PARTIAL CAPTURE – AN OPPORTUNITY TO DECARBONIZE PRIMARY STEELMAKING

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

Licentiate candidate: Maximilian Biermann
Discussion leader: Dr. Lawrence Hooey, Swerim AB, Luleå
Supervisor of the candidate: Assoc. Prof. Fredrik Normann
Examiner and chair of this seminar: Prof. Filip Johnsson

This work has been carried out at:
The Division of Energy Technology
Department of Space, Earth and Environment

Financial support:
Gassnova (CLIMIT Demo)
The Swedish Energy Agency
A Challenge: CO$_2$ emissions from industry

Challenge
- CO$_2$ arises from the production process, not only from heating
  - Steel: C as reducing agent
  - Cement: CO$_2$ from calcination

CCS as opportunity
- Carbon capture and storage (CCS) is one of the few mitigation options
- Industry provides large point sources with high CO$_2$ concentrations

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

CO₂ source

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

Heat

Electricity

CO₂ transport: ship or pipeline

CO₂ storage in geologic formations: aquifers, depleted oil fields

Technology readiness level (TRL)

TRL 9 commercial

TRL 9 demonstration

TRL 7

TRL 9

ICChemE Energy Centre. *A Chemical Engineering Perspective on the Challenges and Opportunities of Delivering Carbon Capture and Storage at Commercial Scale; 2018.*
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

Dedicated storage
- Gas processing
- Power
- Industry

Enhanced Oil Recovery
- Gas processing
- Power
- Industry

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 CO₂ 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 CO₂) 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

± flow
± CO₂ concentration

Paper II

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

Paper III

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

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

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

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

**Full capture**

Solvent

100% Gas

**Two principle paths for partial capture design:**

**Split Stream Path (SSP)**

Solvent

Split flow

90% CO₂ separated

++ Lower specific CAPEX

**Separation Rate Path (SRP)**

Solvent

100% Gas

< 90% CO₂ 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 CO₂ concentration

Separation Rate Path
lower L/G → maximum T in liquid phase lowered
Design of partial capture

How to bring down heat demand?

- High \( \text{CO}_2 \) 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 CO₂ sources

Reference steel mill in Luleå: 3 major sources investigated

- Blast furnace gas
  - Hot stoves: 22.3%
  - CHP plant: 59.4%

- CHP plant flue gas

- Hot stove flue gas
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 against p_CO₂ in bar.
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;
Partial capture with excess heat can reduce CO$_2$ intensity of primary steel …

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

Full chain cost = capture + transport\(^1\) + storage

\[ \text{CO}_2 \text{ price scenarios} \]

Partial capture with excess heat requires a carbon price of 40-60 €/tonne CO\(_2\)

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

\(^1\)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.

![Graph showing emission intensity in t CO₂/t steel over years]

- BAU → HDR
- PCC
- PCC /PCC on POX
- PCC + biomass
- PCC + adv. solv.

18 Mt CO₂

Zero 2050 target
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