dynamic modelling of capture from a steel mill off-gas; control structure, load change, capture performance

**CO₂ absorption model in Aspen Plus**
- Rate-based mass and heat transfer
- Detailed reaction kinetics
- 30 wt% aqueous Monoethanolamine (MEA) solvent
- Optimization after heat demand through manipulation of liquid-to-gas ratio

**Steel mill model (Swerim AB)**
- Mass and energy balances for steel mill process units
- Detailed blast furnace, burden and hot stove calculations

**Cost estimation (SINTEF Industry)**
- Aspen In-Plant Cost Estimator

**Dynamic absorption model - Dymola**
- GLC library by Modelon
- Rate-based mass and heat transfer
- Equilibrium reactions

- Detailed installation factors from in-house data base
- ± 40% uncertainty

**License Seminar, 24th May 2019, Chalmers University of Technology**
Design of partial capture

Full capture

Solvent
100% Gas

90% \( \text{CO}_2 \) separated

Two principle paths for partial capture design:

Split Stream Path (SSP)

Solvent
Split flow

90% \( \text{CO}_2 \) separated

++ Lower specific CAPEX

Separation Rate Path (SRP)

Solvent
100% Gas

\(< 90\% \ \text{CO}_2 \) separated

++ Flexibility: variations and increase capture later on

→ The choice of design path affects heat demand and specific cost
Design of partial capture

Impact of changing separation rate depends on CO$_2$ concentration

**Separation Rate Path**
lower L/G $\rightarrow$ maximum T in liquid phase lowered

![Graph showing the relationship between L/G and maximum temperature in the liquid phase. The graph compares standard design, literature from Kvamsdal 2008, full capture, and partial capture 45% (SRP). The x-axis represents L/G in kg/kg, while the y-axis shows maximum temperature in the liquid phase in °C.]

![Graph showing the reboiler heat demand in MJ/kg CO$_2$ against CO$_2$ concentration in the absorber inlet in vol.%. The graph includes curves for SRP capture rate 45%, SRP capture rate 67%, and SSP capture rate 90%. The shaded area represents the range of CO$_2$ concentrations relevant for high CO$_2$ concentrations.]

Steel mill off-gases
Design of partial capture

How to bring down heat demand?
- High CO$_2$ concentrations: separation rate path
- Process modifications: Rich solvent splitting (RSS)
  Absorber intercooling (ICA)

→ Design choice for partial capture at a steel mill: Separation rate path + ICA + RSS
Steel mill CO$_2$ sources

Reference steel mill in Luleå: 3 major sources investigated
High- or low-level integration?

Capture from blast furnace gas requires less heat compared to capture from atmospheric flue gases.

The LHV of blast furnace gas increases with CO₂ capture:
- Gas management on-site can be changed to supply more excess heat to CCS at the expense of electricity production.

![Graph showing specific heat demand in MJ/kg CO₂ vs. p_CO₂ in absorber top gas in bar]

- BFG
- CHP flue gas
- Hot stoves flue gas
Excess heat at an integrated steel mill

Assumption: constant heat load (yearly average)

• 5 sources of excess heat to supply steam of 3 bar investigated

• Most are implementable and low-cost compared to steam supply via combustion of external fuel
Emissions reductions and capture cost

- Capturing from blast furnace gas is most economic → 20%–38% less CO₂ emissions

- Partial capture with excess heat costs less than full capture with external energy
Cost structure

i) Partial capture with excess heat is dominated by CAPEX;

ii) Full capture is dominated by steam cost and is thus more sensitive to changes in energy markets.
Dynamic partial capture from BFG

Hourly changes can be coped with well

→ Capture performance similar to steady-state if:
  the unit is designed to manage the entire span of experienced loads in heat and gas flow;
Carbon versus energy intensity?

Partial capture with excess heat can reduce CO\textsubscript{2} intensity of primary steel …

…without affecting significantly the energy demand!
Near-term implementation

Full chain cost = capture + transport + storage versus CO₂ price scenarios

Partial capture with excess heat requires a carbon price of 40-60 €/tonne CO₂

Window of opportunity: coming 5-15 years
Later: economic lifetime of partial capture unit would be too short before policies will require close to 100% emission reduction

\[ \text{Full chain cost} = \text{capture} + \text{transport} + \text{storage} \]

1 Assuming ship transport to storage
Transition to low-carbon technologies

i. Accumulated emissions are relevant!
   Partial capture could de-risk late arrival of HDR

ii. CCS infrastructure could be used in HDR concepts
   - capture remaining fossil & biogenic emissions
   - produce "blue" hydrogen from fossil fuels

iii. Partial capture could evolve
    - co-mitigation with biomass
    - solvent improvement

- Integrated steel works with 2Mt steel slabs p.a.
Conclusions

- Amine absorption cycles can be designed for separation rates << 90% → save energy and possibly cost compared to full capture; target: industry with CO₂ conc. > 20 vol.%

- Steel mill: Partial capture powered by excess heat is more cost-efficient than full capture that relies on external energy

- Steel product: Partial capture can reduce CO₂ footprint without significant energy penalty

- Near-term implementation in 2020s: possible if policies value carbon at 40-60 €/t CO₂

- Partial capture may allow for synergies with other mitigation options (biomass, electrification) and could be a step toward the transition to low-carbon economies