Techno-Economic Evaluation of Capturing CO$_2$ from a Generalized Integrated Steel Mill

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Financing Partners
Project Group

swerea | MEFOS

Project leader
Overall technical modelling
Reporting

Cost modelling
Technical assistance

CO₂ Capture modelling
& optimization

Project initiator
Technical assistance
Review and reporting

Tata Steel Consulting UK

TATA STEEL

SINTEF

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Contents

- Objectives
- System boundaries
- Technical assumptions
- Financial assumptions
- CO$_2$ Capture
- Energy systems
- Emissions
- Costs
- Conclusions
Objectives

- Scoping level (+/-) 30% costs of CO\(_2\) capture from a generalized integrated steel mill
  - Establish appropriate system boundaries
  - Assessment of CO\(_2\) emissions from different sources in steelmaking
  - Transparent
  - Estimate avoidance cost for several cases:

\[
\text{Cost CO}_2 \text{ avoided} = \frac{C_{\text{HRC with CCS}} - C_{\text{HRC reference}}}{C_{\text{CO}_2 \text{ emissions reference}} - C_{\text{CO}_2 \text{ emissions with CCS}}}
\]
Modeling - System Boundary

Incoming streams:
- Ferrous materials
- Fluxes & alloys
- Coal
- Natural gas

Energy input

Outgoing streams:
- Hot rolled coil
- By-products
- Solid wastes
- Flue gases
- Diffuse emission

No import or export of electricity
• **Major Raw Materials Input:**
  - **Iron Burden**
    - Iron Ore Fines
    - Iron Ore Lumps
    - Pellets
  - **Energy and Reductant**
    - Coking Coal
    - PCI Coal
    - Natural Gas
  - **Fluxes**
    - Limestone
    - Burnt Dolomite
    - Quartzite
    - Olivine
    - Calcium Carbide
  - **Merchant Scrap (External)**
  - **Ferroalloys and Aluminium**
    - Ferro Manganese Carbide
    - Ferro Silicon
    - Aluminium
Basic assumptions - technical

- "Typical" Integrated Steel Mill producing 4 million tonnes of standard grade Hot Rolled Coil (HRC)
  - Greenfield site
  - Hot Metal Production: 2 BFs with moderate PCI
  - Basic Oxygen Steelmaking and Secondary Metallurgy
    - Total scrap used is ~190 kg/t liquid steel
    - External (imported) scrap used is ~117 kg/t liquid steel,
  - Casting & Hot Rolling
  - Captive coke, sinter, lime, oxygen and power plant
  - Power production meets the demand of the steel mill. (i.e. no import/export of power). NG imported as necessary.
  - CO₂ is delivered to an existing pipeline at 110 bar
Financial Assumptions

- Location: Coastal Region of W. Europe
  - land purchase not included in the cost
  - Economic Life: 25 years
  - Depreciation: straight line
  - Discount rate: 10%
  - Site is adjacent to existing rail, harbour and natural gas pipeline
  - The cost evaluation was developed in US$ (2010)
Financial Modelling

- Cash flow through-cost model applied
- Cost estimates from:
  - Recent vendors supplied information
  - Database
  - Long term trend prices assumed for raw materials
- European suppliers & operating costs assumed
- Estimate accuracy is within the range +/- 30%.
- $NPV = 0 \rightarrow$ calculate Break Even Price of HRC
CO$_2$ Capture

- 2 levels of end of pipe capture modeled
  LV1: Steam boilers + Hot stoves
  LV2: LV1 + Coke plant + Lime kilns

- Oxygen Blast Furnace scenario
End of Pipe Capture Cases

Amine-type absorber/desorber chosen

- Based on conventional MEA system at 30% MEA
- delivers CO$_2$ at pipeline grade or higher
- well studied, robust reference system
- Costs available from equipment suppliers.
- 90% of CO$_2$ captured from chosen streams
- Energy optimized with split-flow/flash and intercooling to minimize energy consumption
  - More suitable for high CO$_2$ content gas
OBF Capture

Amine-type absorber/desorber chosen

- Based on 40% MDEA with 10% piperazine activator
- More suitable solvent for very high CO₂ content gas
- Delivers CO₂ at pipeline grade or higher
- Somewhat higher level of uncertainty accepted because the OBF system is also under development
- Capture rate was 94%
- Optimization of capture
  - Conventional system optimized for MDEA and piperazine concentrations; only intercooling/flash
## Energy Requirements for Capture

<table>
<thead>
<tr>
<th>Stream for capture</th>
<th>CO\textsubscript{2} in gas %</th>
<th>Capture rate %</th>
<th>First pass Steam 30% MEA Conventional GJ/t CO\textsubscript{2}</th>
<th>Steam GJ/t CO\textsubscript{2}</th>
<th>Power kWh/t CO\textsubscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Stove + Steam Boiler</td>
<td>27</td>
<td>90</td>
<td>3.6</td>
<td>3.03</td>
<td>122</td>
</tr>
<tr>
<td>Lime plant + Coke plant</td>
<td>18</td>
<td>90</td>
<td>3.6</td>
<td>3.18</td>
<td>149</td>
</tr>
<tr>
<td>Reheat furnace</td>
<td>5</td>
<td>90</td>
<td>4.1</td>
<td>Rejected</td>
<td></td>
</tr>
<tr>
<td>Sinter plant</td>
<td>5</td>
<td>90</td>
<td>4.0</td>
<td>Rejected</td>
<td></td>
</tr>
<tr>
<td>OBF Top gas</td>
<td>c. 34</td>
<td>94</td>
<td></td>
<td>2.35</td>
<td>111</td>
</tr>
</tbody>
</table>

*Advanced configuration Incl. compression*

*40% MDEA/ 10% Pz*
Energy - Methodology

Reference scenario

BFG BOFG NG → Condensing power plant 32% eff. 2.45 g CO₂/kWh → El.

Unrealistic to use with capture
## Summary of emissions

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>LV1</th>
<th>LV2</th>
<th>OBF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>kg/t HRC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinter Plant</td>
<td>Flue</td>
<td>289</td>
<td>289</td>
<td>289</td>
</tr>
<tr>
<td>Coke Plant</td>
<td>Flue</td>
<td>191</td>
<td>191</td>
<td>191</td>
</tr>
<tr>
<td>Lime Plant</td>
<td>Flue</td>
<td>72</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td>Blast Furnace</td>
<td>Hot Stoves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue</td>
<td></td>
<td>415</td>
<td>415</td>
<td>415</td>
</tr>
<tr>
<td>Reheat Furnaces</td>
<td>Flue</td>
<td>58</td>
<td>58</td>
<td>58</td>
</tr>
<tr>
<td>Power Plant</td>
<td>Flue</td>
<td>982</td>
<td>211</td>
<td>227</td>
</tr>
<tr>
<td>Steam boilers</td>
<td>Flue</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flue</td>
<td></td>
<td>966</td>
<td>1025</td>
<td>280</td>
</tr>
<tr>
<td>Other</td>
<td>Flare/diffuse</td>
<td>87</td>
<td>87</td>
<td>87</td>
</tr>
<tr>
<td>OBF TG CO₂</td>
<td>Process stream</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Produced CO₂</td>
<td></td>
<td>2094</td>
<td>2289</td>
<td>2364</td>
</tr>
<tr>
<td>Captured CO₂</td>
<td></td>
<td>0</td>
<td>1243</td>
<td>1533</td>
</tr>
<tr>
<td>Emitted CO₂</td>
<td></td>
<td>2094</td>
<td>1046</td>
<td>831</td>
</tr>
<tr>
<td>Avoided CO₂</td>
<td></td>
<td>0</td>
<td>1048</td>
<td>1263</td>
</tr>
<tr>
<td>Avoidance</td>
<td></td>
<td>0</td>
<td>50%</td>
<td>60%</td>
</tr>
</tbody>
</table>

*90% of CO₂ is captured
** total of CO₂ captured within OBF capture process
Energy Input of the Steel Plant

<table>
<thead>
<tr>
<th>Source</th>
<th>Reference GJ/t HRC</th>
<th>Level 1 GJ/t HRC</th>
<th>Level 2 GJ/t HRC</th>
<th>OBF-MDEA GJ/t HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coking coal</td>
<td>16.3</td>
<td>16.3</td>
<td>16.3</td>
<td>12.4</td>
</tr>
<tr>
<td>PCI coal</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.9</td>
<td>4.2</td>
<td>5.5</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>22.2</strong></td>
<td><strong>25.5</strong></td>
<td><strong>26.8</strong></td>
<td><strong>22.4</strong></td>
</tr>
<tr>
<td>PP Efficiency:</td>
<td>32%</td>
<td>57%</td>
<td>57%</td>
<td>57%</td>
</tr>
<tr>
<td>Electricity kWh/t\textsubscript{HRC}</td>
<td>400</td>
<td>573</td>
<td>622</td>
<td>573</td>
</tr>
</tbody>
</table>

**End of Pipe:** Only energy penalty – no advantages!
**OBF –** Allows fuel shift & more efficient system!
## Capital Costs – Steel plant exl. capture

<table>
<thead>
<tr>
<th>Million USD</th>
<th>Reference</th>
<th>EOP LV1</th>
<th>EOP LV2</th>
<th>OBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a. Process Plant (Installed Cost)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinter Plant</td>
<td>220</td>
<td>220</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>Coke Plant</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>310</td>
</tr>
<tr>
<td>Blast Furnace (inc. stoves, de-sulph., PCI, slag granulation)</td>
<td>622</td>
<td>622</td>
<td>622</td>
<td>610</td>
</tr>
<tr>
<td>BOS Plant (inc. Ladle Furnace)</td>
<td>459</td>
<td>459</td>
<td>459</td>
<td>459</td>
</tr>
<tr>
<td>Continuous Casting Plant</td>
<td>195</td>
<td>195</td>
<td>195</td>
<td>195</td>
</tr>
<tr>
<td>Hot Strip Mill (inc. Reheat Furnaces)</td>
<td>450</td>
<td>450</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>Oxygen Plant - High Purity</td>
<td>130</td>
<td>130</td>
<td>130</td>
<td>94</td>
</tr>
<tr>
<td>Oxygen Plant - Low Purity</td>
<td></td>
<td></td>
<td></td>
<td>134</td>
</tr>
<tr>
<td>Lime Plant</td>
<td>16</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>Steam boiler plant</td>
<td></td>
<td>139</td>
<td>160</td>
<td>90</td>
</tr>
<tr>
<td>Power Plant</td>
<td>280</td>
<td>362</td>
<td>362</td>
<td>362</td>
</tr>
<tr>
<td>1b. Auxiliary Plant (Installed Cost)</td>
<td>350</td>
<td>350</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>1c. Other Equipment (Delivered Cost)</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>128</td>
</tr>
<tr>
<td>(1) Total - Plant and Equipment</td>
<td>3366</td>
<td>3590</td>
<td>3611</td>
<td>3531</td>
</tr>
<tr>
<td>(2) Construction and Commissioning</td>
<td>562</td>
<td>562</td>
<td>562</td>
<td>562</td>
</tr>
<tr>
<td>(3) Main Plant Contingency @ 5% of (1) + (2)</td>
<td>196</td>
<td>208</td>
<td>209</td>
<td>205</td>
</tr>
<tr>
<td>(4) Blast Furnace Relines, year 15</td>
<td>232</td>
<td>232</td>
<td>232</td>
<td>232</td>
</tr>
<tr>
<td><strong>Metallurgical, Power and Ancillary</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>(1)+(2)+(3)+(4)</strong></td>
<td>4356</td>
<td>4592</td>
<td>4614</td>
<td>4530</td>
</tr>
</tbody>
</table>

15/11/2013
## Capital Costs – Capture Equipment

<table>
<thead>
<tr>
<th></th>
<th>Ref</th>
<th>EOP LV1</th>
<th>EOP LV2</th>
<th>OBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>(5) Total - CO2 Capture systems</td>
<td>0</td>
<td>679</td>
<td>917</td>
<td>578</td>
</tr>
<tr>
<td>TOTAL CAPITAL COST</td>
<td>4356</td>
<td>5270</td>
<td>5530</td>
<td>5108</td>
</tr>
</tbody>
</table>
# Avoidance Cost

<table>
<thead>
<tr>
<th></th>
<th>Reference</th>
<th>EOP LV1</th>
<th>EOP LV2</th>
<th>OBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>USD/t HRC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluxes</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Other Raw Mat’l &amp; Consumables</td>
<td>12</td>
<td>15</td>
<td>16</td>
<td>13</td>
</tr>
<tr>
<td>Purchased Scrap &amp; FerroAlloys</td>
<td>53</td>
<td>53</td>
<td>53</td>
<td>54</td>
</tr>
<tr>
<td>Maintenance &amp; Other O&amp;M</td>
<td>56</td>
<td>64</td>
<td>68</td>
<td>61</td>
</tr>
<tr>
<td>Labour Costs</td>
<td>70</td>
<td>71</td>
<td>72</td>
<td>71</td>
</tr>
<tr>
<td><strong>Energy and Reductant</strong></td>
<td><strong>118</strong></td>
<td><strong>151</strong></td>
<td><strong>163</strong></td>
<td><strong>139</strong></td>
</tr>
<tr>
<td>Iron Burden Cost</td>
<td>120</td>
<td>121</td>
<td>121</td>
<td>121</td>
</tr>
<tr>
<td><strong>Capital Cost</strong></td>
<td><strong>135</strong></td>
<td><strong>165</strong></td>
<td><strong>174</strong></td>
<td><strong>161</strong></td>
</tr>
<tr>
<td>HRC ”break-even” cost</td>
<td>575</td>
<td>652</td>
<td>678</td>
<td>630</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+13%</td>
<td>+18%</td>
<td>+10%</td>
</tr>
<tr>
<td>Cost of avoidance USD/t CO₂</td>
<td>74</td>
<td>81</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>% Avoided</td>
<td>50</td>
<td>60</td>
<td>47</td>
<td></td>
</tr>
</tbody>
</table>
Avoidance Cost

Avoidance cost
USD/t CO₂

Avoidance rate %

Sensitivity shown to +/- 20 coking coal, NG & Capex
Sensitivity to coking coal price

An increase of $92/t coke for every 50% increase of the coking coal price

OBF/MDEA (Case 3)
CO₂ Avoidance Cost = ~$56.4/t

Steel Mill with Post-Combustion Capture (Case 2A - EOP-L1)
Steel Mill with OBF/MDEA CO₂ Capture (Case 3)
Improved power options for OBF

- **Reference Steel Mill without CO₂ Capture**: $575.23
- **Steel Mill with OBF and MDEA CO₂ Capture (OBF Base Case)**: $630.22 \(+10\%\)
- **CHP 75MWe & twin turbine NGCC**: $626.53 \(+9\%\)
- **CHP 135MWe & single turbine NGCC**: $622.85 \(+8\%\)

Break Even Price of HRC (Ex-Works)
Improved power cases – costs

REFERENCE Steel Mill vs. Steel Mill w/ OBF & MDEA CO2 Capture

- OBF Base Case
- Improved Steam & Power (Case 3A)
- Improved Steam & Power (Case 3B)
Conclusions (1)

- Using the defined assumptions for this study:
  - End-of-pipe capture can achieve 50-60% CO\textsubscript{2} avoidance at a cost of about 74-81 USD/t CO\textsubscript{2}
  - Using OBF-MDEA process appears to be favourable than end-of-pipe capture cases, with costs of about 56 USD/t CO\textsubscript{2} avoided
  - Break-even cost of HRC increases by about 10%, best case is OBF

- Energy system optimization can improve economics

- Further work are needed to evaluate other CO\textsubscript{2} capture systems

- Cost and Technical Models have been developed and such that this can be used as a template for comparison on a like for like basis.
Conclusions (2) – Process integration!

System selection
- Steam intensive: e.g. MEA/MDEA chemical solvents
- Electricity intensive: e.g. VPSA, PSA, physical solvents

Energy system modification
- Low grade heat recovery?
- CHP plant?
- Electricity price & grid emissions?
- Energy sources – NG, nuclear, renewables, coal?

Optimization

CO₂ capture & compression

Steam  Electricity

At site production  At site and imported
Thank you for your attention

IRON AND STEEL CCS STUDY (TECHNO-ECONOMICS INTEGRATED STEEL MILL)

Report: 2013/04
July 2013