Challenges to the Deployment of CCS in the Energy Intensive Industries
(Part 1: Iron and Steel Sector)

Stanley Santos
IEA Greenhouse Gas R&D Programme
Cheltenham, UK
CHINESE STEEL INDUSTRY DEPLOYMENT OF CCS…
WHAT ARE THE CHALLENGES???
Regional Ironmaking Capacity in China

Except for Tibet and Hainan Island, all 31 provinces and administrative regions have ironmaking facilities.
World Crude Steel Production
(Data and Figure from World Steel)

• **Total Crude Steel Production has reached 1.49 Billion Tonnes of crude steel in 2011.**
  • As compared to 2001 crude steel production has increased by ~80% from 851 million tonnes

• **Major Steel Producing Regions**
  • China (683.3 million tonnes)
  • EU27 (177.4 million tonnes)
  • NAFTA (118.9 million tonnes)
  • CIS (112.4 million tonnes)
  • Japan (107.6 million tonnes)
  • India (72.2 million tonnes)
# Top 10 Steel Producers in the World
(Data from World Steel Association)

<table>
<thead>
<tr>
<th>Top 10 Producers</th>
<th>2001</th>
<th>2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Steel Production (in tonnes)</td>
<td>851,073,000</td>
<td>1,490,060,000</td>
</tr>
<tr>
<td><strong>Top 10 Producers</strong> (in million tonnes)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arcelor (now w/ AM)</td>
<td>43.1</td>
<td>ArcelorMittal (AM)</td>
</tr>
<tr>
<td>POSCO</td>
<td>27.8</td>
<td>Hebei Group</td>
</tr>
<tr>
<td>Nippon Steel</td>
<td>26.2</td>
<td>Baosteel Group</td>
</tr>
<tr>
<td>Ispat Int’l (now w/ AM)</td>
<td>19.2</td>
<td>POSCO</td>
</tr>
<tr>
<td>Shanghai Baosteel</td>
<td>19.1</td>
<td>Wuhan Group</td>
</tr>
<tr>
<td>Corus (now w/ Tata)</td>
<td>18.1</td>
<td>Nippon Steel</td>
</tr>
<tr>
<td>ThyssenKrupp</td>
<td>16.2</td>
<td>Shagang Group</td>
</tr>
<tr>
<td>Riva</td>
<td>15.0</td>
<td>Shougang Group</td>
</tr>
<tr>
<td>NKK (now w/ JFE)</td>
<td>14.8</td>
<td>JFE</td>
</tr>
<tr>
<td>Kawasaki (now w/ JFE)</td>
<td>13.3</td>
<td>Ansteel Group</td>
</tr>
</tbody>
</table>
CHALLENGES OF DEPLOYING CCS IN AN INTEGRATED STEEL MILL
An integrated steel mill is composed by numerous facilities. From iron ore to steel products.
Baosteel: Ironmaking Facilities

- 1 raw materials yard with an annual handling capacity of 0.14 billion tons of materials.
- 3 sinter machines with a 495 m² grate area each. Annual sinter production is 17.7 million tons.
- 12 coke batteries with 50 ovens each. Annual coke production is 5.35 million tons.
- 4 BF s with an inner volume 4,000 – 5,000 m³. Annual hot metal production is 15 million tons.
- 2 Corex-3000. Annual hot metal production for No. 1 Corex is 1.1 million tons.
First Challenge...

• There are no steel mill in this world which are alike...
  • Steel are produced with different processes
  • Steel are produced with different type of finished or semi-finished products
  • Steel are produced with different grades
  • …
ThyssenKrupp Steel Europe – Main CO₂-Emitters (schematically)
up to 20 mio t CO₂ p.a.
2nd and 3rd Challenges...

• There are no steel mill which are alike...
• Emissions from the Integrated Steel Mills comes from multiple sources.
• The source of CO$_2$ may not be the emitter of the CO$_2$.
  • Strongly dependent on how you define Boundary Limit
  • In addition to the direct use of fossil fuels, the emissions is also strongly dependent on the management of the use of By-Product Gases
4th Challenge...

BF Technology is already near the Theoretical Limit of Efficiency

Source: 10th CO₂ monitoring report of the steel industry in Germany

Graph shows consumption of reducing agents in kg/t HM from 1950 to 2010:
- Coke (dry)
- Oil + others

From 1991 on including new countries

(Source: VDEh Blast Furnace Committee)
Baosteel: Ironmaking Facilities

- 1 raw materials yard with an annual handling capacity of 0.14 billion tons of materials.
- 3 sinter machines with a 495 m² grate area each. Annual sinter production is 17.7 million tons.
- 12 coke batteries with 50 ovens each. Annual coke production is 5.35 million tons.
- 4 BFIs with an inner volume 4,000 – 5,000 m³. Annual hot metal production is 15 million tons.
- 2 Corex-3000. Annual hot metal production for No. 1 Corex is 1.1 million tons.

<table>
<thead>
<tr>
<th>Year</th>
<th>Productivity t/d.m³</th>
<th>PCI kg/tHM</th>
<th>Coke rate kg/tHM</th>
<th>Fuel rate kg/tHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>2.121</td>
<td>140.2</td>
<td>348.7</td>
<td>498.3</td>
</tr>
<tr>
<td>1999</td>
<td>2.263</td>
<td>237.9</td>
<td>265.1</td>
<td>503.0</td>
</tr>
<tr>
<td>2000</td>
<td>2.290</td>
<td>228.3</td>
<td>269.0</td>
<td>497.3</td>
</tr>
<tr>
<td>2001</td>
<td>2.281</td>
<td>234.1</td>
<td>262.8</td>
<td>496.8</td>
</tr>
<tr>
<td>2002</td>
<td>2.293</td>
<td>233.9</td>
<td>262.2</td>
<td>496.1</td>
</tr>
<tr>
<td>2003</td>
<td>2.221</td>
<td>209.3</td>
<td>286.1</td>
<td>495.4</td>
</tr>
<tr>
<td>2004</td>
<td>2.237</td>
<td>211.7</td>
<td>287.0</td>
<td>498.6</td>
</tr>
<tr>
<td>2005</td>
<td>2.181</td>
<td>202.5</td>
<td>293.6</td>
<td>498.3</td>
</tr>
<tr>
<td>2006</td>
<td>2.213</td>
<td>204.1</td>
<td>288.5</td>
<td>492.5</td>
</tr>
</tbody>
</table>
### 22 Sites with > 2 MT CO2 Emissions (2008)
(Data from C. Beauman – EBRD)

<table>
<thead>
<tr>
<th>Site Name</th>
<th>CO2 Emissions (m t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AM Bremen</td>
<td>2</td>
</tr>
<tr>
<td>SSAB Oxelosund</td>
<td>2.3</td>
</tr>
<tr>
<td>Lucchini Piombino</td>
<td>3.2</td>
</tr>
<tr>
<td>AM Sollac Lorraine</td>
<td>4.15</td>
</tr>
<tr>
<td>Salzgitter Glocke</td>
<td>4.2</td>
</tr>
<tr>
<td>Rauturuuki</td>
<td>4.4</td>
</tr>
<tr>
<td>AM Gent</td>
<td>4.5</td>
</tr>
<tr>
<td>VoestAlpine Linz (inc. coke ovens)</td>
<td>4.6</td>
</tr>
<tr>
<td>AM Espana</td>
<td>5.4</td>
</tr>
<tr>
<td>Dillingen</td>
<td>5.5</td>
</tr>
<tr>
<td>Teeside (now SSI)</td>
<td>6.2</td>
</tr>
<tr>
<td>AM Ostrava</td>
<td>6.4</td>
</tr>
<tr>
<td>Tata Ijmuiden</td>
<td>6.4</td>
</tr>
<tr>
<td>AM Fos</td>
<td>6.45</td>
</tr>
<tr>
<td>AM Poland (inc. coke ovens)</td>
<td>6.8</td>
</tr>
<tr>
<td>Tata Scunthorpe</td>
<td>6.9</td>
</tr>
<tr>
<td>Tata Port Talbot</td>
<td>6.9</td>
</tr>
<tr>
<td>AM Galati</td>
<td>7.6</td>
</tr>
<tr>
<td>USSteel Kosice</td>
<td>8.96</td>
</tr>
<tr>
<td>Riva Taranto</td>
<td>10.7</td>
</tr>
<tr>
<td>AM Dunquerque</td>
<td>11.3</td>
</tr>
<tr>
<td>TKS Duisberg/HKM Duisenberg</td>
<td>13.5</td>
</tr>
</tbody>
</table>

**5th Challenge...**

*Amount of CO₂ captured per site could be far greater than what we get from a single site of coal fired power plant.*
On February 21, 2012, Shougang Jintang Steel achieved a record for daily hot metal production (total 26,900 metric tons). ~9.9 MTPY Hot Metal

**Largest dry-dedusting equipment in the world**

**Pioneer in Top Fired Hot Stoves reaching 1315°C**

---

**Design Features of 2 x 5,500 m³ BFs**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Factor</th>
<th>Parameter</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective inner volume</td>
<td>5,500 m³</td>
<td>Blast temperature</td>
<td>1,300°C</td>
</tr>
<tr>
<td>Productivity</td>
<td>2 t/m³/d</td>
<td>Number of tuyeres</td>
<td>42</td>
</tr>
<tr>
<td>Annual production capacity</td>
<td>8.98MM t</td>
<td>Top pressure</td>
<td>0.28 MPa</td>
</tr>
<tr>
<td>Coke rate</td>
<td>200 kg/t</td>
<td>Oxygen enrichment ratio</td>
<td>3.5%</td>
</tr>
<tr>
<td>Coal injection rate</td>
<td>200 kg/t</td>
<td>Overall smelting rate</td>
<td>1,035 t/m³/d</td>
</tr>
<tr>
<td>Fuel rate</td>
<td>490 kg/t</td>
<td>Clean gas dust concentration</td>
<td>5 mg/m³</td>
</tr>
<tr>
<td>Sintered and/or pelletized charge in burden</td>
<td>90%</td>
<td>TRT power generation</td>
<td>45 kWh/t</td>
</tr>
<tr>
<td>Overall Fe content of the charge</td>
<td>61%</td>
<td>Ironmaking process energy consumption</td>
<td>404 kgce/t</td>
</tr>
<tr>
<td>Slag ratio</td>
<td>250 kg/t</td>
<td>One generation campaign life</td>
<td>25 years</td>
</tr>
<tr>
<td>Number of tapholes</td>
<td>4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**Shagang: Record Production with the World’s Largest (5,800 m³) BF...and Still Growing**

<table>
<thead>
<tr>
<th>Design Features</th>
<th>Design</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner volume, m³</td>
<td>5,800</td>
<td></td>
</tr>
<tr>
<td>Daily production, thm/d</td>
<td>12,876</td>
<td>14,500</td>
</tr>
<tr>
<td>Productivity, thm/m³/d</td>
<td>2.22</td>
<td>2.50</td>
</tr>
<tr>
<td>Wind, Nm³/min</td>
<td>8,300</td>
<td>9,500</td>
</tr>
<tr>
<td>Blower discharge P, KPa</td>
<td>520</td>
<td>550</td>
</tr>
<tr>
<td>Top pressure, KPa</td>
<td>250-280</td>
<td>300</td>
</tr>
<tr>
<td>Hot blast temperature, C</td>
<td>1,250</td>
<td>1310</td>
</tr>
<tr>
<td>Coke rate, kg/thm</td>
<td>&lt; 290</td>
<td></td>
</tr>
<tr>
<td>PCI, kg/thm</td>
<td>&gt; 200</td>
<td>250</td>
</tr>
<tr>
<td>Slag rate, kg/thm</td>
<td>&lt; 300</td>
<td></td>
</tr>
<tr>
<td>Fe% in ores</td>
<td>&gt; 59</td>
<td></td>
</tr>
<tr>
<td>Metallic burdens</td>
<td>77%Sinter + 18%PE + 5%Ore</td>
<td></td>
</tr>
<tr>
<td>Campaign life, years</td>
<td>&gt; 20</td>
<td></td>
</tr>
<tr>
<td>Stove lifespan, years</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

In September 2011, their 5,800 m³ blast furnace achieved a daily record for hot metal production of 14,500 metric tons.

Company target is 15,000 tons of hot metal per day.
Industry Application of CCS (to date)

- **Sleipner**: 1 Mt/y CO₂
- **Weyburn**: 2.5 Mt/y CO₂
- **In-Salah**: 1.2 Mt/y CO₂
- **Snohvit**: 0.7 Mt/y CO₂
- **Gorgon**: 3 Mt/y CO₂

- **1996**
- **2000**
- **2004**
- **2008**
- **2012**
- **2014**
- **2016**
- **2018**

- **350km overland pipeline**
- **160km sub sea pipeline**

**WE HAVE NOT DONE ENOUGH THAT IS REQUIRED BY THE STEEL INDUSTRY TO DEPLOY CCS**
Essential to CCS Deployment

• Accounting of CO₂ Emissions that could be comparable is an **Essential Activity** for Deployment of CO₂ Capture Technology in the Iron and Steel Sector.

• Accounting of CO₂ Emissions should be based on a globally consistent methodology that will allow production normalised CO₂ emission comparable between regions that are not possible today.

• This should result to a better benchmarking – therefore providing a meaningful number for CO₂ Avoidance Cost.
UNDERSTANDING THE COST OF INCORPORATING CO$_2$ CAPTURE IN AN INTEGRATED STEEL MILL
Acknowledgement

- **PROJECT PARTNERS**
  - Swedish Energy Agency
  - swerea MEFOS
  - SSAB
  - LKAB
  - ieaghhg

- **PROJECT DELIVERY**
  - swerea MEFOS
  - TATA STEEL
  - SINTEF

Total value of the Project: ~4.4 million SKr
IEA GHG Contribution: ~1.2 million SKr
Objectives of the Study

• To specify a “REFERENCE” steel mill typical to Western European configuration and evaluate the techno-economic performance of the integrated steel mill with and without CO$_2$ capture.

• To determine the techno-economic performance, CO$_2$ emissions and avoidance cost of the following cases:
  • An integrated steel mill typical to Western Europe as the base case.
  • An end of pipe CO$_2$ capture using conventional MEA at two different levels of CO$_2$ capture rate
  • An Oxygen Blast Furnace (OBF) and using MDEA for CO$_2$ capture.
Cost of Steel Production - Breakdown

Break Even Price
- Capital Cost: $135
- Fuel & Reductant: $118
- Iron Ore (Fines, Lumps & Pellets): $120
- Purchased Scrap & FerroAlloys: $53
- Fluxes: $11
- Other Raw Mat'l & Consummables: $12
- Labour: $70
- Maintenance & Other O&M: $55

Breakeven Price of HRC & Breakdown ($/t)

55% of the Cost is related to Raw Materials, Energy and Reductant
Oxy-Blast Furnace Operation

(Picture of OBF courtesy of Tata Steel)

- **Nitrogen**: 5 Nm³
- **Raw Materials**
  - Coke 253 kg
  - Sinter 1096 kg (70%)
  - Pellets 353 kg (22%)
  - Lump 125 kg (8%)
  - Limestone 6 kg
  - Quartzite 3 kg
- **OBF Screen**
  - Undersize 21 kg

**OBF Top Gas**

- **OBF Top Gas**
  - 1385 Nm³

**CO₂ Capture & Compression Plant**

- **Carbon Dioxide**
  - 867 kg

**OBF Process Gas**

- **OBF Process Gas**
  - 938 Nm³

**Top Gas Cleaning**

- **BF Dust**
  - 15 kg
- **BF Sludge**
  - 4 kg
- **Steam**
  - 2.0 GJ

**OBF Process Gas Fired Heaters**

- **Air**
  - 332 Nm³
- **Natural Gas**
  - 18 Nm³
- **Flue Gas**
  - 352 Nm³
- **Oxygen**
  - 253 Nm³
- **PCI Coal**
  - 152 kg
- **Nitrogen**
  - 5 Nm³
- **Nitrogen**
  - 5 Nm³
- **BF Dust**
  - 15 kg
- **BF Sludge**
  - 4 kg
- **Hot Metal**
  - 1000 kg
  - 1470oC
- **BM Si**: 0.5%
- **BM C**: 4.7%
- **DRR**: 11%
- **FT**: 2140oC
- **TGT**: 170oC

**OBF-PG to Steel Works**

- **OBF-PG to Steel Works**
  - 171 Nm³
Impact of the OBF/MDEA CO₂ Capture Plant to the Breakeven Cost of HRC Production
(Very Specific to this Study & Cost Does Not include Transport & Storage)

**Breakevan Cost of HRC Production for OBF @ $630/t**
(An Increase of $55/t as compared to the REFERENCE Plant)

- **Capital Cost** increased by 18.8%
- **Fuel and Reductant Cost** increased by 17.3%
  - Coking Coal Cost – decreased by ~24%
  - Natural Gas Cost – increased by ~495%
- **Iron Burden Cost** increased by 1.0%
  - Iron Ore (Fines, Lumps and Pellets), Purchased Scrap & Ferroalloys
- **Fluxes Cost** decreased by 9.4%
  - Significant reduction of limestone and quartzite consumption
- **Other Consumable Cost** increased by 15.7%
  - Increased in cost of raw water consumption
  - Additional cost due to Chemicals & Consumables used by SGP.
  - Additional cost due to MDEA/Pz Solvent Make Up
- **Labour Cost** increased by 1.4%
- **Maintenance and Other OPEX** increased by 10.4%
Summary of Results
(Sensitivity to Coke Price)

+ $92/t Coke

OBF Base Case
CO₂ Avoidance Cost = ~$56.4/t

It should be noted that Steel Mill used a significant variety of coking coal depending on market price (low to high quality coking coal)

COKE is a tradable commodity
OVERVIEW OF SOME OF THE MAJOR CCS R&D PROJECTS WORLDWIDE
### The 4 process routes

<table>
<thead>
<tr>
<th>Coal &amp; sustainable biomass</th>
<th>Natural gas</th>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revamped BF</td>
<td>Greenfield</td>
<td>Revamped DR</td>
</tr>
<tr>
<td>ULCOS-BF</td>
<td>Hilsarna</td>
<td>ULCORED</td>
</tr>
<tr>
<td>Pilot tests (1.5 t/h)</td>
<td>Pilot plant (8 t/h) start-up 2010</td>
<td>Pilot plant (1 t/h) to be erected in 2013?</td>
</tr>
</tbody>
</table>

- **ULCOS**
  - Pilot tests (1.5 t/h) Demonstration under way
  - Laboratory

- **Hilsarna**
  - Pilot plant (8 t/h) start-up 2010

- **ULCORED**
  - Pilot plant (1 t/h) to be erected in 2013?

- **ULCOWIN**
  - ULCOLYSIS

**Note:** CCS refers to Carbon Capture and Storage.
The Ulcos Blast Furnace Concepts

Coke
Top gas
(CO, CO2, H2, N2)
Gas cleaning
CO2 scrubber
Gas net
(N2 purge)
CO2 400 Nm3/t

CO, H2, N2
Gas heater
Re-injection

Gas net
(N2 purge)

Oxygen
PCI

V4
900 °C
1250 °C

V3
1250 °C
X

V1
25 °C
900 °C

Expected C-savings
25 %
24 %
21 %

Challenges & Opportunities of CCS in the Iron & Steel Industry, IEA-GHG, Düsseldorf, 8-9 November 2011
(1) Technologies to reduce CO$_2$ emissions from blast furnace

- Iron ore
- Coking plant
- Coke production technology for BF hydrogen reduction
- Coke substitution reducing agent production technology
- Reaction control technology for BF hydrogen reduction
- High strength & high reactivity coke
- CO$_2$ capture technology

(2) Technologies for CO$_2$ capture

- Chemical absorption
- Physical adsorption

- CO$_2$ storage technology

- COG reformer
- Kalina cycle
- Kalina cycle Power generation
- Hot air
- Cold air
- Steam
- Electricity
- Hot metal
- BOF

COURSE50 / CO$_2$ Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50
Development of the chemical absorption process

Test Equipment: Process Evaluation Plant (30t/D)

- Off gas
- CO₂
- Absorber
- Regenerator
- Rebolier

Nippon Steel Kimitsu Works No. 4BF

Bench Plant (1t/D)

- Absorber
- Regenerator
Ideas/Projects for CO₂ Reduction

- CO₂ Capture from BFG stream using aqueous ammonia
- Waste heat recovery from molten slag and hot sinter
- CO₂ utilization

Research Activities of CO₂ Project in RIST

(1) CO₂ Capture from BFG stream using aqueous ammonia
(2) Waste heat recovery from molten slag and hot sinter
(3) CO₂ utilization
2nd Stage pilot plant

Operation of 2nd stage pilot plant (May. 2011~)

- Development of CO₂ capture process for commercialization using aqueous ammonia in iron & steelmaking Ind.
- Utilizing the waste heat at low and mid-temperature waste heat as regeneration energy
- Ultimate goal: CO₂ removal > 90%, CO₂ purity > 95%, energy requirement < 2.0 GJ/ton-CO₂

Dimensions:
- Absorber: D 1.4m, H 27m
- Stripper: D 0.9m, H 20.6m
- Concentrator: D 0.5m, H 11.7m

Capacities:
- 1000 Nm³-BFG/hr as 0.5 MW (CO₂ conc: 20~25%)
Concluding Remarks…

• **CCS is an important technology for the steel industry to achieve deep CO₂ reduction.**

• **We have recognised the different challenges to CCS deployment in the steel industry.**

• **Demonstration is required to validate and gain the confidence in CCS for iron and steel production.**
  * It would take time to fully demonstrate its technical viability.

• **Addressing storage requirement is an important aspect in the deployment of CCS in steel industry**

• **We are only starting to understand the economics of CCS deployment in the steel industry…**
  * Study done by IEAGHG – providing detailed information on the techno-economics of incorporating CO₂ capture in an integrated steel mill is just touching the surface.
Challenges and Important Considerations in the Deployment of CCS in Chinese Steel Industry

- **Chinese integrated steel mills are one of the most efficient globally.**
- **Upcoming consolidation of the industry should be expected…**
  - More M&A of state enterprise.
  - Elimination of inefficient and small steel mills
- **Relocation to coastal region has started…**
  - This should represent 40% of steel production in China by 2015.
  - Cost reduction in logistics and redistribution of environmental burdens are the main drivers…
- **What are the targets for CO₂ emissions reduction…**
  - Promoting various efficiency improvement measures – Is a Definite Yes…
  - How about CCS(???)
Cash-costs slab, BOF-route, 2010/11 (% costs / t)
Data from TKS Presentation at 1st IEAGHG Iron and Steel CCS Workshop

Calculation:
1.40 US-Dollar is 1.00 Euro
1) Western Europe
2) Exporting Producer

<table>
<thead>
<tr>
<th>Region</th>
<th>Costs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WE</td>
<td>100</td>
</tr>
<tr>
<td>RUS</td>
<td>79</td>
</tr>
<tr>
<td>Japan</td>
<td>99</td>
</tr>
<tr>
<td>China</td>
<td>87</td>
</tr>
<tr>
<td>India</td>
<td>75</td>
</tr>
<tr>
<td>LAM</td>
<td>83</td>
</tr>
<tr>
<td>NAM</td>
<td>96</td>
</tr>
</tbody>
</table>

Profit Margin of All State Enterprise
Data from Chinese Iron and Steel Association

State Enterprise Profit Margin (%)
Year 2011

TO DEPLOY CCS WOULD REQUIRE ADDRESSING MARKET COMPETITIVENESS
China has an overcapacity of nearly 200 million tonnes in 2012.
Acknowledgement