Iron and Steel

HIGHLIGHTS

■ **PROCESSES AND TECHNOLOGY STATUS –** The basic materials for iron production are iron ore, coal and coke (also used as energy input to the process) or alternative reducing agents, limestone and dolomite. Steel production requires iron, steel scrap and lime (burnt limestone). The iron ore is smelted to produce an impure metal called "hot metal" when in liquid phase or "pig iron" when in solid phase. In smelting, a reducing agent - usually coke - and heat are used to remove oxygen from the metal ore. Carbon dioxide (CO_2) and carbon monoxide (CO) are produced during the reduction process. Limestone is used to remove impurities such as slag. Blast Furnace, Midrex Direct Reduction Iron (DRI), Corex Smelting Reduction Iron (SRI) and Hylsa are currently commercial processes. Hismelt Smelting Reduction Iron and Hi-Oxy coal plants (with a high rate of coal powder injection) are new processes currently available at the pilot plant level. Iron and steel production processes with CO_2 emissions capture and storage (CCS) are still under development and testing.

■ **COST –** The main components of the iron and steel production cost are capital investment and raw materials. Investment costs for the traditional production processes are approximately $211 for Blast Furnaces (BF) with a capacity of one ton of pig iron per year (US $/(t/a)) and $100 for a Basic Oxygen Furnace (BOF) with a unit capacity (US $/(t/a). Investment costs for the alternative production technologies range from $220/t-yr for Direct Reduced Iron (DRI) and Electric Arc Furnace (EAF) combinations to $320/t-yr for the Smelting Reduction (SRI) technology. Other main cost drivers are scrap and electricity. Total costs amount to $92/t for BF and BOF combinations (including energy inputs), $214/t for DRI and EAF combinations and $198/t for SRI.

■ **POTENTIAL & BARRIERS –** The iron and steel production sector is the second-largest industrial consumer of energy - after the chemical sector. It accounts for about 20% of industrial energy consumption and is the largest industrial emitter of CO_2, including all the process emissions from coke ovens, blast furnaces, etc.

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PROCESS OVERVIEW

Pure iron is not readily available since it easily oxidises in the presence of air and moisture. The iron industry reduces iron oxides to obtain pure iron, i.e. *metallic iron*. Steel is an alloy based on iron and carbon, with carbon concentration ranging from 0.2% to 2.14% in weight. High carbon content results in higher hardness, tensile strength, and lower ductility. The resulting steel is also more brittle. Steel alloys can be enriched with other materials to tune the final material properties that also depend on production techniques and on the quality of the basic materials. ■ **Iron Ore classification** – The basic material for iron and steel production is iron ore or ferrous scrap. Iron ores are classified based on shape and volume. *Iron fines* have a majority of particles with a diameter of < 4.75 mm; *iron lump* ore has a majority of particles with a diameter of > 4.75 mm; *iron pellets* are a fine-grained concentrate rolled into balls (with a binder) and *indurated* in a furnace. Their diameter ranges from 9.5 to 16.0 mm. ■ **Iron and Steel production** – The iron and steel production process can be subdivided into 3 sub-processes: iron-making, steel-making and steel manufacturing. All processes can be summarized as in Figure 1 [2]. A more detailed scheme and material flow can be found in Figure 9. Conventional steel production takes place in integrated steel mills that often include facilities for coking and sintering. In the basic process, the input materials - a combination of sinter, iron pellets, limestone and cokes - enter a *blast furnace* (BF) to be converted into molten *pig iron*. The pig iron is then loaded into an oxygen furnace to produce steel slabs. Alternative processes are *direct reduction iron* (DRI) and smelting *reduction iron* (SRI). Ferrous scrap can also be processed in an electric arc furnace (EAF) to obtain steel. Today most used steel-making processes consist of a combination of a blast furnace and basic oxygen furnace. Some SRI processes can produce steel directly.
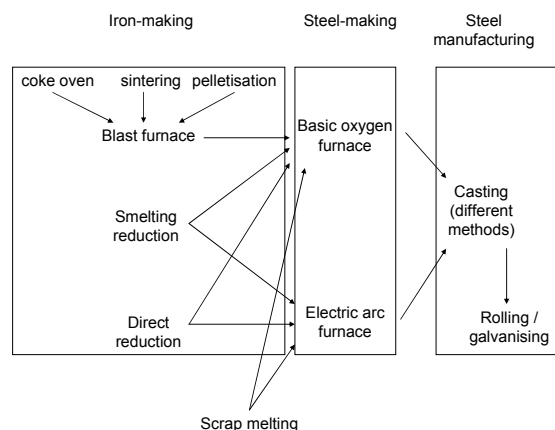

Fig. 1 - Iron and steel production technologies [2]

IRON PRODUCTION

■ **Blast Furnace (pig iron)** – Blast furnace (Figure 2) is a process for producing liquid raw iron by smelting pellets or sinter in a reducing environment. The end products are usually molten metal, slag and blast furnace gas. In the reduction process, oxygen (O_2) is taken out of the pellets or sinter. Coke is often used as a reducing agent, as well as fuel. Fuel (coke) and pellets or sinter are supplied continuously through the top of the furnace and O_2-enriched air is blown out the bottom by electrical air ventilators. The chemical reactions take place while the materials move downward. Coke also serves as a carrier to move the bulk material column downward in the blast furnace [5]. Various alternative reducing agents are available, such as hydrocarbons, coke, coal, oil, natural gas (nowadays in some cases, also plastics). In the past, a widely used reducing agent was charcoal, in particular charcoal from eucalyptus trees. Whatever the fuel and

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reducing agent, the content of the furnace needs to have optimum permeability to the flow of gaseous and molten products. Blast furnace gas contains CO (20-28%), H_2 (1–5%), inert compounds such as N_2 (50-55%) and CO_2, (17-25%), some sulphur and cyanide compounds, and large amounts of dust from impurities of coal and iron ore. The lower heating value of blast furnace gas ranges from approximately 2.7 to 4.0 MJ/Nm3. The production of blast furnace gas is approximately 1200 to 2000 Nm3/t pig iron [5]. Much effort is devoted to increasing efficiency and reducing emissions of the blast furnaces [1].

■ **Coking** – Coking or coal pyrolysis is the way coke is produced by heating coal in an oxidation free atmosphere. Flue gases at temperatures between 1150°C and 1350°C heat up coal indirectly to 1000-1100°C for 14-24 hours. At the end of the grate, coke is fully carbonised and it is quenched mostly by water, or by inert gas. Air cannot be used for this purpose, as the oxygen would cause the hot cokes to ignite spontaneously. Some 1000 kg of coal usually yields 750-800kg of coke and approximately 325 m³ COG (Coke Oven Gas) [6].

■ **Sintering and Pelletisation** – Sinter and pellets are produced by mixing together raw or recycled materials, which undergo a physical and metallurgic agglomeration process. The high permeability and the reducibility of sinter and pellets enhance the BF performance. In the sintering process, ores, additives, recycled sinter and coke breeze are blended in a mixing drum. This mixture is then loaded onto a moving grate and ignited. As the mixture proceeds along with the grate, air is drawn downwards through the sintering bed by powerful fans causing the combustion front to move downwards through the mixture. The sinter is cooled in a separate cooler, after which it is crushed. Pelletisation is a process to convert iron ore into small balls (9–16 mm) while upgrading its iron content. While sintering is mostly used in integrated steelworks, pelletisation is mostly used at mining sites. The process of forming pellets can be divided into four steps: Grinding and Drying; Green ball preparation; Induration; and Screening and Handling. In the first step, wet or dry ores are ground (grated) and the resulting slurry is mixed with additives to prepare the green balls. Induration involves green balls drying, heating and final cooling. During this process, almost all magnetite is transformed into hematite. This explains the large amount of heat needed for the process (magnetite ore has a low iron content and must be upgraded to make it suitable for steelmaking). In the last screening/handling step, undersized or broken pellets are recycled.

■ **Direct Reduction (direct reduced iron, DRI)** – Direct reduction is the name of a broad group of processes based on different feedstocks, furnaces, reducing agents, etc. The common principle is the removal of oxygen (reduction) from iron ores in the solid state. Natural gas (and in some cases coal) is used as a reducing agent to enable this process. In 2000, some 92.6% of DRI was based on natural gas processed in shaft furnaces, retorts and fluidized bed reactors. The metallization rate of the end product ranges from 85% to 95 % (often even higher). DRI is prone to combustion and is therefore sometimes called hot briquetted iron (HBI). The concept
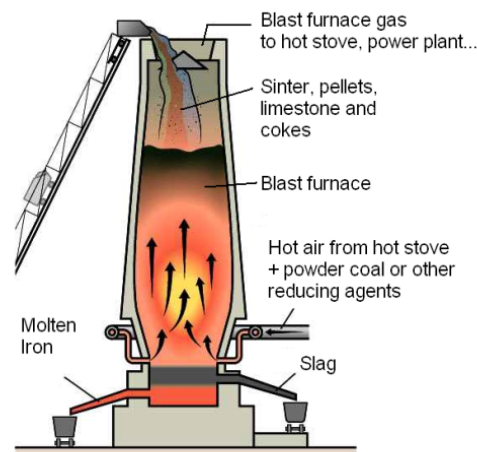

Fig. 2 - Simplified scheme of a blast furnace [10]

of direct reduction dates from the 1950s, with the first plant operated in 1952 [2]. As shown in Figure 3, DRI production has been steadily growing since 1970, with a fallback in 2008 and 2009 due to the ongoing financial crisis [8]. In 2008, the global DRI production amounted to 68.5 Mt and was based primarily on MIDREX technology (58.2%), on HYL/Energiron (14.5%), and on other gas-based (1.6%) and coal-based (25.7%) technologies. Gojic and Kozuh [3, 4, 5] have identified 30 different DRI processes of which MIDREX (Figure 4) is the world's leading technology. The MIDREX process often consists of four stages: 1) Reduction gas; 2) Reforming; 3) Heat recovery; and 4) Briquette making. A mixture of pellets or lump ore, possibly including up to 10% of fine ore, enters the furnace shaft. As ore descends, oxygen is removed by counter-flowing reduction gas, which is enriched in hydrogen and carbon monoxide. Further information on different DRI processes can be found in [3] and [6]. In total, some 166 DRI facilities were in operation in 2008. Based on Figure 5, the concentration of DRI plants is higher in emerging countries that do not have a significant number of blast furnaces. Some 25% of DRI facilities are in Asia and Oceania, 18% in the Middle East and North Africa, 18% in Latin America, 4.6% in the former Soviet Union and Eastern Europe, 1.2% in Sub-Saharan Africa, and 1.4% in North America and West Europe [8].
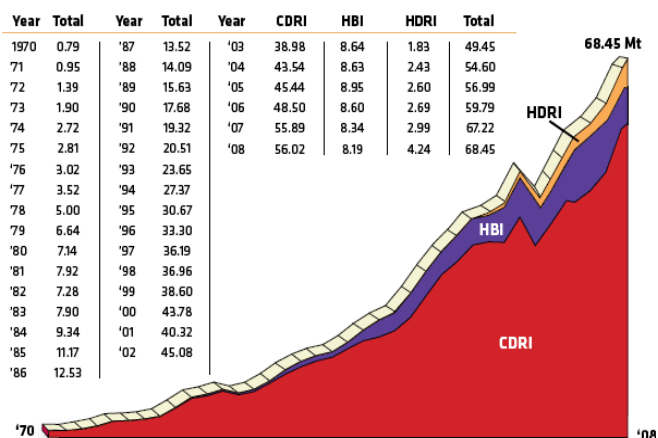
Year	Total	Year	Total	Year	CDRI	HBI	HDRI	Total
1970	0.79	'87	13.52	'03	38.98	8.64	1.83	49.45
71	0.95	'88	14.09	'04	43.54	8.63	2.43	54.60
72	1.39	'89	15.63	'05	45.44	8.95	2.60	56.99
73	1.90	'90	17.68	'06	48.50	8.60	2.69	59.79
74	2.72	'91	19.32	'07	55.89	8.34	2.99	67.22
75	2.81	'92	20.51	'08	56.02	8.19	4.24	68.45
'76	3.02	'93	23.65					
'77	3.52	'94	27.37					
78	5.00	'95	30.67					
79	6.64	'96	33.30					
'80	7.14	'97	36.19					
'81	7.92	'98	36.96					
'82	7.28	'99	38.60					
'83	7.90	'00	43.78					
'84	9.34	'01	40.32					
'85	11.17	'02	45.08					
'86	12.53							

Fig. 3 – Global DRI production over time (mill. tonnes) [8]

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■ **Smelting Reduction (smelting reduced iron, SRI)** – Smelting reduction iron is a recent alternative to DRI and to the BFs. The final product obtained is liquid pig iron or, in some cases, liquid steel. SRI (Figure 6) is a common name for a number of processes, some of which have been commercially proven while others are still under demonstration. The basic principle is akin to that of a blast furnace, but using coal instead of cokes.

Iron ore first undergoes a solid-state reduction in the pre-reduction unit. The resulting product – very similar to DRI - is then smelted and further reduced in the smelting reduction vessel where coal is gasified, thus delivering heat and CO-rich hot gas. Coal gasification takes place due to the reaction with oxygen and iron ore in liquid state. The heat is used to smelt iron and the hot gas is transported to the pre-reduction unit to reduce the iron oxides that enter the process. Reduced iron-oxides (now similar to DRI) are in turn transported to the smelting reduction vessel for final reduction and smelting. The CO-rich gas generated in the smelting reduction vessel can be further oxidized to generate additional heat in order to smelt the iron. This process is called post-combustion and thus leads to a trade-off in the utilization of the gas between increased pre-reduction potential or increased heat delivery for smelting [2, 4].

The key parameters of a smelting reduction process are the *post-combustion degree*, the *pre-reduction degree* and the *heat transfer efficiency*. The *post-combustion degree* is the degree to which the CO formed in the smelting reduction vessel by coal gasification is converted into CO_2. A too high degree of post-combustion results in a gas too lean for pre-reduction and off-gas that is too hot. A too low degree of *post-combustion* results in a gas too rich and increased coal consumption. The *pre-reduction degree* is the degree to which the iron oxides are reduced in the pre-reduction shaft. The *heat transfer efficiency* is the ratio of the heat transferred from hot gases to the bath of molten iron, ore and slag to the heat generated by post-combustion. Low heat transfer results in off-gases that are too hot. Based on these parameters, smelting reduction is subdivided into first- and second-generation processes. First generation is characterized by high pre-reduction rates (up to 90%) and second generation by high post-combustion rates, with reduction in the molten bath of iron and pre-reduced iron. [4] Commercial utilization of smelting reduction is still dominated by first generation processes, notably the COREX process (Figure 7), developed in Germany and Austria.

Further information on these technologies is available in [3, 6]. The first SRI plant started operation in 1989 based on the COREX process [5]. The use of SRI technology is still limited.

STEEL PRODUCTION

■ **Basic Oxygen Furnace** – [11] The basic oxygen furnace (also called LD converter, from the Linz-Donawitz process, 1956) is based on an oxygen injection into the melt of the hot metal. The oxygen burns out the carbon as carbon monoxide CO and carbon dioxide CO_2 gas
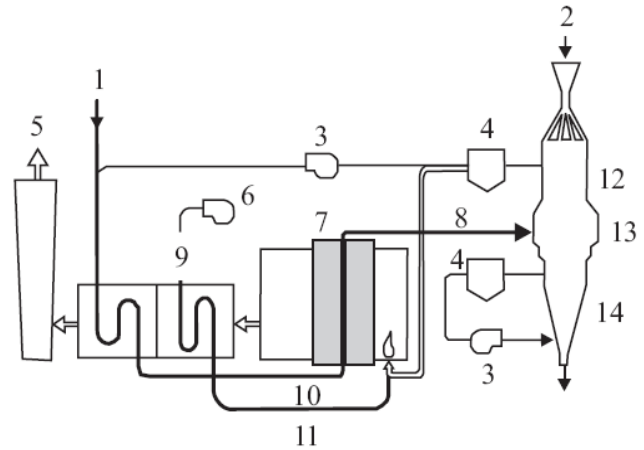

Fig. 4 - MIDREX Process: 1) natural gas; 2) iron ore; 3) compressor; 4) scrubber; 5) off-gas; 6) air blower; 7) gas reformer; 8) reducing gas; 9) heat recovery; 10) reformer gas; 11) combustion air; 12) reduction zone; 13) shaft furnace; 14) cooling zone; [3]

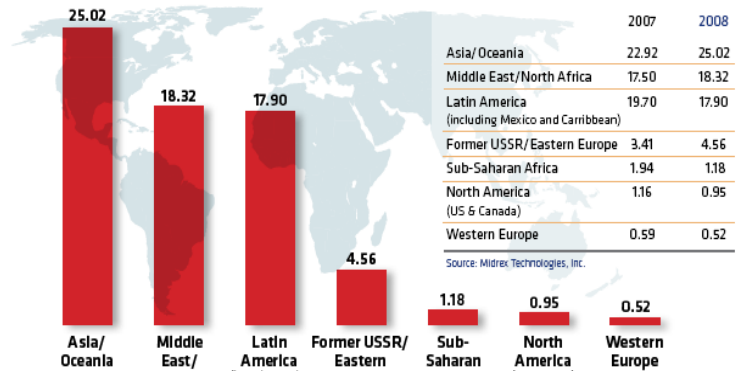|	2007	2008
Asia/Oceania	22.92	25.02
Middle East/North Africa	17.50	18.32
Latin America (including Mexico and Carribbean)	19.70	17.90
Former USSR/Eastern Europe	3.41	4.56
Sub-Saharan Africa	1.94	1.18
North America (US & Canada)	1.16	0.95
Western Europe	0.59	0.52

Source: Midrex Technologies, Inc.

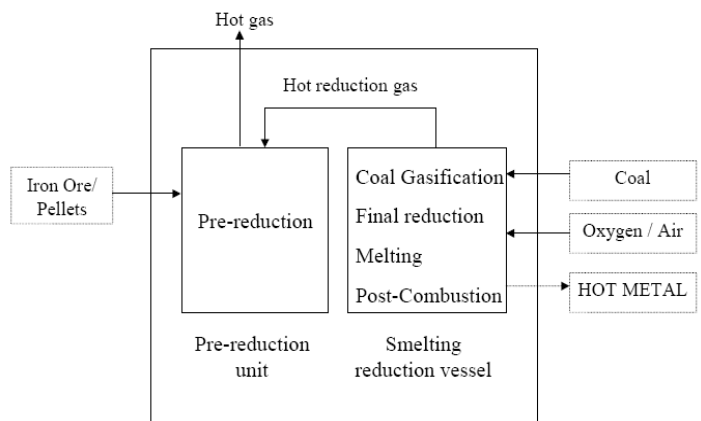Fig. 5 - 2008 DRI production by region (mill. tons) [8]

Fig. 6 - Smelting reduction technology [2]

which is collected in the chimney stack and dust-cleaned. As the oxidation reactions are highly exothermic, the process needs cooling in order to control the temperature of the melt. This cooling is done by charging scrap (recycled and mill scrap) and by adding iron ore during the blowing process. Scrap and lime are charged into the converter to also remove phosphorus, silicon and manganese. The converter is lined with dolomite or magnesite refractory which best resist erosion by slag

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and heat during oxygen blowing. The life of a converter lining is about 800 to 1400 cycles. The process provides a high productivity of steel with low levels of impurities. Inert gas (e.g. argon) is injected into the bottom of the converter to stir melt and slag. This increases productivity and metallurgical efficiency by lowering iron losses and phosphorus content. The amount of O_2 consumed depends on the hot metal composition (C, Si, P, etc.).

■ **Electric Arc Furnace (EAF)** – EAFs were first used to convert ferrous scrap into steel. Scrap is first pre-heated by EAF off-gases (energy recovery) and then charged into the EAF together with lime or dolomitic lime. Lime is used as a flux for the slag formation (dolomitic lime contains calcium and magnesium whereas normal lime contains more calcium). Charging the EAF is a gradual process. At about 50%–60% load, the electrodes are lowered to the scrap and an arc is struck. This melts the first load before further loading. When fully loaded, the entire content of the EAF is melted. To achieve this result, oxygen lances and/or oxy-fuel burners can be used in the initial stages of melting. The ferrous scrap used in the EAF includes scrap from steelworks and steel manufacturers and consumer scrap. DRI is increasingly used as a feedstock in the EAF as it contains a small amount of gangue. [5]

INVESTMENT AND PRODUCTION COSTS

All costs are given in US dollars (US$2000). ■ **Blast Furnace** – The overnight investment cost of a blast furnace ranges between $148 and $275 per ton of hot metal per year ($/t-yr) [6]. The variable operation and maintenance (O&M) cost is around $90/t-yr of hot metal [6] ■ **Direct Reduction (DRI)** – The investment costs of Midrex and Hylsa direct reduction technologies are about $142-145/t-yr. The economical lifetime is estimated at 20 years. The O&M cost for both technologies is around $13/t-yr of DRI. Not included in this cost are pellets, fuel (natural gas) and electricity. [6] ■ **Smelting Reduction (SRI)** – The investment costs for the Tecnored smelting reduction process (with/out cogeneration) are $122/t-yr and $98/t-yr ($ per ton of hot metal per year), respectively. The investment cost of the Hismelt smelting reduction process is $320/t-yr. For both processes, the economical lifetime is estimated at about 20 years and variable O&M costs range between $13/t-yr and $19/t-yr. For the Tecnored technology this excludes coke, pellets, lime, natural gas and electricity consumption. For Hismelt, this excludes iron ore fines, coal fines, oxygen gas, flux (lime), natural gas and electricity. [6]. ■ **Electric Arc Furnace** – The EAF investment cost is about $80/t of steel per year. The O&M costs are about $32/t-yr and do not include steel scrap, lime, O_2 gas, natural gas (auxiliary fuel) and electrical power. [6]

IMPROVING EFFICIENCY AND REDUCING EMISSIONS IN IRON AND STEEL PRODUCTION

■ **Blast Furnace (pig iron)** – According to conservative estimates, scrap pre-heating in the BF process could increase the yield from today's rate of about 20% up to about 30%. Also, recirculating basic oxygen slag to the BF would result in a reduced demand for limestone and
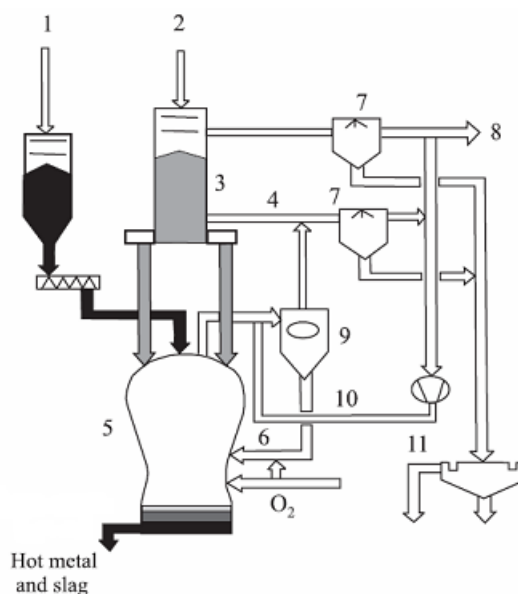

Fig. 7 - COREX process: 1) non-coking coal; 2) ore; 3) reduction shaft; 4) reduction gas; 5) melter gasifier; 6) dust; 7) scrubber; 8) export gas; 9) hot gas cyclone; 10) cooling gas; 11) settling pond.

thereby reduced CO_2 emissions. An alternative option could be the use of the slag for other applications, e.g. cement production. ■ **Oxygen Blast Furnace (pig iron)** – The efficiency of a blast furnace can also be increased by using pure oxygen instead of oxygen-enriched air, and by recycling part of the blast furnace gas (i.e. Top Gas Recycling) [1]. Top gas recycling minimises the need for reducing agents (e.g. coke) and therefore enables emissions reduction. In combination with the CO_2 capture and storage (see below), this technology can minimise the carbon emissions from blast furnaces. ■ **Plasma Blast Furnaces (pig iron)** – Plasma-heated blast furnaces require neither hot blast nor oxygen and additional auxiliary reductants [14]. In this process, part of the top gas flow is fed to a plasma burner and heated to a temperature of about 3400°C. The CO_2 content of the top gas is transformed into CO by an endothermic reaction with carbon from coke. This results in a calculated flame temperature of 2150°C. Another portion of the top gas undergoes CO_2 removal in a scrubber, as in the case of the nitrogen-free blast furnace, before being externally heated at about 900°C and injected into the lower part of the blast furnace shaft via a second tuyere row.

■ **Electric Arc Furnace (steel)** – The CO_2 emissions from the EAF process are 0.058 tons per ton of EAF iron. Dust emissions are 1-780 g/ton of EAF iron. The SO_2 emissions ranges from 24 to 130 g/ton of EAF iron depending on basic input materials and conditions. The NOx emissions range from 120 to 240 g/ton of EAF iron [5, 6]

■ **Direct Reduction** – The CO_2 emissions from DRI Midrex and Hylsa processes are 0.65 and 0.53 tons CO_2 per ton DRI [6]. The use of DRI is appropriate if the availability of good quality scrap is not sufficient enough to get good quality steel, if the regional demand is insufficient to run a blast furnace, or if the BF hot metal output needs to be increased [5]. When using the DRI

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process, the quality of the end product depends highly on the quality of the input ores since pollutants cannot be removed in solid state. [2]

■ **Smelting Reduction (pig iron or steel)** – The CO_2 emissions for the Tecnored and Hismelt processes are 1.79 and 1.57 tons CO_2 per ton of hot metal [6]. Smelting reduction has advantages and disadvantages. Some SR processes cannot use fine iron ore. On the other hand, SR processes are more flexible as far as the quality of used coal is concerned, and no coking is necessary. Power consumption in SR is nominally higher than in the BFs but off-gas can be used as an energy source. Hence, specific process and operation can have a significant impact on the overall efficiency. Future developments will probably improve energy efficiency by 5% to 30% in comparison with BFs [2, 5]. SR processes are also expected to reduce pollutants emissions. By avoiding coking, dust and VOC emissions are reduced. If sintering is omitted, the emission of metallic and non-metallic dust and gaseous pollutants is also reduced. However, first of a kind SR processes do not yet report these reduced emissions and the potential for future reductions is a matter of debate [2]

■ **Carbon Capture and Storage (CCS) in Iron and Steel Production** – Two main options exist for capturing CO_2 from the blast furnaces. The first consists of using a shift reaction and the physical absorption capture. Blast furnace gas is upgraded to a reducing feedstock (CO) to be used in the blast furnace itself. This reduces coal and coke consumption, and the emissions as well, while

physical absorption is used to capture the remaining CO_2. The second option (see Figure 8) is based on the use of an oxy-fuelled blast furnace where pure oxygen is used as a feedstock [13], re-cycling blast furnace gas and capturing emissions from the top gas. The recycling stream can be split into two different flows - a cold stream, injected into the bottom of the BF and a hot stream to be injected higher. It improves the process at the reaction level. CCS processes are also under consideration for direct reduction and smelting reduction processes. By combining it with oxygen injection, CCS could result in a 85% to 95% reduction in CO_2 emissions.[1]
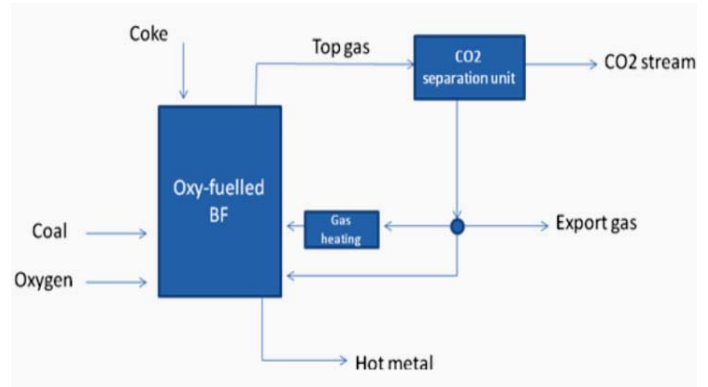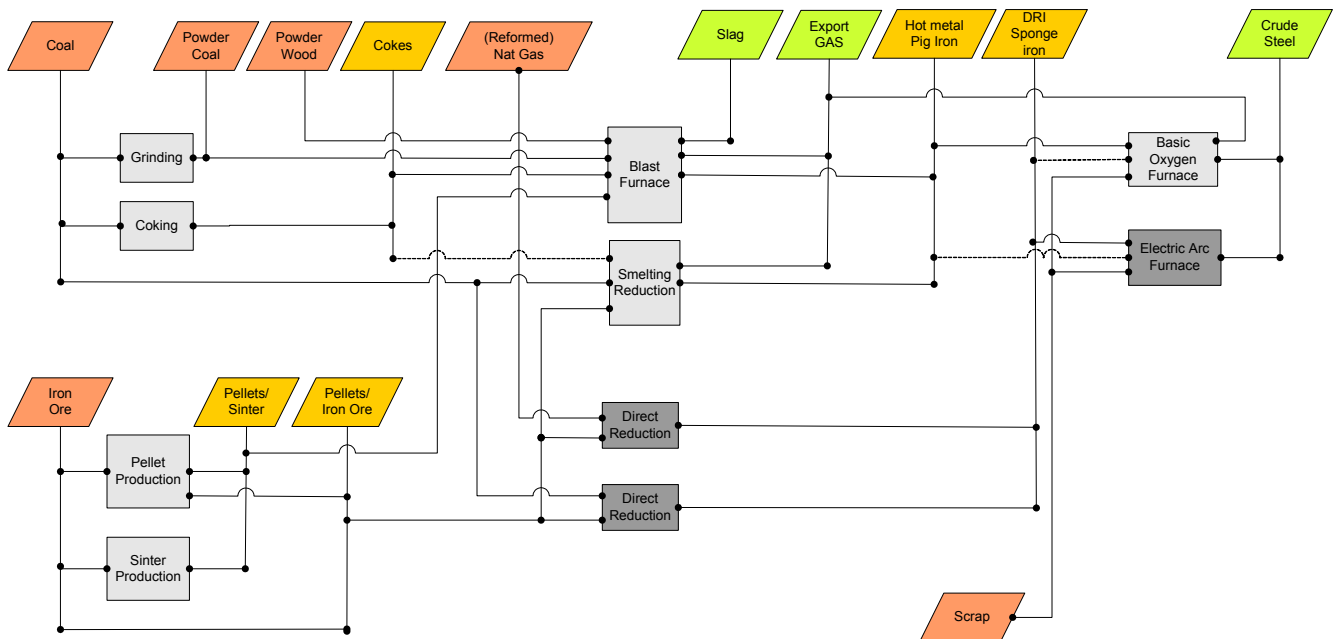

Fig. 8 - Oxy-fuelled BF with CCS

Fig. 9 - Material flows for the production of iron and steel

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Table 1 – Summary Table: Key Iron and Steel Data and Figures

Technical Performance				
Energy input	Natural gas, Coal			
Output	Hot and cold Direct reduced iron, Hot Briquetted iron, Hot metal, Steel,…			
Environmental Impact	**Blast Furnace PCI**	**Blast Furnace - TGR- with CCS**	**COREX**	**COREX with CCS**
CO_2 from material inputs (mt/mt metal, integrated numbers only with a model)	1.5	1.1	2.9	2.9
Costs				
Overnight Capital cost, (€$_{2010}$/mt/year)	273	500	200	400
Variable O&M cost (€$_{2010}$/mt)	2	5	2	5
Fixed O&M cost (€$_{2010}$/mt)	10	15	10	15
Materials (all per mt hot metal)				
Input Hard Coal (PJ)	6.20	5.58	27.00	27.00
Input Coke (PJ)	9.30	6.27	3.1	3.10
Input Pellet (mt)	0.155	0.04	0.75	0.75
Input Sinter (mt)	1.34	1.58	0.75	0.75
Input Electricity (PJ)	0.5	1.25	0.324	1.075
Input Oxygen (mt)	0.05	0.3	0.69	0.69
Output Blast Furnace Slag (mt)	0.25	0.25	0.35	0.35
Output Blast Furnace or COREX gas (PJ)	3.25	0.378	10.90	10.90
Sinked CO_2 (t)		0.796		0.763

Environmental Impact	Midrex	Hylsa	Tecnored		Hismelt	EAF
CO2 mt/mt DRI or EAF iron	0.65	0.53	1.79		1.57	0.058
NOx (g/ton EAF iron)						120-240
SO2 (g/ton EAF iron)						24-130
Dust (g/ton EAF iron)						1-780
Costs	**Midrex**	**Hylsa**	**Tecnored no cogen**	**Technored cogen**	**Hismelt**	**EAF**
Overnight Capital cost, ($_{2000}$/mt/year)	145.23	142.64	97.68	122.16	319.45	80.96
Variable O&M cost ($_{2000}$/mt) (are excluded modelled material costs)	12.93	12.93	13.29	13.29	18.55	31.78
Materials						
Input pellets (ton in/ton out)	1.7	1.7	1.78	1.78		
Input fuel (natural gas) (ton in/ton out)	0.24	0.20	0.18	0.18	46.7 Nm³/ton	0.002
Input electrical power (kWh/ton out)	135.4	104.2	70	Output 1055	174.8	697.7
Input coke (ton in/ton out)			0.42	0.42		
Input burnt lime (ton in /ton out)			0.006	0.006		0.012
Input iron ore fines (ton in/ton out)					1.49	
Input coal fines (ton in/ton out)					0.57	
Input oxygen gas (Nm³/ton out)					171.42	10.43
Input flux lime (ton in /ton out)					0.17	

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