CCUS in Industry
Review of the Current State of Art
(Case Studies for H₂ Production and Steel Industry)

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Cheltenham, UK

Industry CCS Scoping Workshop
Birmingham, UK
8th June 2015
2013 CCS Roadmap: Key Findings

- CCS is a **critical component** in a portfolio of low-carbon energy technologies, contributing 14% of the cumulative emissions reductions between 2015 and 2050 compared with business as usual.

- The individual component technologies are generally well understood. **The largest challenge is the integration** of component technologies into large-scale demonstration projects.

- Incentive frameworks are urgently needed to deliver upwards of **30 operating CCS projects by 2020**.

- **CCS is not only about electricity generation**: 45% of captured CO₂ comes from industrial applications between 2015 and 2050.

- The largest deployment of CCS will need to occur in **non-OECD countries, 70% by 2050**. China alone accounts for 1/3 of the global total of captured CO₂ between 2015 and 2050.

- The urgency of CCS deployment is only increasing. **This decade is critical** in developing favourable conditions for long-term CCS deployment.
Rationale for CCS:
Only large-scale mitigation option for many industries

Updated from Tracking Clean energy Progress report 2013, industry-CCS annex (IEA)
HYDROGEN PRODUCTION INDUSTRY
SMR without CO₂ Capture
(Data from Amec FW)

Flue Gas (atm.)
CO₂ 19-20%

Feedstock
Steam

Steam Reforming

Raw Syngas (~23 Bar)
CO₂ 7-10%
CO 12-19%
CH₄ 2-6%

Shifted Syngas (~22 Bar)
CO₂ 15-16%
CO 4-5%
CH₄ 3-4%

Flue Gas (atm.)
CO₂ 19-20%

Shift

PSA (H₂ Purification)

H₂ (99.9+%

PSA Tail Gas (~1.3 Bar)
CO₂ 45-50%
CO 14-15%
CH₄ 8-10%

Steam Reforming

Shift

PSA (H₂ Purification)

H₂ (99.9+%

PSA Tail Gas (~1.3 Bar)
CO₂ 45-50%
CO 14-15%
CH₄ 8-10%
SMR with CO₂ Capture
(Data from Amec FW)

By firing H₂ fuel instead of NG/light HC, CO₂ Capture of ~90% could be achievable for options #1 and #2.
CO2 Capture from SMR

• **Option 1:**
  - Chemical Absorption:
    e.g. Amine, Benfield, et al
  - PSA / VPSA

• **Option 2:**
  - Chemical Absorption,
  - PSA/VPSA
  - Low Temperature Capture
    e.g. CryoCAP, CO2LDsep

• **Option 3:**
  - Chemical Absorption

CO2 Capture Unit at Air Products’ Wilton Plant
Large Scale Demo and Pilot CCUS Projects from SMR Based H₂ Production

• **Large scale demo projects**
  - AP Port Arthur Project (USA)
    - Operational - ~1 million tpy CO₂ captured for EOR
  - Shell Quest Project (Canada)
    - Under construction - ~ 1 million tpy CO₂ captured and stored (on-shore) in saline aquifer

• **Large scale pilot projects**
  - AL Port Jerome Project (France)
    - Under commissioning - ~100k tpy CO₂ captured for sale as food grade CO₂.
  - Japan CCS Tomakomai Project (Japan)
    - Under construction - ~200k tpy CO₂ captured and stored (off-shore) in saline aquifer
Port Arthur Project - CO2 Capture Plant
Simplified Block Flow Diagram
(Courtesy of Air Products)
Port Jerome Project - CO2 Capture Plant

Simplified Block Flow Diagram

(Courtesy of Air Liquide)
IRON AND STEEL INDUSTRY
## Overview of Steel Production

(Picture from VDEH)

<table>
<thead>
<tr>
<th>Virgin raw materials</th>
<th>Coke</th>
<th>BF - BOF - CC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coke</td>
<td>Corex/Finex - BOF - CC</td>
</tr>
<tr>
<td></td>
<td>Scrap</td>
<td>DR - EAF - CC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scrap</th>
<th>Scrap</th>
<th>EAF - CC</th>
</tr>
</thead>
</table>

Diagram shows the processes involved in steel production, with different stages and materials used.
OVERVIEW OF STEEL PRODUCTION VIA BF/BOF ROUTE

NOTE:

• Presentation is derived from the results of IEAGHG Study (Report No. 2013-04)
Integrated Steelmaking Process (BF/BOF)

- **Raw Materials Preparation Plants**
  - Coke Production
  - Ore Agglomerating Plant (Sinter Production)
  - Lime Production

- **Ironmaking**
  - Blast Furnace
  - Hot Metal Desulphurisation

- **Steelmaking**
  - Basic Oxygen Steelmaking (Primary)
  - Secondary Steelmaking (Ladle Metallurgy)

- **Casting**
  - Continuous Casting

- **Finishing Mills**
  - Hot Rolling Mills (Reheating & Rolling)
Point Source Emissions
(Results of IEAGHG Study – An Example)

CO₂ Emissions are released at various stacks within the integrated steel mill.

<table>
<thead>
<tr>
<th>UNIT</th>
<th>Source of CO₂ Emissions</th>
<th>Emissions (kg t HRC)</th>
<th>Annual Emission (t/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Coke oven flue gas</td>
<td>191.37</td>
<td>765,485</td>
</tr>
<tr>
<td>100</td>
<td>Coke oven gas flare</td>
<td>3.30</td>
<td>13,196</td>
</tr>
<tr>
<td>200</td>
<td>Sinter plant flue gas (CO₂ + CO)</td>
<td>289.46</td>
<td>1,157,825</td>
</tr>
<tr>
<td>300</td>
<td>Hot Stove flue gas</td>
<td>415.19</td>
<td>1,680,769</td>
</tr>
<tr>
<td>400/1300</td>
<td>PCI/Coal drying, torpedo car and ladle heating (HM Desulphurisation) diffue emissions</td>
<td>7.76</td>
<td>31,042</td>
</tr>
<tr>
<td>300</td>
<td>Blast Furnace Gas flare</td>
<td>19.73</td>
<td>78,931</td>
</tr>
<tr>
<td>500/600</td>
<td>Basic Oxygen Furnace gas flared and system losses, SM diffuse Emissions</td>
<td>51.02</td>
<td>204,089</td>
</tr>
<tr>
<td>700</td>
<td>Continuous Casting - diffuse emissions (from slab cutting)</td>
<td>0.90</td>
<td>3,188</td>
</tr>
<tr>
<td>800</td>
<td>Reheating Furnace flue gas</td>
<td>57.71</td>
<td>230,833</td>
</tr>
<tr>
<td>900</td>
<td>Hot Rolling Mills - diffuse emissions (from cutting and scarfing)</td>
<td>0.04</td>
<td>179</td>
</tr>
<tr>
<td>1000</td>
<td>Lime Plant flue gas</td>
<td>71.62</td>
<td>286,493</td>
</tr>
<tr>
<td>1200</td>
<td>Power Plant flue gas</td>
<td>982.13</td>
<td>3,928,513</td>
</tr>
<tr>
<td>1300</td>
<td>Ancillaries transport fuel emissions (trucks and rails)</td>
<td>4.00</td>
<td>16,000</td>
</tr>
</tbody>
</table>

Total Emissions | 2054.14 | 8,276,554
Direct CO₂ Emissions of an Integrated Steel Mill (REFERENCE)
Producing 4 MTPY Hot Rolled Coil
2090 kg CO₂/t HRC (2107 kg CO₂/thm)

Carbon Balance of Ironmaking Process
(Results of IEAGHG Study)

80-90% of the carbon that caused to the CO₂ emissions of the steel production.
# Composition of Off-Gases

*(Results of IEAGHG Study – An Example)*

<table>
<thead>
<tr>
<th>Wet Basis (%vol.)</th>
<th>Coke Oven Gas (COG)</th>
<th>Blast Furnace Gas (BFG)</th>
<th>Basic Oxygen Furnace Gas (BOFG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH&lt;sub&gt;4&lt;/sub&gt;</td>
<td>23.2</td>
<td>- NA -</td>
<td>- NA -</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;</td>
<td>60.1</td>
<td>3.6</td>
<td>2.6</td>
</tr>
<tr>
<td>CO</td>
<td>3.9</td>
<td>22.1</td>
<td>56.9</td>
</tr>
<tr>
<td>CO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>1.0</td>
<td>22.3</td>
<td>14.4</td>
</tr>
<tr>
<td>N&lt;sub&gt;2&lt;/sub&gt;</td>
<td>5.8</td>
<td>48.3</td>
<td>13.8</td>
</tr>
<tr>
<td>O&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.2</td>
<td>- NA -</td>
<td>- NA -</td>
</tr>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;O</td>
<td>3.2</td>
<td>3.2</td>
<td>12.2</td>
</tr>
<tr>
<td>Other HC</td>
<td>2.7</td>
<td>- NA -</td>
<td>- NA -</td>
</tr>
</tbody>
</table>

| LHV (MJ/Nm<sup>3</sup>) – wet basis | 17.5 | 3.2 | 7.5 |

<table>
<thead>
<tr>
<th>Users of the Off-Gases</th>
<th>Hot Stoves, Coke Ovens, Lime Kilns, Reheating Furnaces and others</th>
<th>Hot Stoves, Power Plant</th>
<th>Power Plant</th>
</tr>
</thead>
</table>
Direct CO₂ Emissions of an Integrated Steel Mill (with OBF & MDEA CO₂ Capture) Producing 4 MTPY Hot Rolled Coil 1115 kg CO₂/t HRC (1124 kg CO₂/thm)

Carbon Balance of Ironmaking Process
Results from IEAGHG Study – Case 3: OBF with MDEA/Pz CO₂ Capture

<table>
<thead>
<tr>
<th>Carbon Input</th>
<th>Carbon Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>(kg C/thm)</td>
<td>(kg C/thm)</td>
</tr>
<tr>
<td>Coke</td>
<td>227.7</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.7</td>
</tr>
<tr>
<td>PCI Coal</td>
<td>132.2</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>12.0</td>
</tr>
<tr>
<td>PG Heater Flue Gas</td>
<td>12.0</td>
</tr>
<tr>
<td>CO₂ Captured</td>
<td>236.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>372.7</strong></td>
</tr>
</tbody>
</table>

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

CO₂ Capture & Compression Plant

OBF Top Gas 1385 Nm³
Steam 2.0 GJ
 BF Dust 15 kg
BF Sludge 4 kg

OBF Process Gas 938 Nm³

OBF Process Gas Fired Heaters

Air 332 Nm³
Natural Gas 18 Nm³
563 Nm³ 900oC
205 Nm³ 410oC
352 Nm³

BF Slag 235 kg
Hot Metal 1000 kg 1470oC

OBF-PG to Steel Works 171 Nm³

Carbon Dioxide 867 kg

Oxygen 253 Nm³

Nitrogen 15 kg
5 Nm³

Lime Plant 6.41%
Power Plant 18.94%
Sinter Plant 25.13%
Coke Plant 11.22%
Reheating & HRM 5.18%
Slab Casting 0.07%

Steam Generation Plant 25.13%
Iron Making 4.58%
Steelmaking 4.58%
Slab Casting 0.07%
Reheating & HRM 5.18%
Sinter Plant 23.83%
Coke Plant 11.22%
### The 4 ulcos 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><strong>ULCOS-BF</strong></td>
<td><strong>HIsarna</strong></td>
<td><strong>ULCORED</strong></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>
<tr>
<td>Demonstration under way</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CCS** indicates the presence of Carbon Capture and Storage technology in the processes.
Blast Furnace (TGR BF)

**Raw Top Gas**
- CO: 46-49%
- CO2: 37-38%
- H2: 8 - 9%
- Balance: N2

**Recycled Top Gas**
- CO: 73-75%
- CO2: ~3%
- H2: 14-15%
- Balance: N2

**CO2 Removal evaluated by ULCOS consists of:**
- PSA, VPSA
- VPSA or PSA + Cryogenic Separation
- Chemical Absorption

**Concentration of CO2 depends on capture technology used**

**Re-injection**

**Expected C-savings**
- 25 %
- 24 %
- 21 %
COURSE50 Programme

1. Technologies to reduce CO₂ emissions from blast furnace
   - Iron ore pre-reduction technology
   - 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
   - Sensible heat recovery from slag (example)
   - Waste heat recovery boiler
   - Kalina cycle Power generation
   - Technology for utilization of unused waste heat

2. Technologies for CO₂ capture
   - Chemical absorption
   - Physical adsorption
   - CO₂ capture technology
   - CO₂ storage technology
   - Regeneration Tower
   - Reboiler
   - Absorption Tower
   - Steam
   - Electricity
   - Hot metal
   - BOF
COURSE50 Programme

(1) Technologies to reduce CO₂ emissions from blast furnace
- H₂ amplification
- Coke production technology for BF hydrogen reduction
- Coke substitution reducing agent production technology
- High strength & high reactivity coke

(2) Technologies for CO₂ capture
- Chemical absorption
- Physical adsorption

CAT-1 & CAT-10 at Nippon Steel Kimitsu Works
- 1 t/d CO₂ for solvent testing

CAT-30 30 t/d CO₂ for process improvement evaluation

ASCOA at JFE Steel Fukuyama Works
- ASCOA-3* (JFE Steel Fukuyama Area)
  *Advanced Separation System by Carbon Dioxide Adsorption
  Capacity: Stone-CTO Plant
  Plant Area: 21m x 25m

LKAB’s EBF Trial
- Schedule: 16th April ~ 11th May, 2012
- Ferrous Materials: Steel 70% + Pellet 30%
- Coke, F.C. from SSAB
  - Probing, Sampling
  - Operational Data, Analyzing
  - [Hot Top Gas Injection]
  - [Reformed COG Injection]

Sensible Heat Recovery from Slag
- Tiltling Equipment
- Slag Ladle
- Slag Heat Recovery Chamber
- Mist Spray Nozzle
- Cooling Roll
- Bucket Elevator
- Cyclone
- Blower
- Slag after Heat Recovery
- Slag Plates
- Hot Crusher

Start: March 2011
POSCO – RIST Programme
POSCO – RIST Programme

CO₂ Capture Using Aqueous Ammonia (II): Milestones

☐ R&D history
  • Lab-scale research (2006-2007)
  • 1st stage pilot plant research (2008-2010): 50 Nm³-BFG/hr (Dec. 2008)
  • 2nd stage pilot plant research (2010-2014): 1,000 Nm³-BFG/hr
    - One-site pilot tests are on-going (May 2011-), Purification/Liquefaction facilities integrated (Apr. 2012)

☐ 2nd Pilot Plant Spec.

<table>
<thead>
<tr>
<th>Item</th>
<th>Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Gas</td>
<td>BFG (Blast Furnace Gas, CO₂ ~ 22%)</td>
</tr>
<tr>
<td>Feed Gas Flow rate</td>
<td>1,000Nm³/hr</td>
</tr>
<tr>
<td>Absorber Sol</td>
<td>&lt;10% NH₃</td>
</tr>
<tr>
<td>Product CO₂</td>
<td>10 t-CO₂/Plant, 0.5MW power plant</td>
</tr>
<tr>
<td>Purity of product CO₂</td>
<td>&gt;95% (Gas)</td>
</tr>
<tr>
<td></td>
<td>&gt;99.8% (Liquid)</td>
</tr>
</tbody>
</table>

☐ Test Results
  • CO₂ recovery > 90%, L-CO₂ purity > 99.5%

☐ Further Plan
  • Long-term continuous operation
  • Additional pump around and higher NH₃ concentration in absorbent solution
  • Basic engineering design for commercial scale

CO₂ Capture Programme

CO₂ Conversion using COG Reforming (I) : Concept/Feature

☐ Background
  - Need for the conversion of capture CO₂ and the utilization in steel industry

☐ Steel-industry-specific CO₂ conversion and utilization

[Conceptual scheme for production and utilization of the reducing gas in the steel process]

- Mass production of the H₂ and/or CO rich gases by using COG reforming with steam and CO₂
  - Require highly coking-resistant catalyst for the COG reforming
  - Require optimization of reaction condition, heat integration, and scale-up by using reactor modeling

CO₂ Usage Programme
CO₂ as Raw Materials to Different Chemical Industries

Traditional Market (60%)
- Acetic Acid
- Formaldehyde
- Silicone
- Methyl Methacrylate

Emerging Market (40%)
- MTO (MTBE & Olefins)
- Marine Fuel
- DME
- Fuel Blending
- Biodiesel

MeOH to Ethylene or Propylene

Figures from P. Styring (CO2Chem), Methanex

CO₂ as a raw material
Climate gas to move cars

ThyssenKrupp is launching the first cross-industry initiative to utilize carbon dioxide. Its aim is to exploit steel mill gases as the starting material in the production of ethylene or propylene. The project is contributing not only to climate protection but also to the success of the economy.

Carbon Dioxide Transformed into Methanol

In February 2011, Bayer MaterialScience started a new pilot plant at Chempark Leverkusen, North Rhine-Westphalia state of Germany for producing plastics from carbon dioxide (CO₂). It will be used to develop polyurethanes from the waste gas released during power generation.

The Leverkusen pilot plant will test a new process technology on technical scale for producing raw material of polyurethane. The production will be on a kilogram scale. If the testing phase is successful, it will be extended to commercial production on an industrial scale in 2015.

Technology

The process technology is based on a zinc catalyst. The catalyst process was developed by MaterialScience. Bayer’s role is largely that of technical support. The process is now being tested with pilot plants around the world.

Bayer MaterialScience CO₂-to-Plastics Pilot Plant, Germany
Thank You, Any Questions?

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Website: • www.ieaghg.org
LinkedIn: • www.linkedin.com/groups/IEAGHG-4841998
Twitter: • https://twitter.com/IEAGHG
IEAGHG Activities on CCS for the Iron & Steel Industry

• **Reports**
  
  • 2013-04 – “Understanding the Economics of Deploying CO₂ Capture Technologies in an Integrated Steel Mill”
  
  • 2013-TR3 – “Overview of the Current State and Development CO₂ Capture Technologies in the Ironmaking Process”

• **Stakeholders Engagement**
  
  • 1ˢᵗ Workshop (Nov. 2011) 
    Dusseldorf, Germany 
    in collaboration with VDeH, Swerea MEFOS
  
  • 2ⁿᵈ Workshop (Nov. 2013) 
    Tokyo, Japan 
    in collaboration with IETS, World Steel, Swerea MEFOS

- Total Cost of the Study: ~ £ 440,000
- IEA GHG Contribution: ~ £ 120,000