Understanding the Cost of Deploying CO_2 Capture in an Integrated Steel Mill

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Seminar on the Economics of CO_2

September 2013

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Presentation Outline

- IEA Greenhouse Gas R&D Programme
- Steel Production Overview
- Understanding Cost of Deploying CO_2 Capture in an Integrated Steel Mill
  - An Overview
  - Summary of Results
- What We Have Learned

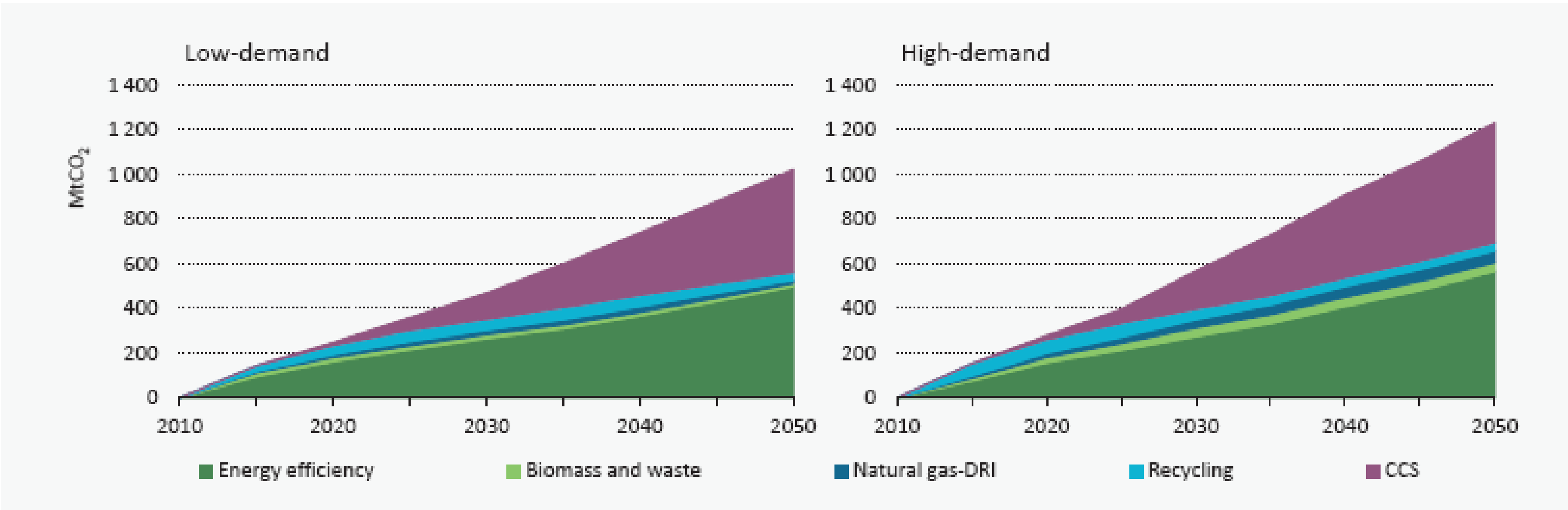
IEA Greenhouse Gas R&D Programme

- A collaborative research programme founded in 1991
- Aim: Provide members with definitive information on the role that technology can play in reducing greenhouse gas emissions.
- Producing information that is:
  - ✓ Objective, trustworthy, independent
  - ✓ Policy relevant but NOT policy prescriptive
  - ✓ Reviewed by external Expert Reviewers
  - ✓ Subject to review of policy implications by Members
- IEA GHG is an IEA Implementing Agreement in which the Participants contribute to a common fund to finance the activities.
- Activities:
  - Studies and Reports (>120);
  - International Research Networks
  - Communications (GHGT conferences, IJGGC, etc);
  - facilitating and focusing R&D and demonstration activities e.g. Weyburn

Members and Sponsors

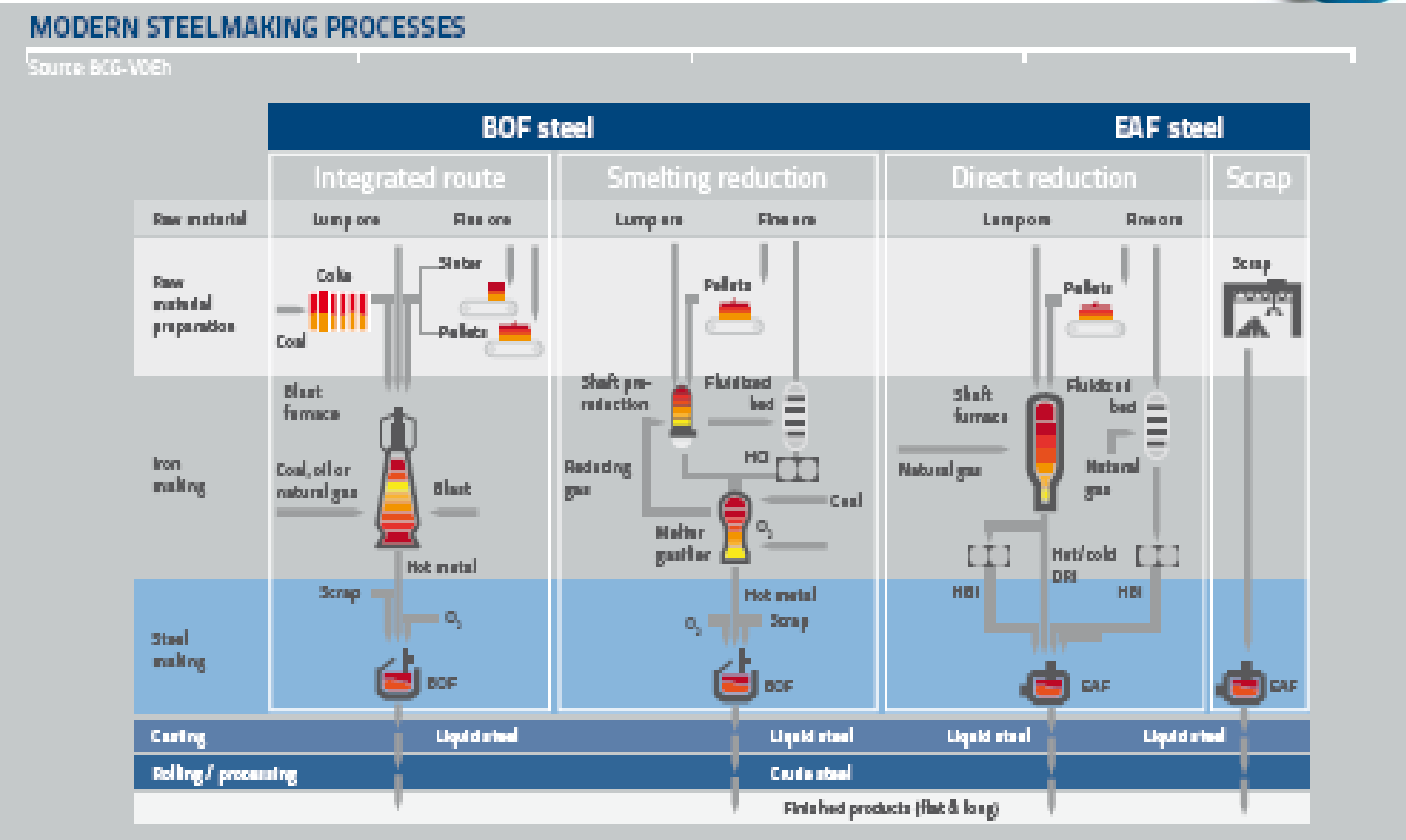
IEA ETP2012 Projection

Iron and Steel Industry

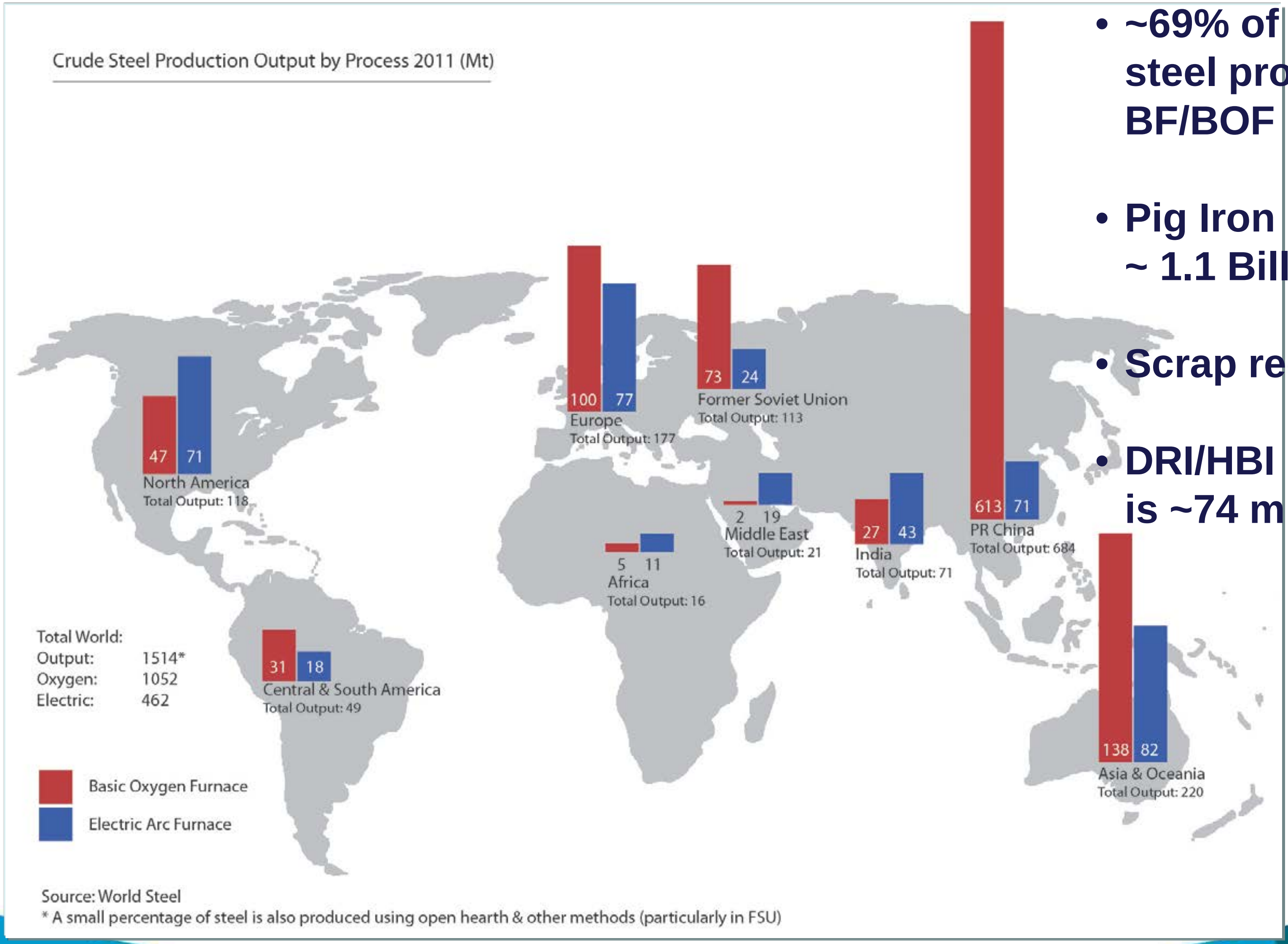


Key point *Half of the CO_2 reductions between the 2DS and 4DS are from improved energy efficiency.*

Steel Production Routes



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**

Top 10 Steel Producers in the World

(Data from World Steel Association)

	2001		2011	
Global Steel Production (in tonnes)	851,073,000		1,490,060,000	
Top 10 Producers (in million tonnes)	Arcelor (now w/ AM)	43.1	ArcelorMittal (AM)	97.2
	POSCO	27.8	Hebei Group	44.4
	Nippon Steel	26.2	Baosteel Group	43.3
	Ispat Int'l (now w/ AM)	19.2	POSCO	39.1
	Shanghai Baosteel	19.1	Wuhan Group	37.7
	Corus (now w/ Tata)	18.1	Nippon Steel	33.4
	ThyssenKrupp	16.2	Shagang Group	31.9
	Riva	15.0	Shougang Group	30.0
	NKK (now w/ JFE)	14.8	JFE	29.9
	Kawasaki (now w/ JFE)	13.3	Ansteel Group	29.8

UNDERSTANDING COST OF CO_2 CAPTURE OF AN INTEGRATED STEEL MILL

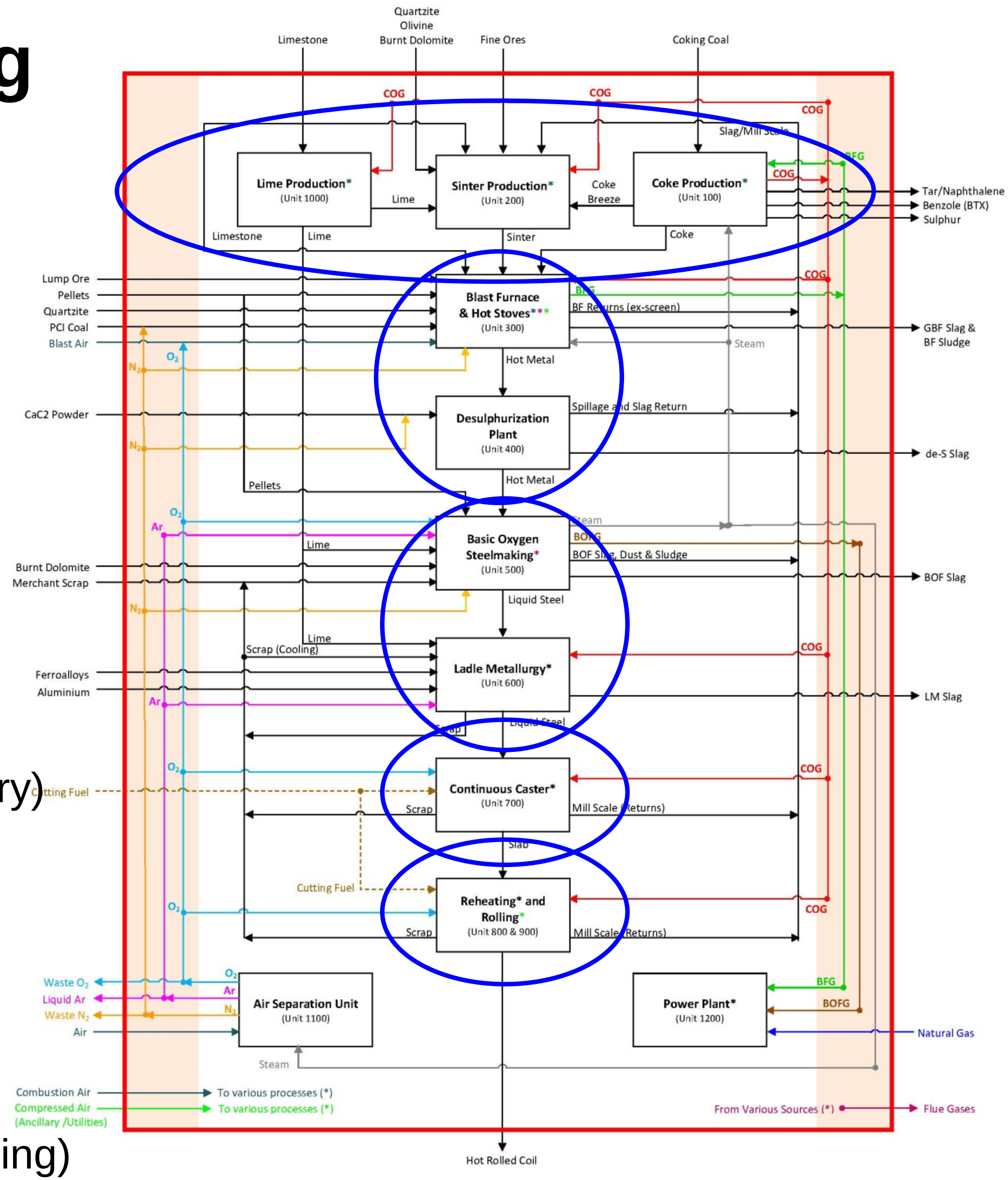
Objectives of the Study

- 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.

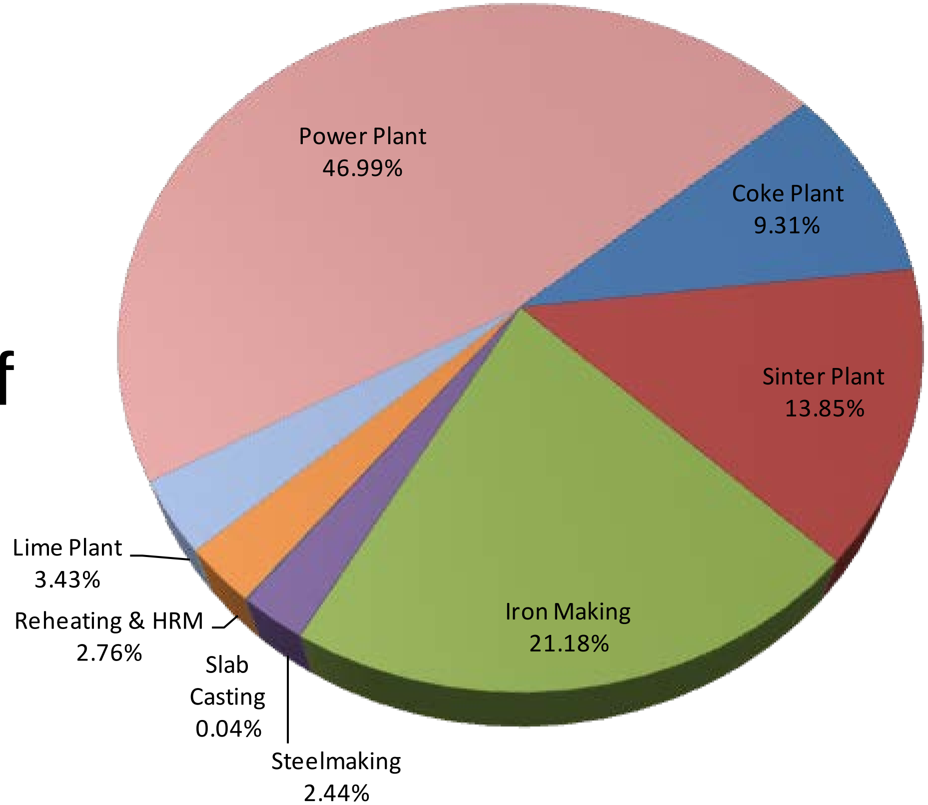
Integrated Steelmaking Process

- 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)



Direct CO_2 Emissions from the REFERENCE Steel Mill

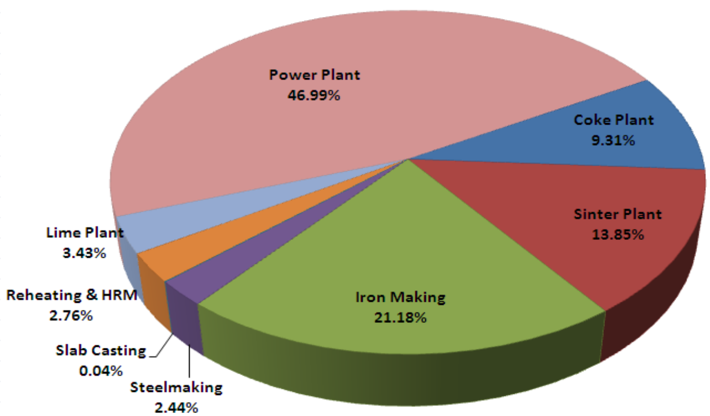
- Nearly 95% of the total CO_2 Emissions from the Integrated Mill that produces 4 million tonnes of Hot Rolled Coil:
  - Power Plant (47.0%)
  - Ironmaking (21.2%)
  - Sinter Production (14.0%)
  - Coke Production (9.3%)
  - Lime Production (3.4%)



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

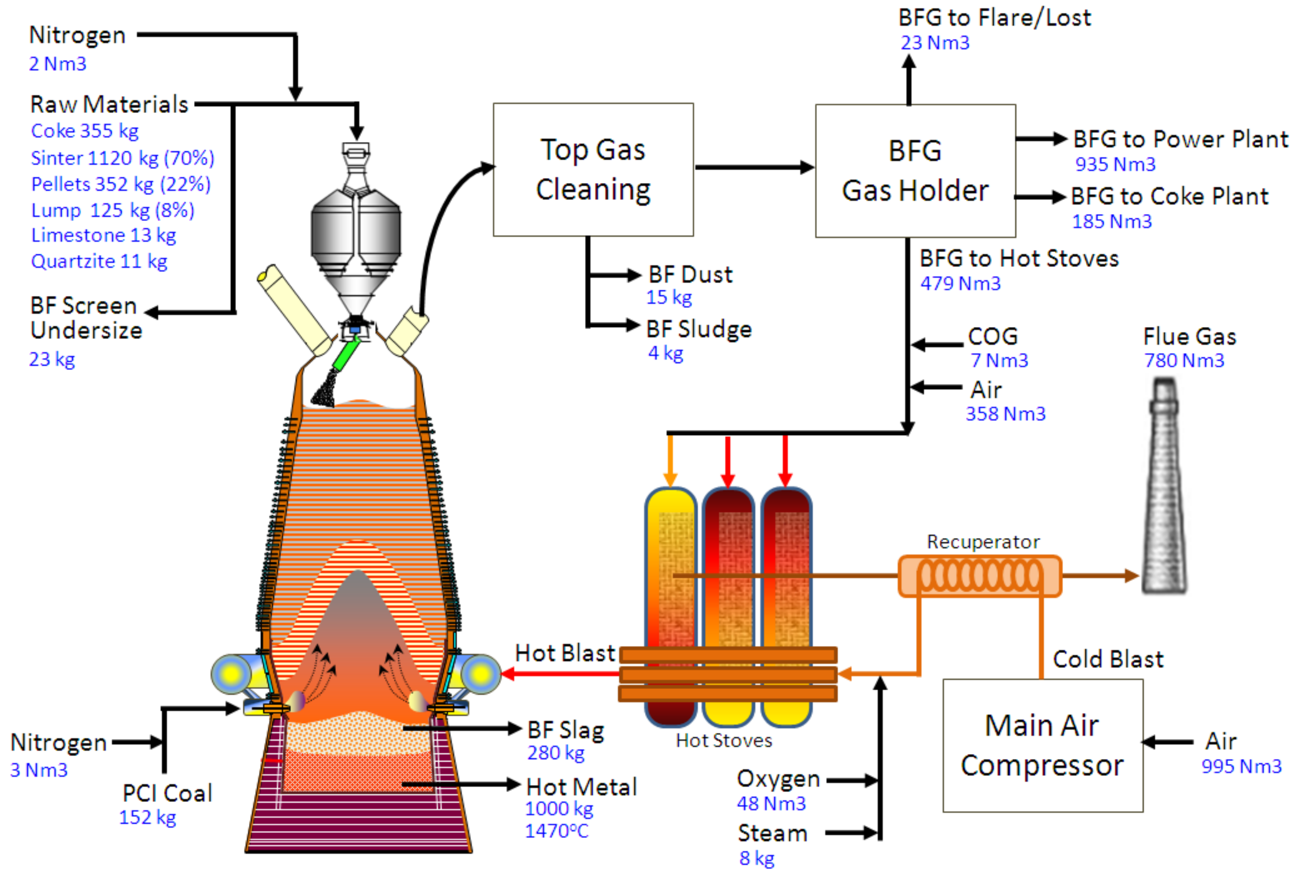
Carbon Balance of Ironmaking Process

Direct CO_2 Emissions of an Integrated Steel Mill (REFERENCE) Producing 4 MTPY Hot Rolled Coil
<u>2090 kg CO_2/t HRC (2107 kg CO_2/thm)</u>



Carbon Balance of Ironmaking Process

Carbon Input (kg C/thm)		Carbon Output (kg C/thm)	
Coke	312.4	Hot Metal	47.0
Limestone	1.5	BF Screen Undersize	6.3
PCI Coal	132.2	Dust & Sludge	8.0
COG	1.3	BFG Export	266.4
		BFG Flared	5.4
		Hot Stove's Flue Gas	114.1
Total	**447.5**	**Total**	**447.2**



For this case study, it was demonstrated that the ironmaking process is responsible for 78% of the total carbon input of the steel mill. <u>BUT</u> only 21% of the carbon emitted as CO_2 emissions is attributed to this process. The rest of the carbon emitted as CO_2 are accounted to other processes (mostly end users of the by-product fuel gases) within the steel mill.

STEEL MILL Battery Limit

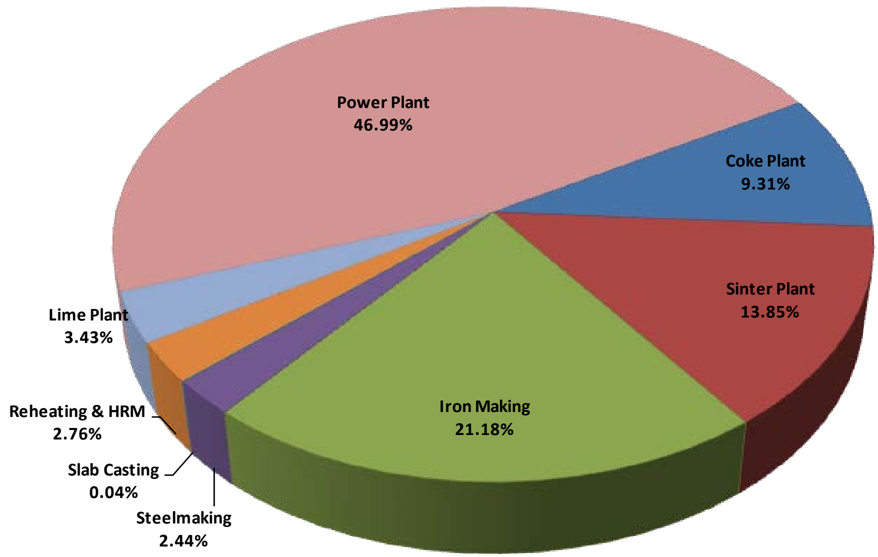
(Case 2A: Steel Mill with Post Combustion Capture)

CO_2 is captured from the flue gases of the hot stoves and the steam generation plant

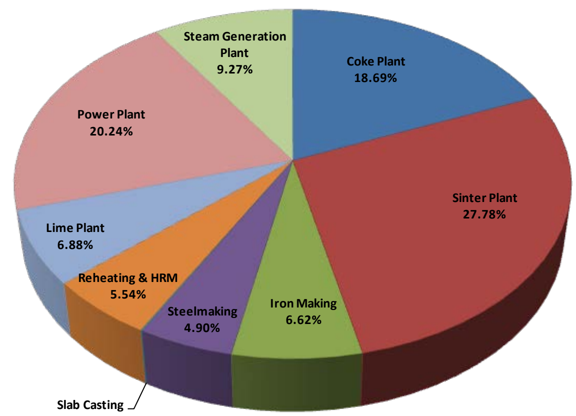
CO_2 Emissions from Integrated Steel Mill

Annual Production: 4 Million Tonnes Hot Rolled Coil

(REFERENCE vs. EOP-L1)



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



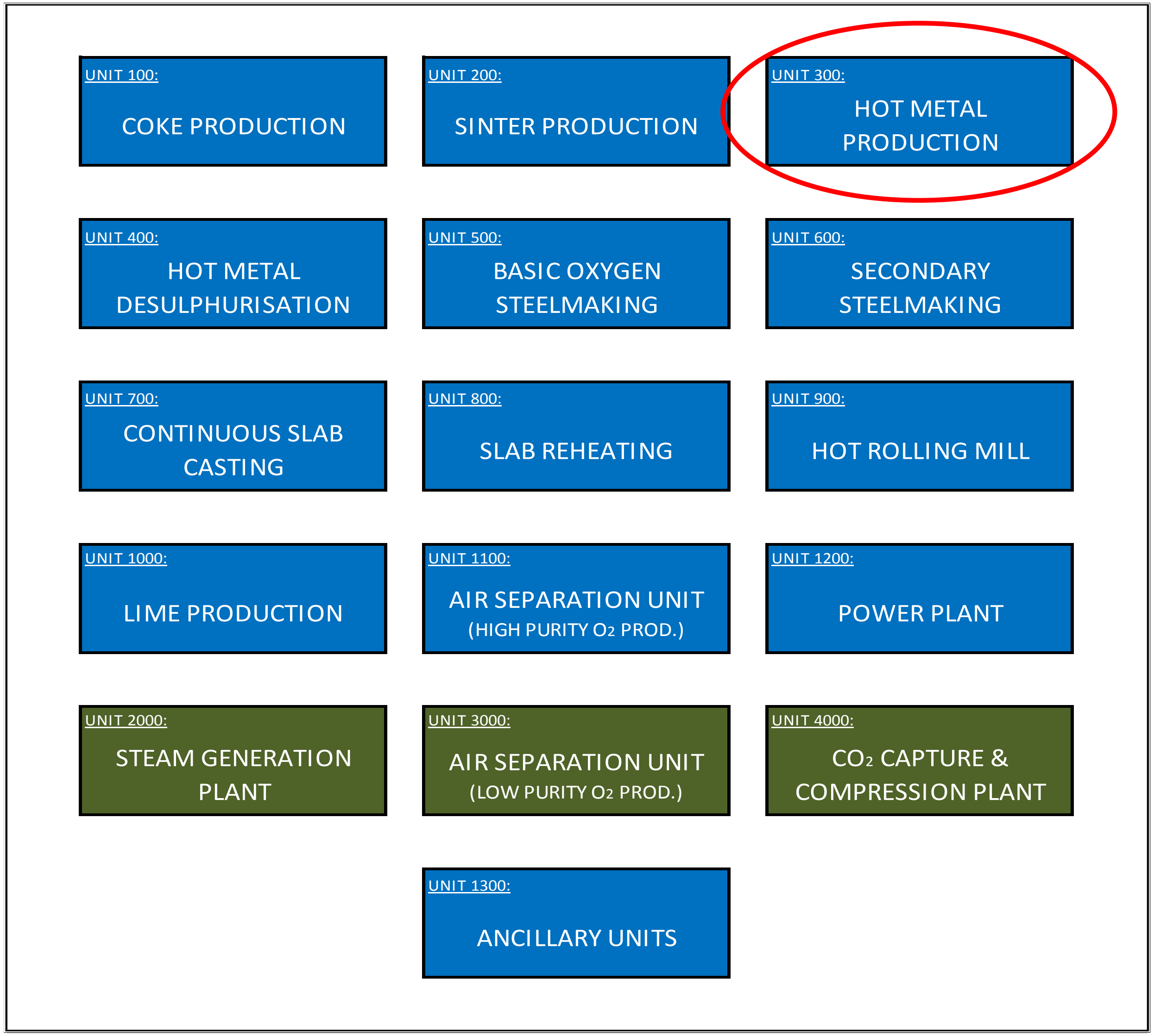
Steel Mill with CO_2 Capture (EOP-L1)
(1042 kg per tonne of Hot Rolled Coil)

<u>Post-Combustion CO_2 Capture (EOP-L1):</u>

- CO_2 Captured: 1243 kg/t HRC
- CO_2 Avoided: 50.2%

STEEL MILL Battery Limit

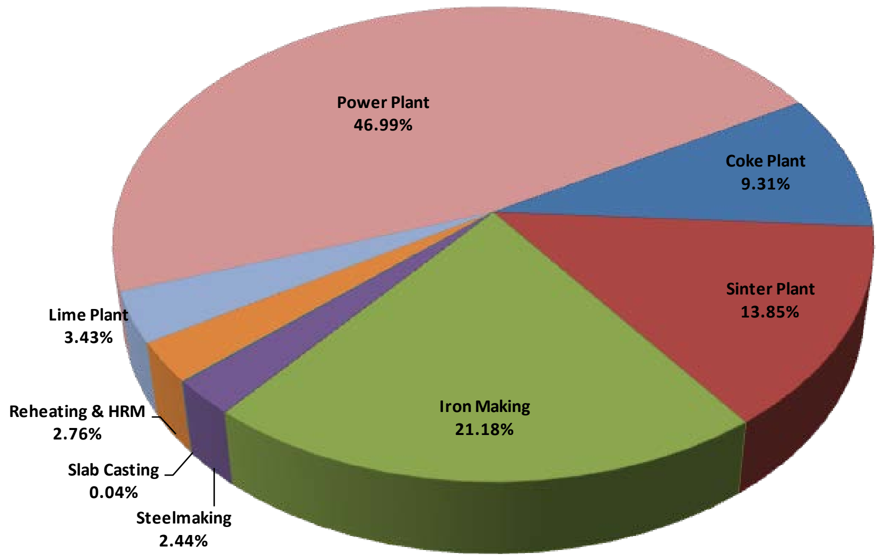
(Case 3: Steel Mill with OBF & MDEA CO_2 Capture)



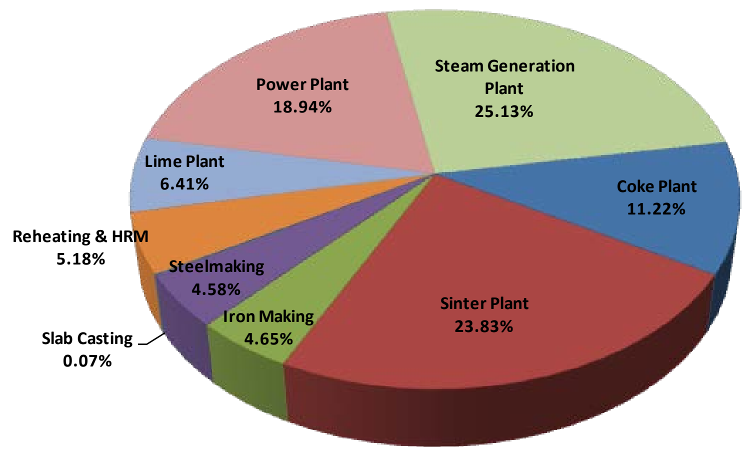
CO_2 Emissions from Integrated Steel Mill

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 CO_2 Capture
(1115 kg per tonne of Hot Rolled Coil)

<u>OBF with MDEA CO_2 Capture:</u>

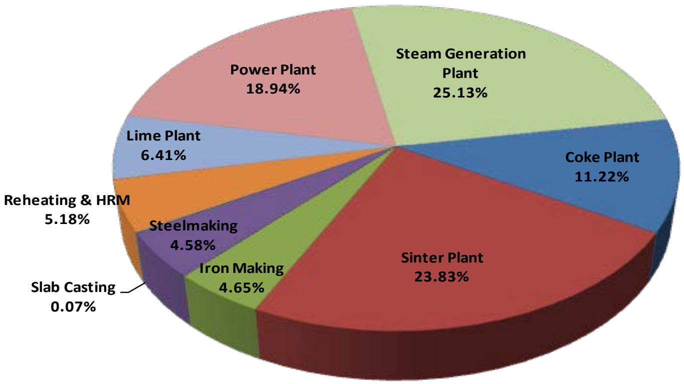
- Total CO_2 Captured: ~860 kg/t HRC
- CO_2 Avoided: 46.7%

Carbon Balance of Ironmaking Process

(Equipped with OBF and MDEA/Pz CO_2 Capture)

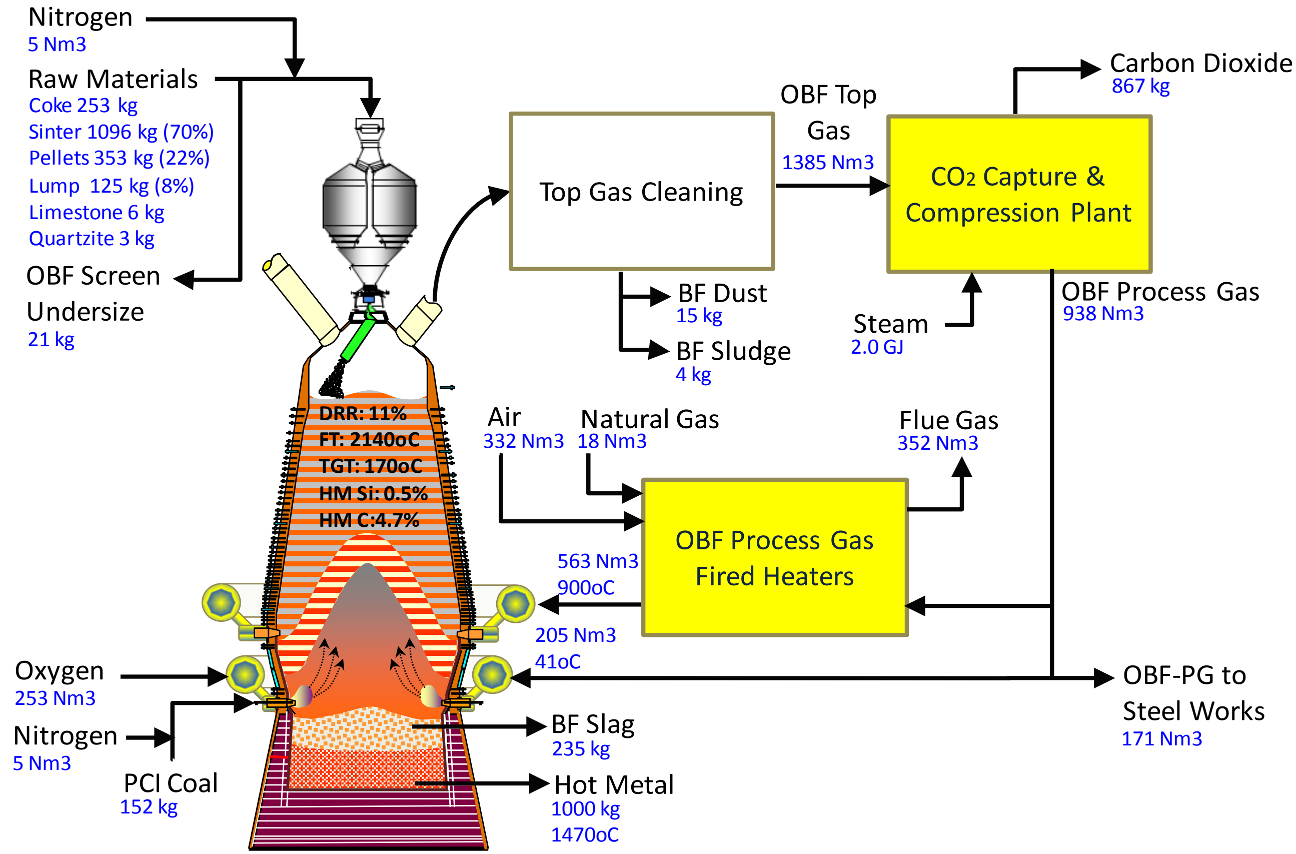
Direct CO_2 Emissions of an Integrated Steel Mill (with OBF & MDEA CO_2 Capture) Producing 4 MTPY Hot Rolled Coil

<u>1115 kg CO_2/t HRC (1124 kg CO_2/thm)</u>



<u>Carbon Balance of Ironmaking Process</u>

Carbon Input (kg C/thm)		Carbon Output (kg C/thm)	
Coke	227.7	Hot Metal	47.0
Limestone	0.7	BF Screen Undersize	4.6
PCI Coal	132.2	Dust & Sludge	8.0
Natural Gas	12.0	OBF PG Export	64.5
		PG Heater Flue Gas	12.0
		CO2 Captured	236.3
Total	**372.7**	**Total**	**372.4**



For this case study, the Oxy-Blast Furnace has the potential to reduce carbon input to the iron making process by 17% as compared to the REFERENCE case (@447.5 kg C/thm). This is due to the reduced consumption of the coke. ULCOS has reported a higher carbon input reduction potential of up to ~28%. Further reduction of CO_2 emissions could only be achieved by CCS.

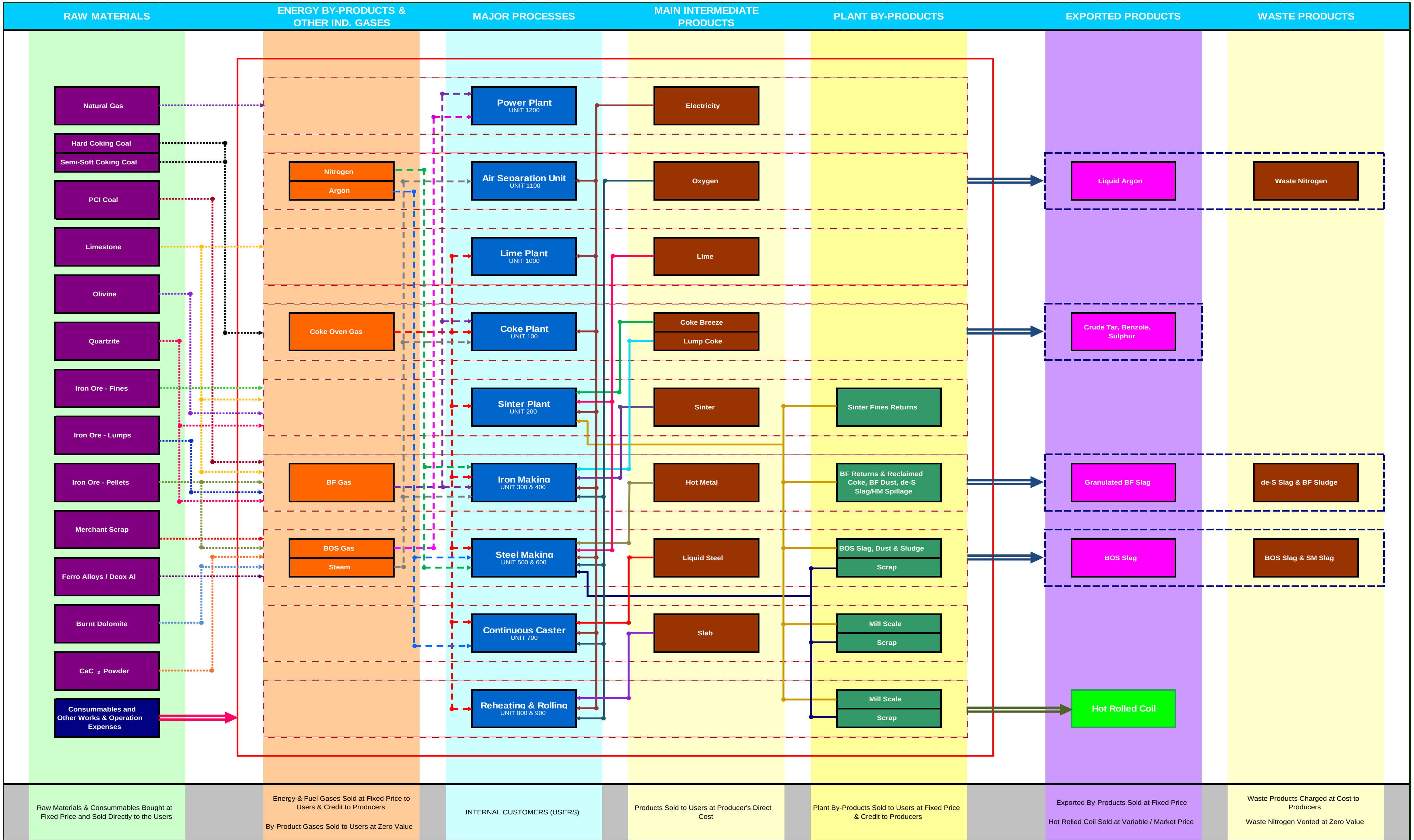
Note:

- 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

Techno-Economic Model

(REFRENCE Steel Mill)



Total Investment Cost

(REFERENCE vs. Case 2A & Case 3)

		REFERENCE Steel Mill without CO_2 Capture (Case 1)		Steel Mill with Post-Combustion Capture (Case 2A - EOP-L1)		Steel Mill with OBF/MDEA CO_2 Capture (Case 3)	
		Cost Breakdown	CAPEX (US$ Million)	Cost Breakdown	CAPEX (US$ Million)	Cost Breakdown	CAPEX (US$ Million)
Unit	**Plant and Equipment – Major Processes**		**$ 2,772**		**$ 2,993**		**$ 2,940**
100	Coke Production	400		400		310	
200	Sinter Production	220		220		220	
300 & 400	Blast Furnace and Hot Metal Desulphurisation	622		622		610	
500 & 600	Basic Oxygen Steelmaking and Ladle Metallurgy	459		459		459	
700	Continuous Slab Caster	195		195		195	
800 & 900	Reheating Furnace & Hot Rolling Mills	450		450		450	
1000	Lime Production	16		16		16	
1100	ASU – O_2 Production (High Purity)	130		130		94	
1200	Power Plant	280		362		362	
2000	Steam Generation Plant	-		139		90	
3000	ASU – O_2 Production (Low Purity)	-		-		134	
	Plant and Equipment – Material Handling & Spare		**244**		**247**		**242**
	Raw Material Handling	128		128		128	
	Spare Parts and First Fill	116		119		114	
	Plant and Equipment – Auxiliary, Utilities and BOP		**350**		**350**		**350**

Total Investment Cost - Cont'd

(REFERENCE vs. Case 2A & Case 3)

Unit	Item	REFERENCE Steel Mill without CO_2 Capture (Case 1) Cost Breakdown	REFERENCE Steel Mill without CO_2 Capture (Case 1) CAPEX (US$ Million)	Steel Mill with Post-Combustion Capture (Case 2A - EOP-L1) Cost Breakdown	Steel Mill with Post-Combustion Capture (Case 2A - EOP-L1) CAPEX (US$ Million)	Steel Mill with OBF/MDEA CO_2 Capture (Case 3) Cost Breakdown	Steel Mill with OBF/MDEA CO_2 Capture (Case 3) CAPEX (US$ Million)
	Site Development, Construction & Project Eng'g		**562**		**562**		**562**
	Pre-operating Expenses	21		21		21	
	Land Preparation, Site Development & Waste Disposal	144		144		144	
	Buildings and Site Infrastructure	196		196		196	
	Project Engineering	201		201		201	
	Total Installed Cost - Steel Mill (US$ Million)		**$ 3,928**		**$ 4,152**		**$ 4,094**
	Contingency @ 5% of Total Installed Cost - Steel Mill		**196**		**208**		**205**
Unit	**CO_2 Capture Plant**		**-**		**679**		**578**
4000	Plant & Equipment, First Fill, Spare Parts, BOP, Site Dev.	-		590		503	
	Contingency (15% of Installed Cost – CO_2 Capture Plant)	-		89		75	
	Total Investment Cost – excl. Recurring CAPEX (US$ Million)		**$ 4,124**		**$ 5,038**		**$ 4,877**
	Recurring CAPEX (Blast Furnace Reline – Every 15th Year)		**232**		**232**		**232**
	Specific Investment Cost – excl. Recurring CAPEX (US$/t HRC)		**$ 1,031**		**$ 1,259**		**$ 1,219**

Annual O&M Cost

(REFERENCE vs. Case 2A & Case 3)

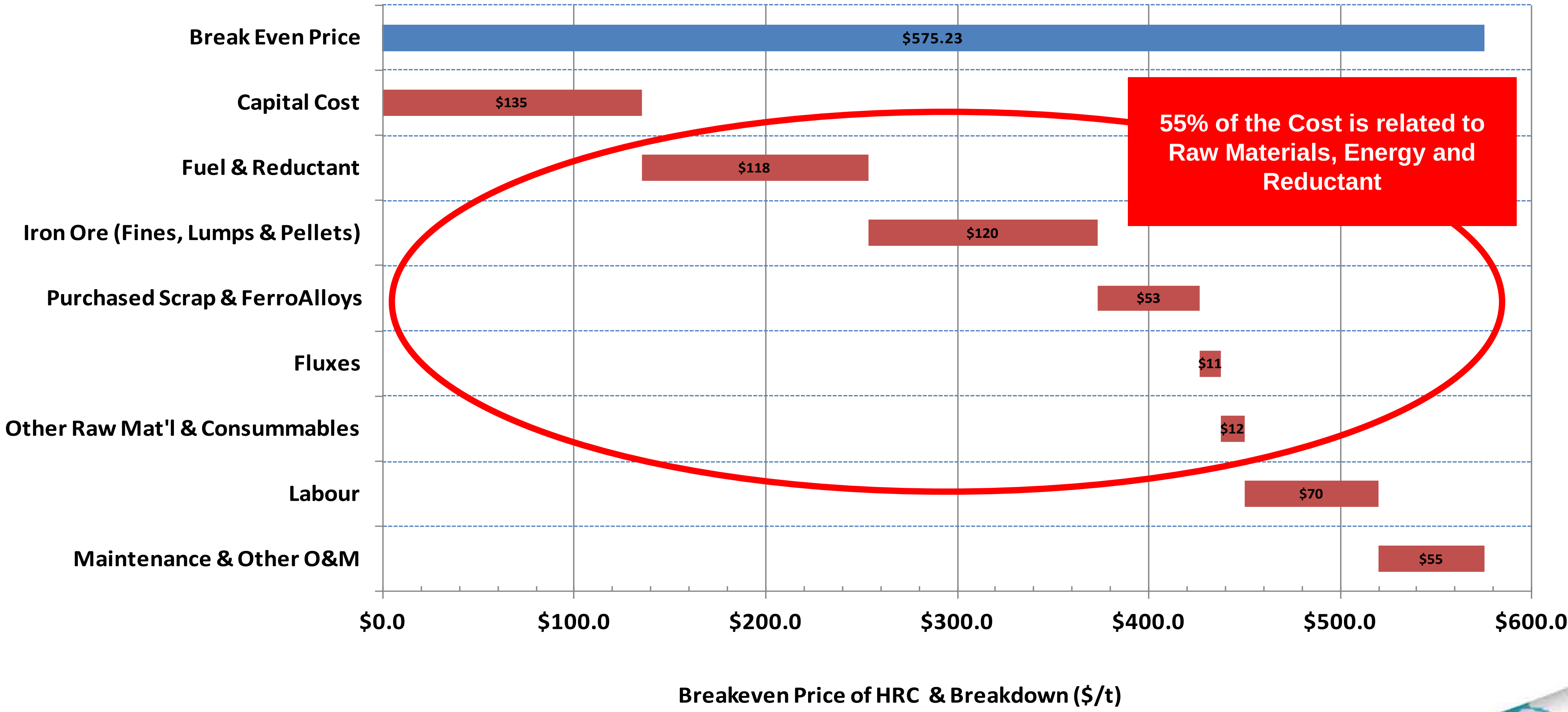
	REFERENCE Steel Mill without CO_2 Capture (Case 1)		Steel Mill with Post-Combustion Capture (Case 2A - EOP-L1)		Steel Mill with OBF/MDEA CO_2 Capture (Case 3)	
	Cost Breakdown	Annual OPEX (US$ Million/y)	Cost Breakdown	Annual OPEX (US$ Million/y)	Cost Breakdown	Annual OPEX (US$ Million/y)
Fixed O&M Cost		422.72		454.29		445.29
Maintenance	141.996		169.903		163.633	
Direct Labour	204.581		208.247		205.521	
Indirect Labour	76.140		76.140		76.140	
Variable O&M Cost		1288.65		1438.36		1369.90
Fuel and Reductant	483.938		615.481		562.214	
Iron Ore (Fines, Lumps and Pellets)	492.054		492.054		492.291	
Purchased Scrap and Ferroalloys	218.228		218.228		218.228	
Fluxes	44.650		44.650		40.091	
Consumables & Other Utilities	49.781		67.943		57.080	
Miscellaneous Expense		62.25		62.25		59.04
Miscellaneous Works Expense	50.398		50.398		48.066	
Other Misc. OPEX (incl. environmental clean up)	11.849		11.849		10.970	
Other O&M Cost		8.18		11.33		8.60
Slag Processing	3.578		3.578		3.568	
On-Site Haulage	0.268		0.268		0.265	
Disposal and Landfill	4.335		7.488		4.769	
Annual O&M Cost (US$ Million/y)		$ 1,781.80		$ 1,966.23		$ 1,882.84

Revenues from By-Products

(REFERENCE vs. OBF/MDEA Case)

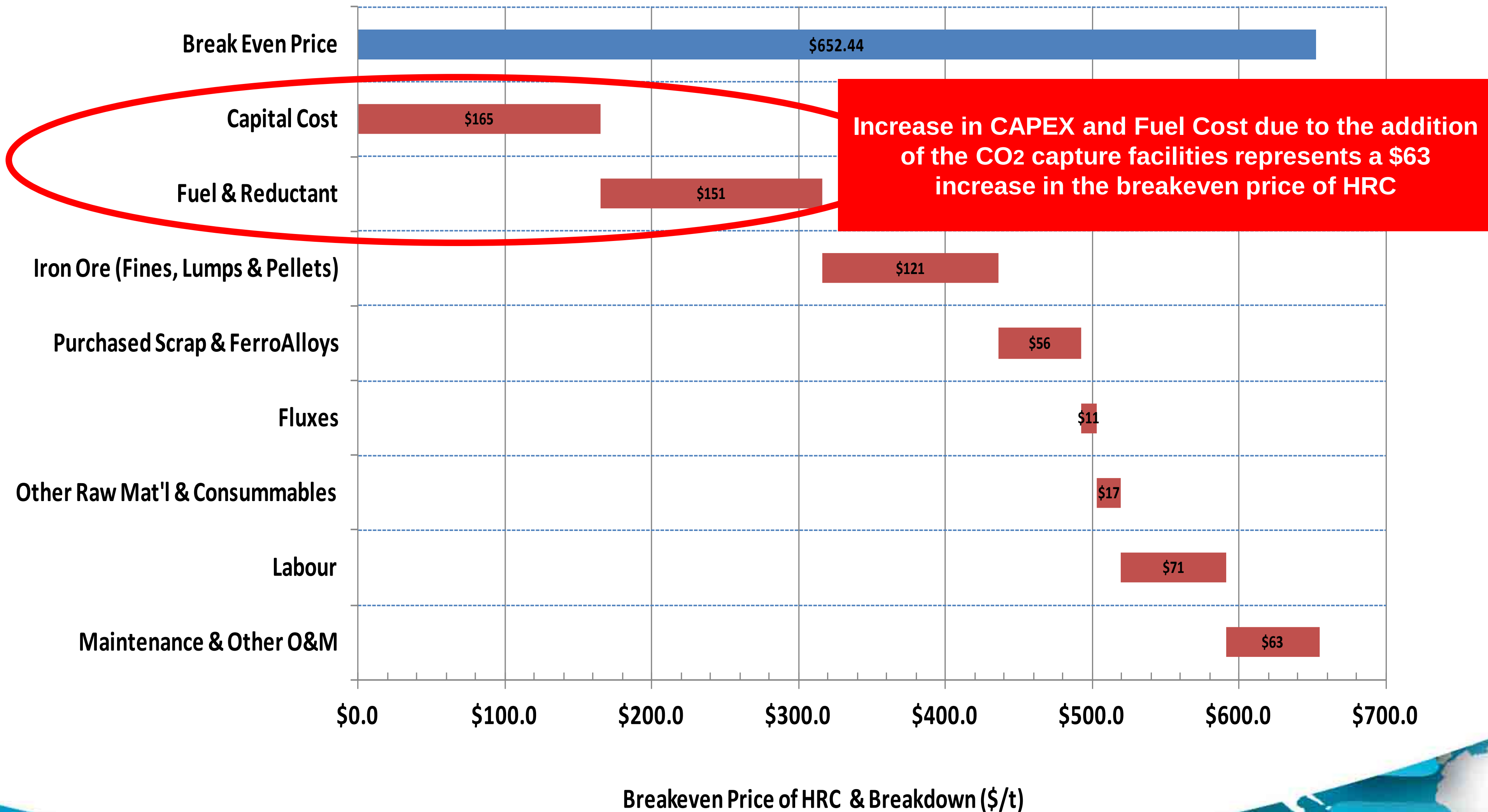
Cost Items	REFERENCE Steel Mill		Steel Mill with OBF / MDEA CO_2 Capture	
	Sales Breakdown	Annual Sales (US$ Million/y)	Sales Breakdown	Annual Sales (US$ Million/y)
Coke By-Products		**21.423**		**16.341**
Crude Tar	11.806		9.005	
Benzole	9.197		7.016	
Sulphur	0.420		0.320	
Steel Mill Slags		**18.230**		**15.370**
Granulated BF Slag	17.780		14.922	
BOS Slag	0.450		0.448	
Liquid Argon		**14.018**		**3.248**
Annual Sale Revenue – By Products (US$ Million/y)		**53.670**		**34.959**

Cost of Steel Production – Breakdown Breakeven Price of $575.23

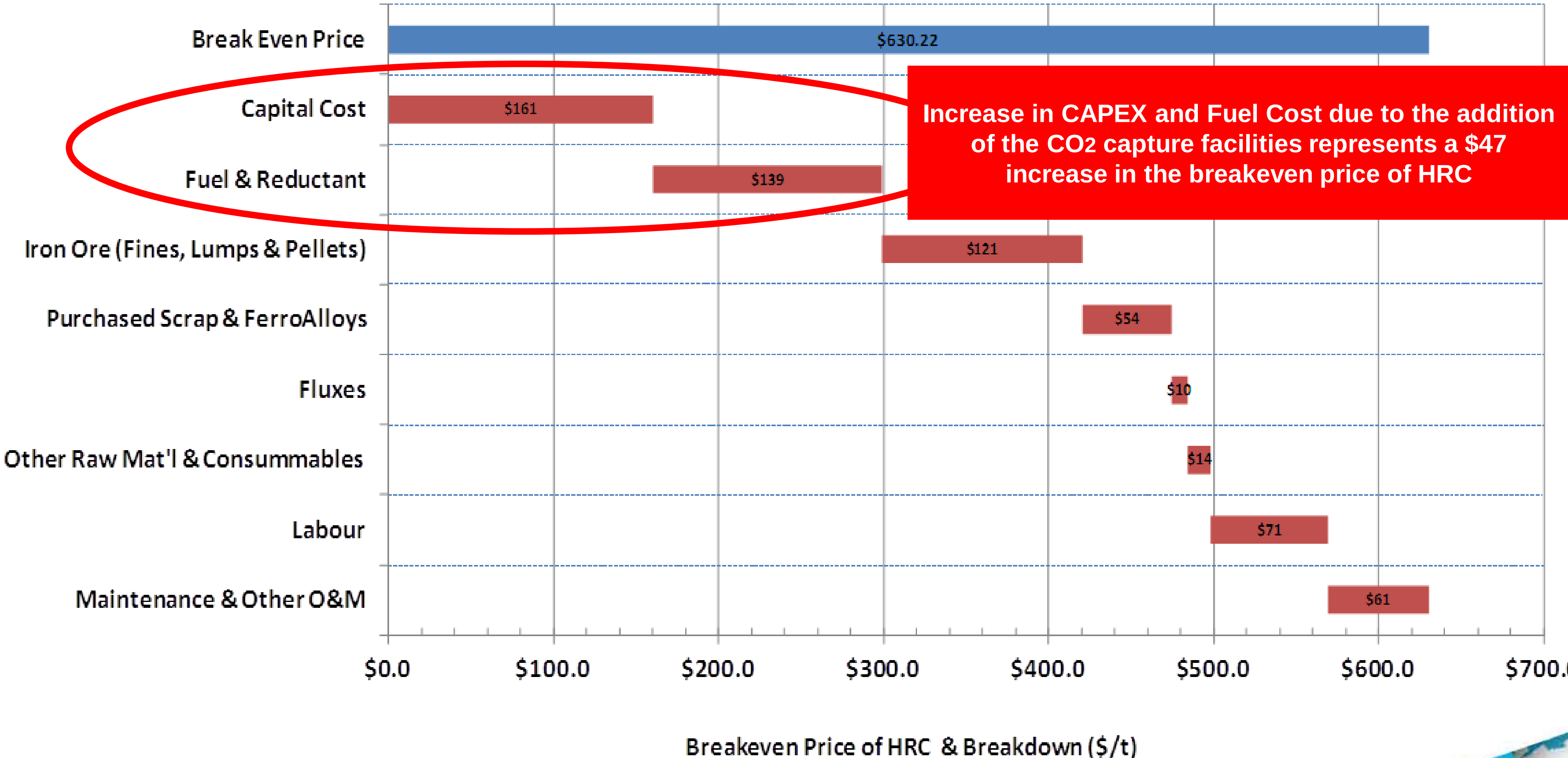


Cost of Steel Production – Breakdown Breakeven Price of $652.44

(Steel Mill with Post-Combustion CO_2 Capture EOP-L1 Case)



Cost of Steel Production – Breakdown Breakeven Price of $630.22



Key Message from this Study

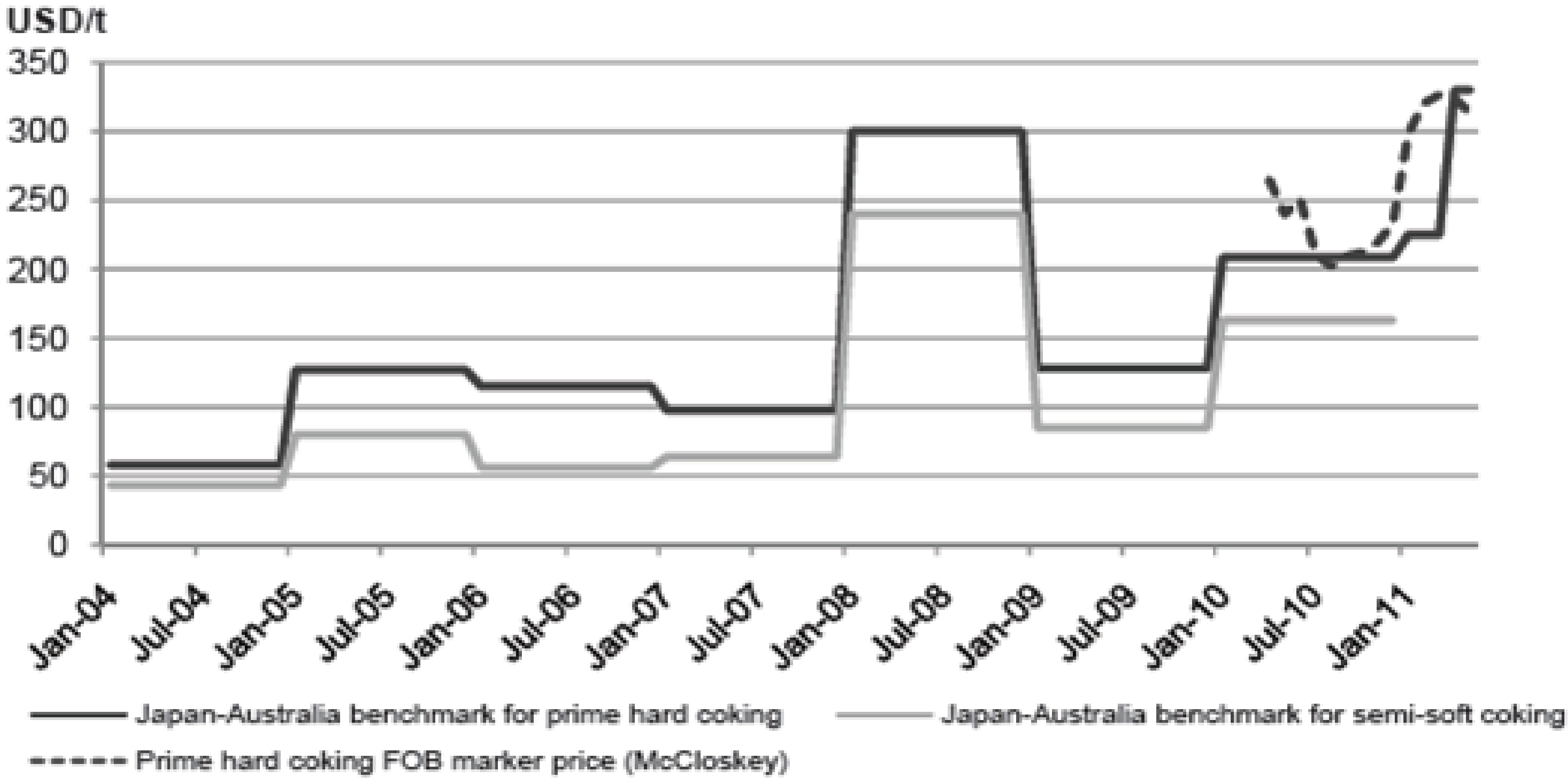
- **Key to the deployment of CO_2 capture technologies using top gas recycle to a blast furnace should also maximise the reduction in the coke consumption to make it cost competitive.**

- **Post-Combustion CO_2 Capture – i.e. capture of CO_2 from the flue gas of different stacks within the integrated steel mill - is not a cost competitive option!**
  - **This is not the options considered by the global steel community.**

- REPORTING CO_2 Avoidance Cost for a complex industrial processes is meaningless – without establishing the assumptions used for the REFERENCE Plant without CO_2 Capture.
  - **This is not a good indicator for these cases yet we are trapped in it...**

Evolution of Coking Coal Price

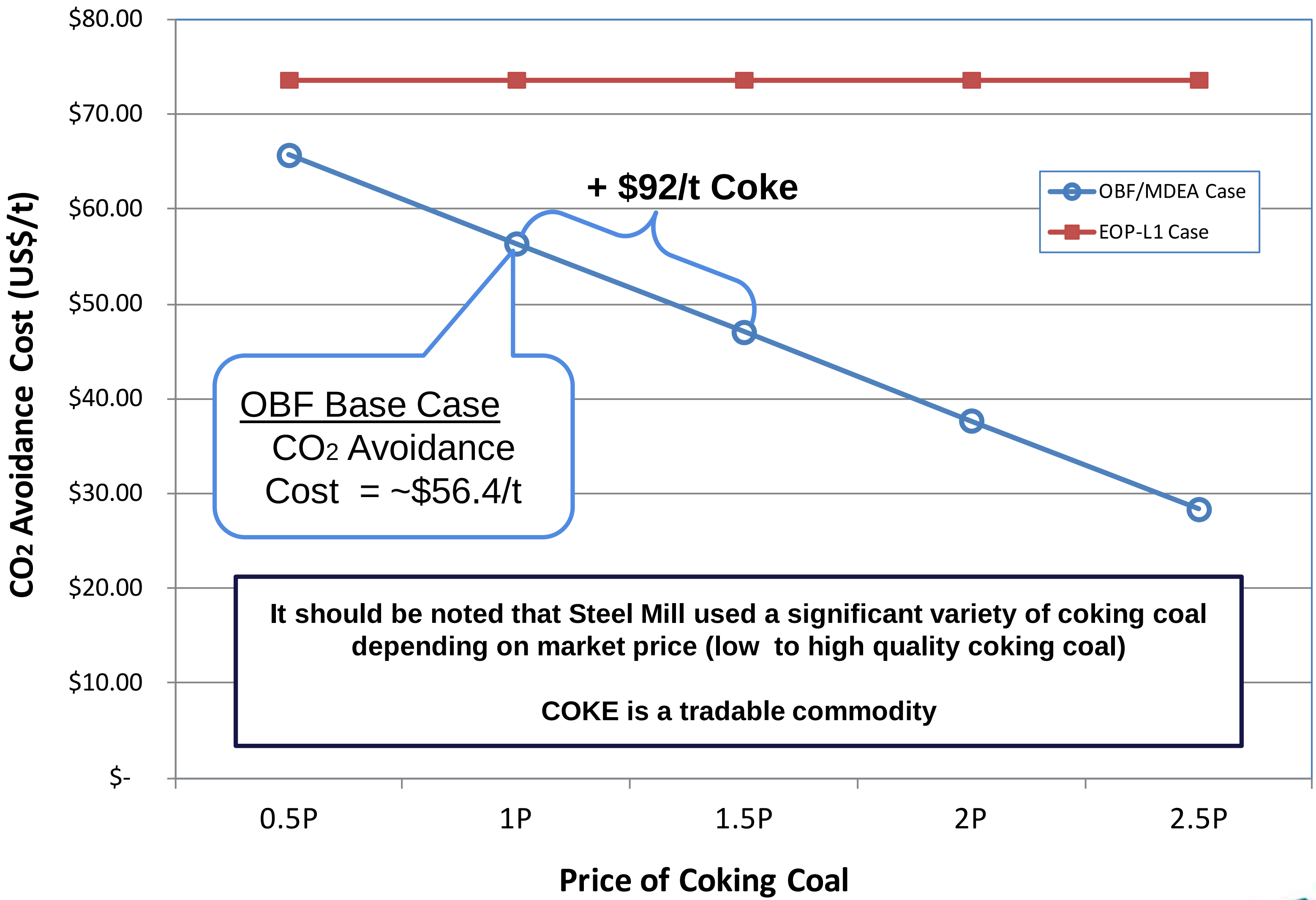
(Data provided by P. Baruya – IEA CCC)



Source: McCloskey (2011); ABARES (2011a).

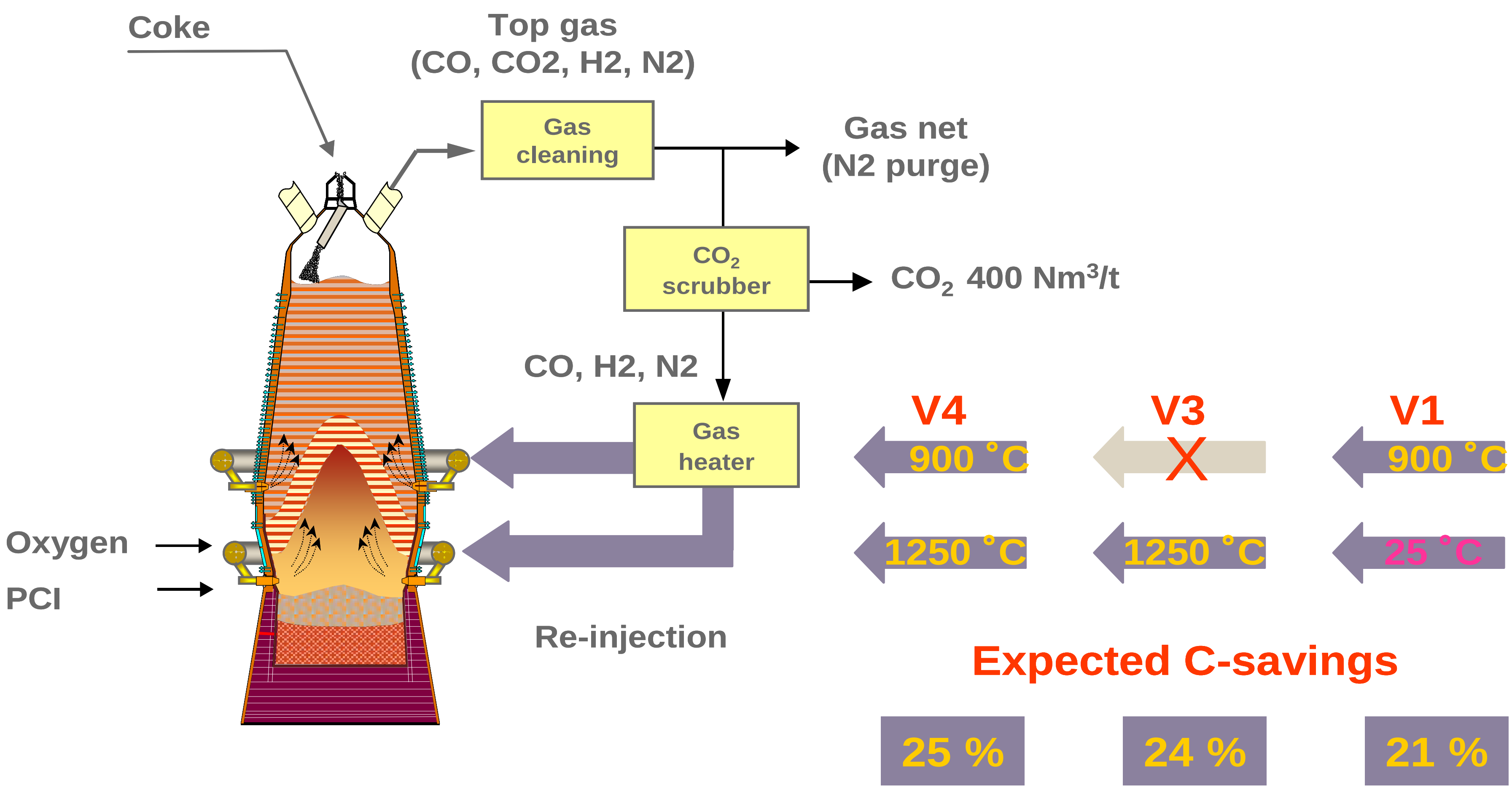
Summary of Results

(Sensitivity to Coke Price)



WHAT WE HAVE LEARNED

The Ulcos Blast Furnace Concepts



Separation and Capture of CO_2 from OBF also has several other options

(Data from ULCOS Programme)

- PSA, VPSA
- VPSA + Cryogenics Separation of non-CO_2 components
- Chemical Absorption

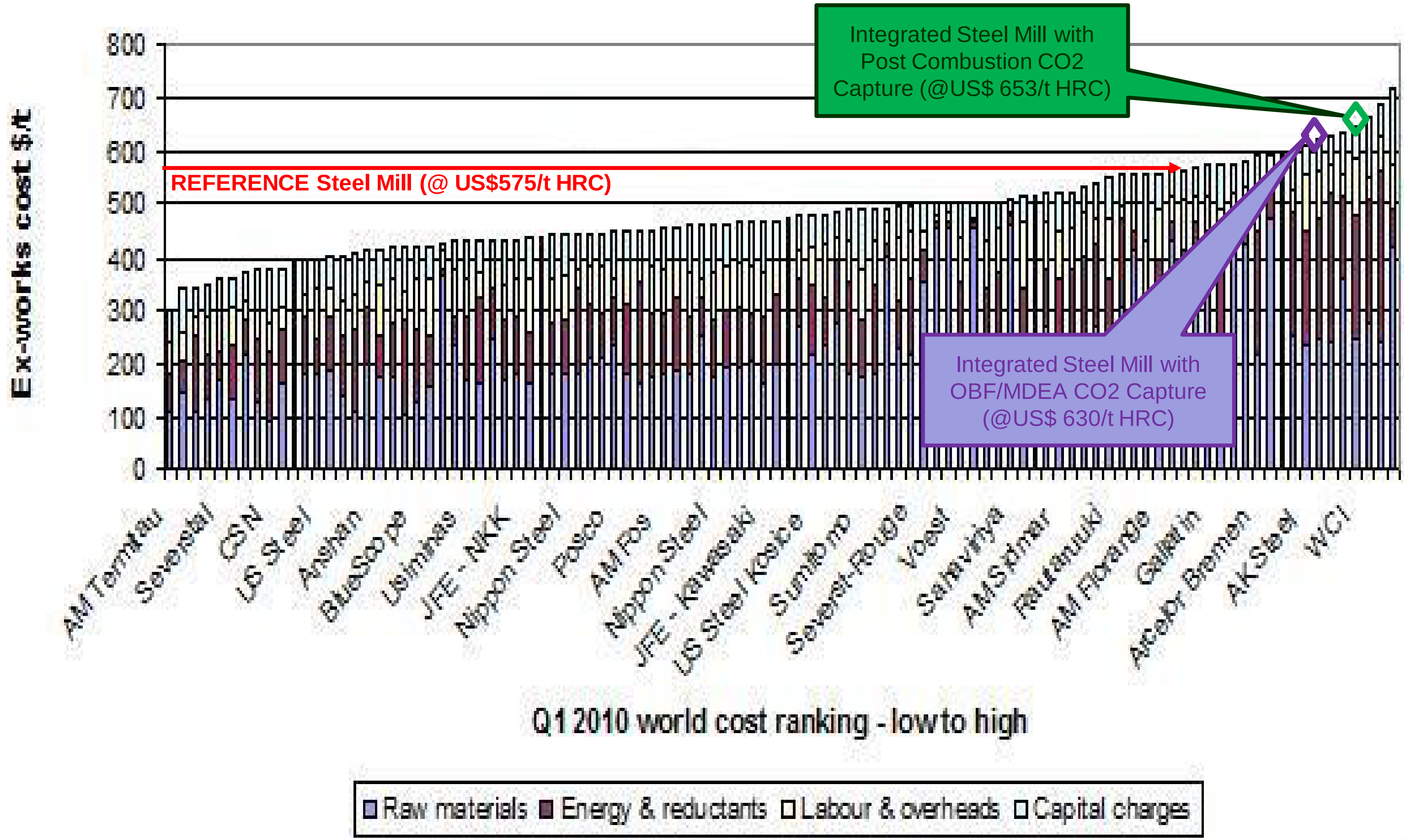
		PSA	VPSA	VPSA & Cryo Flash + Compression	Amines + Compression	PSA & Cryo Distil. + Compression
Recycled Top Gas (Process Gas)						
CO yield	%	88.0	90.4	97.3	99.9	100.0
Process Gas Composition						
CO_2	%v	2.7	3.0	3.0	2.9	2.7
CO	%v	71.4	69.2	68.9	67.8	69.5
H_2	%v	12.4	13.0	12.6	12.1	12.4
N_2	%v	13.5	15.7	15.6	15.1	15.4
H_2O	%v	0.0	0.0	0.0	2.1	0.0
Captured CO_2 Rich Gas						
CO_2	%v	79.7	87.2	96.3	100.0	100.0
CO	%v	12.1	10.7	3.3	0.0	0.0
H_2	%v	2.5	0.6	0.1	0.0	0.0
N_2	%v	5.6	1.6	0.3	0.0	0.0
Suitable for CO_2 Transport & Storage?		No	No	Yes (?)	Yes	Yes
Electricity Consumption						
Capture Process	kWh/t CO_2	100	105	292	170	310
CO_2 Compression (110 Bar_a)	kWh/t CO_2	100	105	160	55	195
LP Steam Consumption	GJ/t CO_2	0.0	0.0	0.0	3.2	0.0
Total Energy Consumption	GJ/t CO_2	0.36	0.38	1.05	3.81	1.12

Key Message

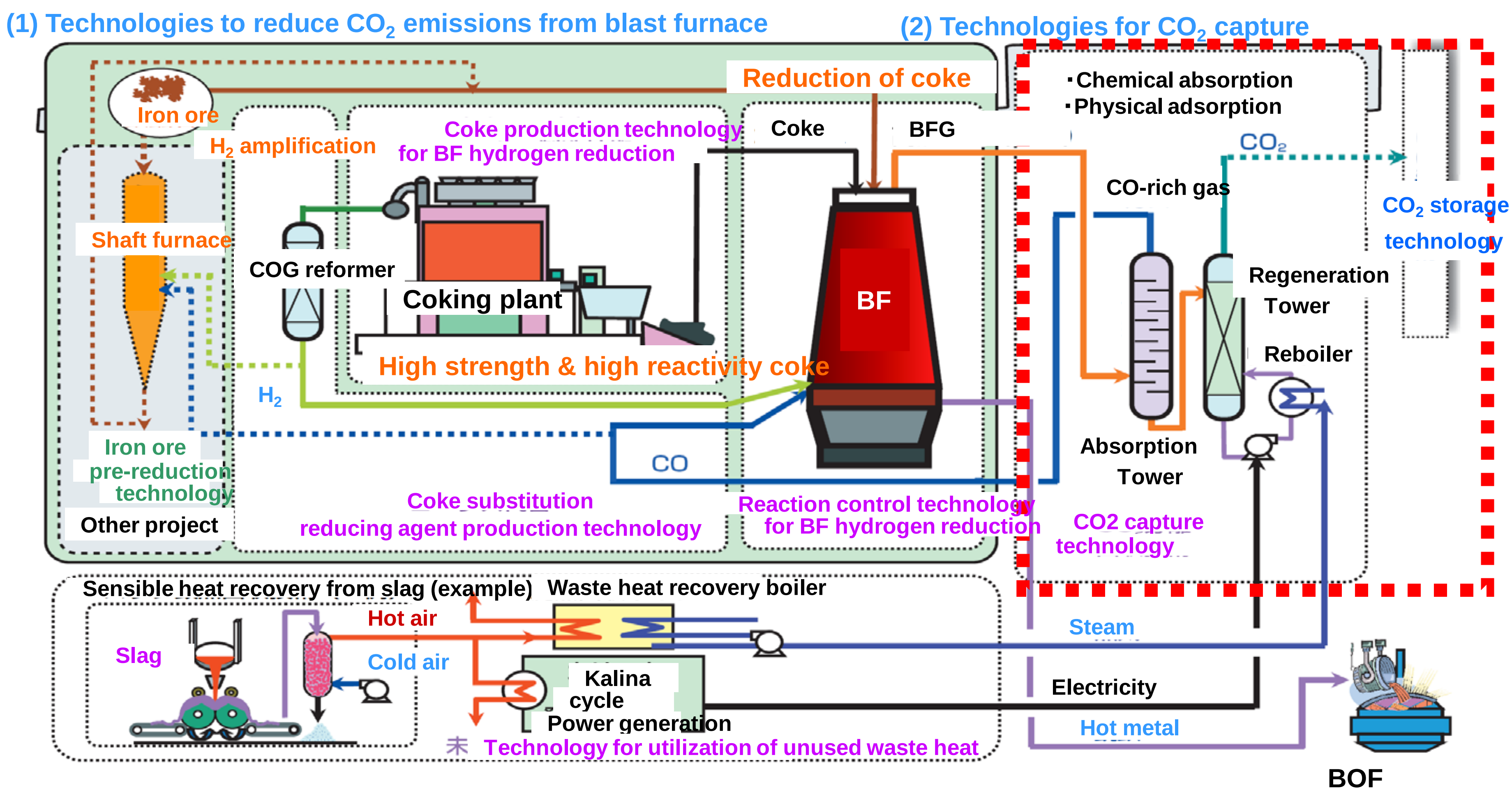
- Analysis as compared to ULCOS indicated that cost could still go down. This is strongly dependent on the coke reduction.
- Electricity price will play a big role in determining the technology of CO_2 Capture Plant. VPSA/Cryogenic could be better option than Chemical Absorption. This study has been limited by availability of cost data.
- Improvement to ASU and other auxiliaries could further bring down cost.

Relative Cost Competitiveness of Steel Production with CO_2 Capture

(2010 Global Cost Curve Data from Metal Consulting Int'l Ltd.)

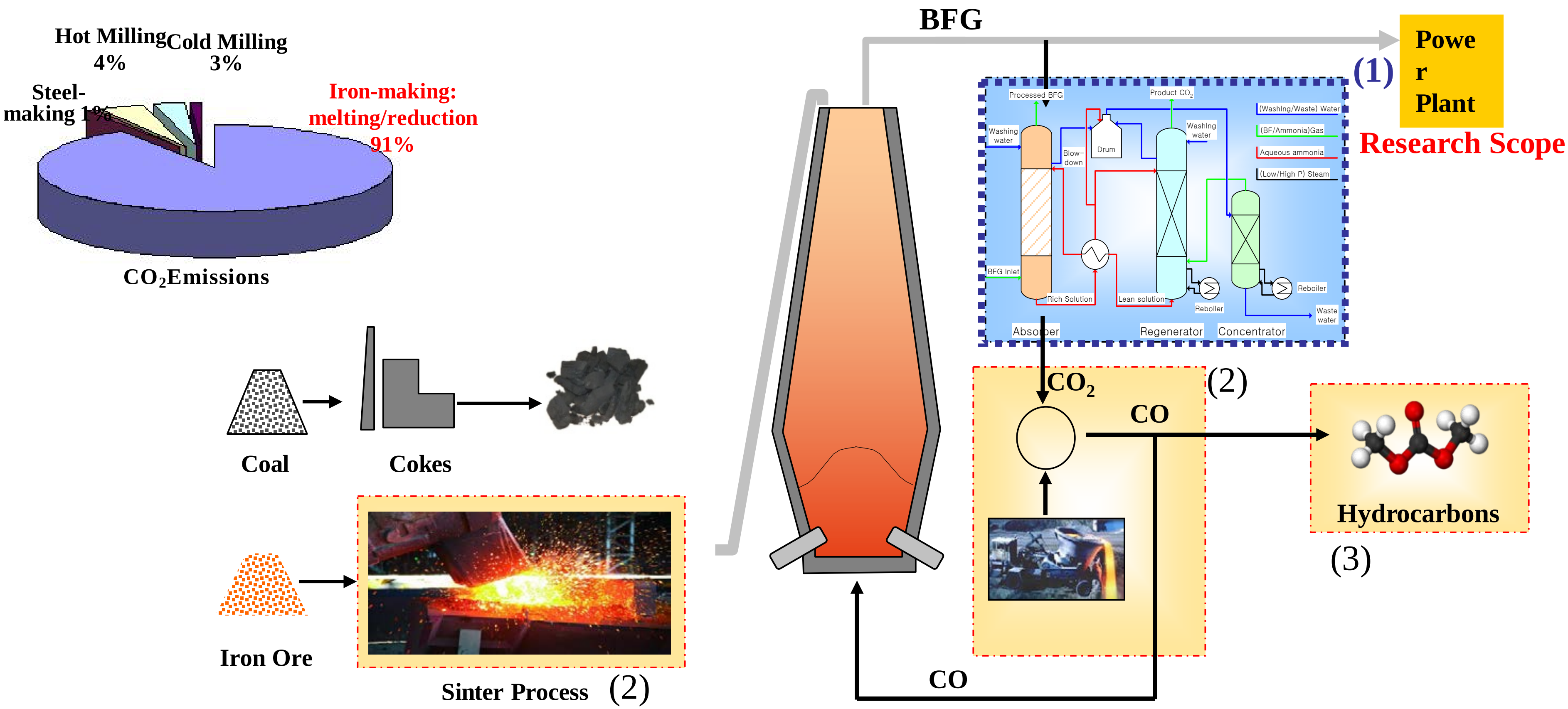


Japanese "Course 50 Programme"



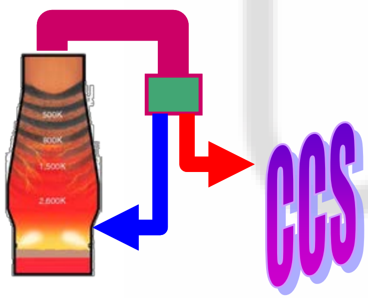
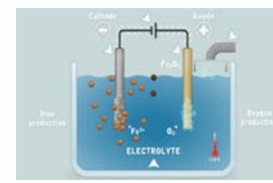
COURSE50 / CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50

Ideas/Projects for CO_2 Reduction



- Research Activities of CO_2 Project in RIST
  - (1) CO_2 Capture from BFG stream using aqueous ammonia
  - (2) Waste heat recovery from molten slag and hot sinter
  - (3) CO_2 utilization

ULCOS II develops all 4 ULCOS solutions

Coal & sustainable biomass		Natural gas	Electricity
Revamping BF	Greenfield	Revamping DR	Greenfield
ULCOS-BF 	**HIsarna** 	**ULCORED** 	**ULCOWIN** **ULCOLYSIS** 
Pilot tests (1.5 t/h) Demo phase under way	Pilot plant (8 t/h) start-up 2010	Pilot plant (1 t/h) to be erected in 2013	Laboratory pilots

Thank You

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Extra-Ordinary Assumptions

(For European Scenarios)

- Only one type of steel product (standard grade HRC) produced and sold.
- Plant Ownership Structure not typical to European Steel Mill Scenario
  - Captive Ownership: Power Plant, ASU and Lime Plant
- Captive Power Plant with Balanced Electricity Supply to the Steel Mill.
- Captive Coke Plant with Balanced Supply of Coke to the Steel Mill.
- Direct emissions related to the Pellets and Merchant Scrap not included in overall CO_2 emission accounting.

Key Price Inputs

- Price inputs for externally and internally sourced raw materials are based on actual operating price data adjusted to long term trends.
- Major intermediate products are priced based on the gate of the specific operating unit ("Factory").
- Revenues from sale of by-products is credited to the source of this materials.
- Details of these inputs are presented in the excert of the Volume 1 Report

Notes on Investment Cost

- The integrated steel mill is assumed to have an economic life of 25 years as the basis for appraisal.
- The cost evaluation was developed in US$ (2010). Where necessary, the conversion was based on the following exchange rates:
  - € 1.00 = US$ 1.34
  - £ 1.00 = US$ 1.55
- The estimate accuracy is within the range +/- 30%.