Challenges to the Deployment of CCS in the Energy Intensive Industries
(Discussion on Iron and Steel Industry)

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INTRODUCTION

RATIONALE FOR CCS DEPLOYMENT IN ENERGY INTENSIVE INDUSTRY
Deployment of CCS in various industrial applications should provide significant contribution toward reduction of CO2 emission by 2050 (under the 2DS Scenario)
Five most energy intensive sectors are the steel, cement, chemicals & oil refineries, pulp and paper, aluminium accounts for 77% of the total energy use from industry.
Direct CO$_2$ Emissions from Industrial Sources (2007 data)

- Steel, Cement and Chemical Industries accounts for nearly 70% of the Direct CO$_2$ Emissions.

- These emissions are not only from combustion of fossil fuel related CO$_2$ emissions but also to include PROCESS RELATED CO$_2$ EMISSIONS.
Remarks on the ETP-2012 Findings

• It could be concluded from the IEA Energy Technology Perspective 2012 that CCS is an important part to the reduction of CO$_2$ from the industrial sector.
• Technology is not only the main barrier to the CCS deployment in the industrial sector.
• Market competitiveness and global nature of some of these industries is an important issue that should be addressed.
EU Strategic Energy Technology Roadmap for CCS (2011)
(Figure from SETIS Report)
Outline of Presentation

• *Iron and Steel Sector*
  • Background
  • Key Results of IEAGHG Techno-Economic Study
    o What we have learned…
  • ULCOS Programme (Europe)
    o Importance of Florange and Eisenhüttenstadt Project
  • Course 50 Programme (Japan)
  • Posco CCS Programme (South Korea)
  • Other CO₂ Capture Technology Options
BACKGROUND – IRON AND STEEL INDUSTRY
World Crude Steel Production
(Data and Figure from World Steel)

• **Total Steel Production has reached 1.52 Billion tonnes of crude steel.**
  • As compared to 2001 crude steel production has increased by ~80% from 851 million tonnes

• **Major Steel Producing Regions**
  • China (683.9 million tonnes)
  • EU27 (177.2 million tonnes)
  • NAFTA (117.5 million tonnes)
  • CIS (113.5 million tonnes)
  • Japan (107.6 million tonnes)
  • India (71.3 million tonnes)
World Crude Steel Production (Share of BOF vs. EAF Route)

- ~69% of the crude steel produced via BF/BOF Route
- Pig Iron Production ~ 1.1 Billion tonnes
- Scrap recycled
- DRI/HBI Production is ~74 million tonnes

Total World:
Output: 1514
Oxygen: 1062
Electric: 462

Source: World Steel
* A small percentage of steel is also produced using open hearth & other methods (particularly in FSU)
Historical Energy Consumption and CO₂ Emissions from Steel Industry (EU 27) (Data from ESTEP)
BF Technology is already near the Theoretical Limit of Efficiency

475 kg/t HM

source: VDEh, Germany.
UNDERSTANDING THE COST OF INCORPORATING CO₂ CAPTURE IN AN INTEGRATED STEEL MILL
## Acknowledgement

<table>
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<tr>
<th>PROJECT PARTNERS</th>
<th>PROJECT DELIVERY</th>
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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 CO₂ capture.

• To determine the techno-economic performance, CO₂ emissions and avoidance cost of the following cases:
  • An integrated steel mill typical to Western Europe as the base case.
  • An end of pipe CO₂ capture using conventional MEA at two different levels of CO₂ capture rate
  • An Oxygen Blast Furnace (OBF) and using MDEA for CO₂ capture.
STEEL MILL Battery Limit
(REFERENCE Integrated Steel Mill)

UNIT 100:
- COKE PRODUCTION

UNIT 200:
- SINTER PRODUCTION

UNIT 300:
- HOT METAL PRODUCTION

UNIT 400:
- HOT METAL DESULPHURISATION

UNIT 500:
- BASIC OXYGEN STEELMAKING

UNIT 600:
- SECONDARY STEELMAKING

UNIT 700:
- CONTINUOUS SLAB CASTING

UNIT 800:
- SLAB REHEATING

UNIT 900:
- HOT ROLLING MILL

UNIT 1000:
- LIME PRODUCTION

UNIT 1100:
- AIR SEPARATION UNIT (OXYGEN PRODUCTION)

UNIT 1200:
- POWER PLANT

UNIT 1300:
- ANCILLARY UNITS
STEEL MILL Battery Limit
(Steel Mill with OBF & MDEA CO₂ Capture)
Materials Input & Output

• **Major Raw Materials Input:**
  - Iron Burden (Fines, Lumps, Pellets)
  - Energy and Reductant
    - Coking Coal
    - PCI Coal
    - Natural Gas
  - Fluxes (Limestone, Quartzite, Olivine, CaC₂, Burnt Dolomite)
    Merchant Scrap (External)
  - Ferroalloys (FeMnC, FeSi-75, De-Ox Aluminium)

• **Major Intermediate Products**
  - Coke (Lump & Breeze)
  - Sinter
  - Hot Metal
  - Liquid Steel
  - Slab
  - Lime
  - **HP & LP Oxygen**
  - Electricity
  - **Steam**

• **Products and By-Products:**
  - Hot Rolled Coil (Standard Grade)
  - Coking Plant By-Products
    - Crude Tar, BTX and Sulphur
  - Steel Mill Slag
    - Granulated BF Slag (Sale)
    - De-S Slag (Landfill)
    - BOF Slag (Sale & Landfill)
    - SM Slag (Landfill)
  - BF Sludge and Dust (Landfill)
  - **MDEA Sludge (Landfill)**
  - Liquid Argon

• **Gas Network within Site**
  - Industrial Gases
    - HP & LP Oxygen, Nitrogen and Argon
  - Off-Gases
    - OBF Top Gas
    - OBF Process Gas (PG)
    - Coke Oven Gas (COG)
    - Basic Oxygen Furnace Gas (BOFG)
  - Steam (9 Bar, saturated)
  - **Carbon Dioxide**
Flow Sheet (Materials)  
Application of CO₂ Capture to an Integrated Steelworks  
Reference Steel Mill (Base Case)  

Production: 4,000,000 tonnes HRC/y  
(YEAR 06)
Integrated Steel Mill is typically well equipped and flexible with delivery of off-gases, steam and industrial gases to the different “Factory Sites”

CO₂ Pipeline could be equally as large in diameter as compared to the BFG Pipeline
CO₂ Emissions from Integrated Steel Mill
Annual Production: 4 Million Tonnes Hot Rolled Coil
(REFERENCE vs. OBF / MDEA)

REFERENCE Integrated Steel Mill
(2090 kg per tonne of Hot Rolled Coil)

Steel Mill with OBF & MDEA CO₂ Capture
(1115 kg per tonne of Hot Rolled Coil)

**OBF with MDEA CO₂ Capture:**
- **Total CO₂ Captured:** ~860 kg/t HRC
- **CO₂ Avoided:** 46.7%
Cost of Steel Production - Breakdown

- Break Even Price: $575.23
- 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

55% of the Cost is related to Raw Materials, Energy and Reductant.
Breakdown of the Breakeven Price of HRC
(Steel Mill with OBF & MDEA CO₂ Capture)
Impact of the OBF/MDEA CO$_2$ Capture Plant to the Breakeven Cost of HRC Production

(Very Specific to this Study)

- **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%
Evolution of Coking Coal Price
(Data provided by P. Baruya – IEA CCC)

Source: McCloskey (2011); ABARES (2011a).
Summary of Results
(Sensitivity to Coke Price)

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
Summary of Results

- **Steel Mill with OBF/MDEA CO\(_2\) Capture producing 4 MTPY standard Hot Rolled Coil was defined in detail in the study.**
  - Mass Balance
  - Gas Network
  - Electricity Network
  - CO\(_2\) emissions of each unit

- **Study was able to established a baseline cost for an Integrated Steel Mill equipped with OBF, Top Gas Recycle and MDEA/Pz CO\(_2\) capture technology.**
Note:

- Current study only illustrates one of the many options available for oxy-blast furnaces.

- This do not represents the choice made by the ULCOS Programme.
  - Florange Project
  - Eisenhüttenstadt Project
What We Have Learned from this Study

- Recognising the different limitations for this study allows us to identify where are the gaps in information are and what we need to evaluate for future studies.

- What are these limitations…
  - Availability of a reliable cost data
  - Limited budget for this study didn’t allow us to optimise certain aspects of the different process evaluated.
What We Have Learned from this Study...

• **Technical Aspects**...
  • Helped us understand the dynamics of the integrated steel mill – especially interaction of various processes with respect to CO$_2$ emissions.
  • Identified the uncertainties with respect to the operation of the oxy-blast furnace.
    - Need to verify and validate coke reduction potential of the coke reduction by the oxy-blast furnace.
    - This study presented a reduction of 24% of coke requirements for the Blast Furnace.
Metal Burden Composition
(EU15 Steelworks 1990 vs 2008)

Data courtesy of VDEH
22 Sites with > 2 MT CO2 Emissions (2008)
(Data from C. Beauman – EBRD)

- Amount of CO$_2$ capture per site could be greater than what we get from coal fired power plant.
What We Have Learned from this Study…

• **Stakeholders discussion**
  - 1st Workshop – November 2011
  - Review Meeting – April 2012
  - Planned 2nd Workshop – April/May 2013

• **ULCOS Data Comparison**
ULCOS PROGRAMME
The 4 process routes

<table>
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<tr>
<th>Coal &amp; sustainable biomass</th>
<th>Natural gas</th>
<th>Electricity</th>
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</thead>
<tbody>
<tr>
<td>Revamped BF</td>
<td>Greenfield</td>
<td>Revamped DR</td>
</tr>
<tr>
<td>ULCOS-BF</td>
<td>HIsarna</td>
<td>ULCORED</td>
</tr>
</tbody>
</table>

- Pilot tests (1.5 t/h) Demonstration under way
- Pilot plant (8 t/h) start-up 2010
- Pilot plant (1 t/h) to be erected in 2013?
- Laboratory

Challenges & Opportunities of CCS in the Iron & Steel Industry, IEA-GHG, Düsseldorf, 8-9 November 2011
1850 – 1990 HRG-trials at BF2 with recycling CO₂ free topgas Toulachermet (Russia)

Mid of 80’s Development of a NFBF by NKK (Japan)

1984 NFBF-concept of Lu (Canada)

Late 70’s Patent of Fink about a NFBF (Germany)

Mid 60’s CRM at Cockerill-Seraing (Belgium)

1920 Lance hot reducing gas injection
The Ulcos Blast Furnace Concepts

Coke

Top gas (CO, CO2, H2, N2)

Gas cleaning

Gas net (N2 purge)

Carbon dioxide (CO2) scrubber

CO2 400 Nm³/t

CO, H2, N2

Gas heater

Oxygen

PCI

Re-injection

V4 900 °C

V3 X

V1 900 °C

1250 °C

1250 °C

25 °C

Expected C-savings

25 %

24 %

21 %
Separation and Capture of CO₂ from OBF also has several other options
(Data from ULCOS Programme)

- **PSA, VPSA**
- **VPSA + Cryogenics**
- **Separation of non-CO₂ components**
- **Chemical Absorption**

### Table C-1: Comparison of CO₂ Capture Technologies for an Integrated Steel Mill (BF-BOF Route)

<table>
<thead>
<tr>
<th>ULCOS Project Evaluation Results [2, 4]</th>
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<tr>
<td>Recycled Top Gas (Process Gas)</td>
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<tr>
<td>CO₂ yield (%)</td>
</tr>
<tr>
<td>PSA 96.0</td>
</tr>
<tr>
<td>VPSA 60.1</td>
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<tr>
<td>PSA &amp; Cryo 97.4</td>
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<tr>
<td>PSA &amp; Cryo Distil + Compression 100.0</td>
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<tr>
<td>Process Gas Composition</td>
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<tr>
<td>CO₂ %</td>
</tr>
<tr>
<td>PSA 2.7</td>
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<tr>
<td>VPSA 3.0</td>
</tr>
<tr>
<td>PSA &amp; Cryo Flash + Compression 3.0</td>
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<tr>
<td>PSA &amp; Cryo Distil + Compression 2.9</td>
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<td>PSA &amp; Cryo Distil + Compression 2.7</td>
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<td>Process Gas Composition</td>
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<td>CO %</td>
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<td>PSA 71.4</td>
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<td>Process Gas Composition</td>
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<td>H₂ %</td>
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<td>PSA 12.4</td>
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<td>VPSA 12.0</td>
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<td>PSA &amp; Cryo Flash + Compression 12.6</td>
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<td>PSA &amp; Cryo Distil + Compression 12.1</td>
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<td>PSA &amp; Cryo Distil + Compression 12.4</td>
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<td>Process Gas Composition</td>
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<td>N₂ %</td>
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<td>PSA 13.5</td>
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<td>VPSA 15.7</td>
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<td>PSA &amp; Cryo Distil + Compression 15.4</td>
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<tr>
<td>Process Gas Composition</td>
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<td>H₂O %</td>
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<tr>
<td>PSA 0.0</td>
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<td>VPSA 0.0</td>
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<td>PSA &amp; Cryo Flash + Compression 0.0</td>
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<td>PSA &amp; Cryo Distil + Compression 2.1</td>
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<td>PSA &amp; Cryo Distil + Compression 0.0</td>
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<tr>
<td>Process Gas Composition</td>
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<tr>
<td>Captured CO₂ Rich Gas</td>
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<tr>
<td>CO₂ %</td>
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<tr>
<td>PSA 79.7</td>
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<td>VPSA 87.2</td>
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<td>PSA &amp; Cryo 96.3</td>
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<tr>
<td>Suitable for CO₂ Transport &amp; Storage?</td>
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<tr>
<td>No</td>
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<td>No</td>
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<td>Yes (?)</td>
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<td>Yes</td>
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<td>Electricity Consumption</td>
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<td>Capture Process kWh/t CO₂</td>
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<td>PSA 100</td>
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<td>VPSA 105</td>
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<td>CO₂ Compression (110 Bar) kWh/t CO₂</td>
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<td>PSA 100</td>
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<td>VPSA 105</td>
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<td>PSA &amp; Cryo 160</td>
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<td>LP Steam Consumption GJ/t CO₂</td>
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<td>PSA 0.0</td>
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<td>VPSA 0.0</td>
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<td>PSA &amp; Cryo 0.0</td>
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<td>PSA &amp; Cryo Distil + Compression 3.2</td>
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<td>Total Energy Consumption GJ/t CO₂</td>
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</table>
(1) Technologies to reduce CO₂ emissions from blast furnace

- Chemical absorption
- Physical adsorption

(2) Technologies for CO₂ capture

- CO₂ storage technology
- CO₂ capture technology
- Reaction control technology for BF hydrogen reduction
- Coke substitution reducing agent production technology
- Coke production technology for BF hydrogen reduction

Other project

- H₂ amplification
- Coke production technology for BF hydrogen reduction
- Iron ore pre-reduction technology

Other project

- High strength & high reactivity coke
- Coke substitution reducing agent production technology

COURSE50 / CO₂ Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50
Collaboration Scheme to Develop New Chemical Absorbents

Development of new chemical absorbents (NSC + RITE + Univ. of Tokyo)

- Quantum chemical calculations
  - Design new amine Compounds.
- Experiment
  - Synthesize new amines
  - Design absorbents
  - Evaluate the performance
- Industrial application
- Suggest new amine compounds
- Evaluation with test plants (NSEC)
- CAT1 (1t-CO₂/d)
  - Absorber
  - Stripper
  - Reboiler
- CAT30 (30t-CO₂/d)
Development of the chemical absorption process

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

Absorber → CO₂ → Regenerator

Off gas

Bench Plant (1t/D)

Absorber → Regenerator
Development of the chemical absorption process

Strategy for Cost Reduction

CO₂ Separation Cost (JP ¥/t-CO₂)

2004Fy

- Waste heat recovery
- Development of the chemical absorbent
- Optimization of the chemical absorption process
- Optimization of the entire system (with the improvement of steel-making process)

Goal

Heat Unit Consumption (GJ/t-CO₂)

P 45
SOUTH KOREAN PROGRAMME
AQUEOUS AMMONIA-BASED CO$_2$ CAPTURE
AT POSCO/RIST
1st stage pilot plant (1/2)

Process improvement

- Removal of condenser at the top of the concentrator
  - Improvement of heat efficiency in the stripper and concentrator
  - Prevent clogging of the pipe line

- Improvement of absorption efficiency
- Suppression of ammonia vaporization

Temperature Sensor

Side stream in the absorber
- Temperature decrement in the middle of the absorber
- Improvement of absorption efficiency
- Suppression of ammonia vaporization
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
- Utilizing the waste heats 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%)
Summary and Conclusions

**CO₂ Reductions Needs in Iron and Steel Industry**
- Iron and steel sector: Comprises large portion of CO₂ emissions
- Desperate needs for reduction CO₂ emissions

**Ammonia-based CO₂ Capture Technology: “low regeneration energy”**
- Viable solution as an alternative to the *state-of-the-art* MEA process

**RIST Technology**
- Steel Industry-specific CO₂ capture process
- Low concentration ammonia solution using waste heat in steel industry
- Pilot plant results (1,000 Nm³-BFG/hr): Removal efficiency ~ 90%, Purity > 95%
- Soft-sensor technique and statistical model for monitoring/controlling system

**Technology Road Map (CO₂ Capture Technology)**

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<td>Work-group</td>
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<td>POSTECH</td>
<td>PNU</td>
<td>POSCO</td>
<td>E&amp;C</td>
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- **Initiation**: Lab-scale Research
- **1st stage PP System**: construction and operation
- **Development of waste heat recovery system**
- **Construction/Operation of CO₂ capture 2nd stage pilot plant (10t/d)**
- **System integration/Utilization of CO₂**
- **Purification/Utilization of CO₂**
- **Process optimization/Long-term operation**
- **Commercialization**
FINEX Development

FINEX Process Flow Sheet: Jointly developed by VAI and research Institute of Industrial Science & Technology, Korea
CO₂ breakthrough programme

- Tackling key programmes for reducing emissions for the industry
- Provides forum for sharing BAT, BAP, mitigation techniques and breakthrough programme
- Work scope: focus on co-ordination of programmes
  - ULCOS - Top Gas Recycling, Hisarna, Ulcoreduction, Ulcowin, Ulcolysis
  - Course 50 Programme, Reduce emissions, Capture CO₂ from BF
  - POSCO – Finex emissions reduction, CCS, H2 steel making
  - Australian Programme – Biomass use, Heat recovery from Slag
  - CSC Taiwan – CO2 concentration and separation from flue gas and CCS
  - AISI – Hydrogen Flash Melting, Molten Oxide Electrolysis
  - CCS promotion – required technique to make sufficient reduction > 50%
Recommendations

• Evaluate other technology options of capturing $\text{CO}_2$ from BF/BOF Integrated Steel Production
  • Air Products - BF Plus Technology
  • Linde’s Co-Production of Methanol Option
  • Praxair Hydrogen Based BF
Recommendations

• *For future studies:* it was recognised from this study that other areas where potential for improvement could be achieved – *For Example:*

  • Improvement to the Air Separation Unit
    o Dual Purity O₂ Production could deliver between US$ 60 to 80 Million of CAPEX savings and at the same time with good potential to reduce electricity demand.

  • Evaluate other options for steam and electricity supply
    o CHP / COGEN Option could bring down CO₂ avoidance cost by 8 - 12% (as compared to results presented in this study).

  • Evaluate other improved solvents (i.e. AMP, etc...)
    o Leading to a reduction to steam demand
Recommendations (cont’d)

• **REPORTING CO₂ Avoidance Cost for a complex industrial processes is meaningless** – without establishing the assumptions used for the REFERENCE Plant without CO₂ Capture.
  • This is not a good indicator for these cases yet we are trapped in it...

• **RECOMMENDATION :-**
  • It is necessary to establish REFERENCE Industrial Plants with different degrees of complexities – which could be used for a good basis of comparison;

  • Worthwhile considerations – probably to do a similar task as what IEA CCC did for the G8 Gleneagles Project – i.e. - establishing a profile of the best performing power plants per region worldwide.