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# CO<sub>2</sub> abatement in the iron and steel industry

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## **Abstract**

The iron and steel industry is the largest industrial source of CO<sub>2</sub> emissions due to the energy intensity of steel production, its reliance on carbon-based fuels and reductants, and the large volume of steel produced – over 1414 Mt in 2010. With the growing concern over climate change, steel makers are faced with the challenge of finding ways of lowering CO<sub>2</sub> emissions without seriously undermining process efficiency or considerably adding to costs. This report examines ways of abating CO<sub>2</sub> emissions from raw materials preparation (coking, sintering and pelletising plants) through to the production of liquid steel in basic oxygen furnaces and electric arc furnaces. Direct reduction and smelting reduction processes are covered, as well as iron making in a blast furnace. A range of technologies and measures exist for lowering CO<sub>2</sub> emissions including minimising energy consumption and improving energy efficiency, changing to a fuel and/or reducing agent with a lower CO<sub>2</sub> emission factor (such as wood charcoal), and capturing the CO<sub>2</sub> and storing it underground. Significant CO<sub>2</sub> reductions can be achieved by combining a number of the available technologies. If carbon capture and storage is fitted than steel plants could become near zero emitters of CO<sub>2</sub>.

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## Acronyms and abbreviations

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AISI	American Iron and Steel Institute
APPCDC	Asia Pacific Partnership for Clean Development and Climate
BAT	best available technology
BAU	business as usual
BF	blast furnace
BFB	bubbling fluidised bed
BFG	blast furnace gas
BOF	basic oxygen furnace
CCS	carbon capture and storage
CDM	clean development mechanism
CDQ	coke dry quenching
CFB	circulating fluidised bed
CHP	combined heat and power
CIS	Commonwealth of Independent States (Armenia, Azerbaijan, Belarus, Georgia (until Aug 2009), Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Uzbekistan, Ukraine)
COG	coke oven gas
CV	calorific value
DRI	direct reduced iron
EAF	electric arc furnace
EU	European Union
FB	fluidised bed
GHG	greenhouse gas
HBI	hot briquetted iron
HRC	hot rolled coil
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCA	life cycle assessment
LBNL	Lawrence Berkeley National Laboratory
MDEA	methyldiethanolamine
MEA	monoethanolamine
Mtoe	million tonnes (10 <sup>6</sup> ) of oil equivalent
OHF	open-hearth furnace
PCI	pulverised coal injection
PSA	pressure swing adsorption
RHF	rotary hearth furnace
SRV	smelting reduction vessel
tce	tonnes of coal equivalent
tcs	tonnes of crude steel
TGR	top gas recycling
thm	tonne of hot metal
tls	tonne of liquid steel
toe	tonne of oil equivalent
ULCOS	ultra-low CO <sub>2</sub> steelmaking
UNFCCC	United Nations Framework Convention on Climate Change
VPSA	vacuum pressure swing adsorption

**Conversions:** 1 EJ = 1018 J or 23.9 Mtoe (1 J = 2.39 toe); 1 EJ = 34.12 Mtce (1 J = 3.41 tce and 1 tce = 2.93 EJ)

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# I Introduction

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Steel is basically an alloy consisting of iron, 0.02 to 2 wt% carbon, and small amounts of alloying elements, such as manganese, molybdenum, chromium or nickel. It has a wide range of properties that are largely determined by its chemical composition (carbon and other alloying elements). This has enabled steel to become one of the major structural materials in the world, being widely used in the construction, transport and manufacturing industries, and in a variety of consumer products. World steel production has been increasing steadily, from 595 Mt/y in 1970 to 1414 Mt/y in 2010 (World Steel Association, 2011). Growth has accelerated since 2000, nearly doubling by 2010, with most of the demand in the emerging economies. China alone produced 626.7 Mt in 2010, almost five times its production in 2000 (128.5 Mt). World production is predicted to continue to grow in the future, particularly in China and India.

Manufacturing steel is an energy- and carbon-intensive process and therefore a major contributor to global anthropogenic CO<sub>2</sub> emissions. The iron and steel industry is the second largest industrial user of energy, consuming 616 Mtoe (25.8 EJ) in 2007 (IEA, 2010b), and is the largest industrial source of direct CO<sub>2</sub> emissions (2.3 Gt in 2007). Overall, iron and steel production accounts for around 20% of the world manufacturing industry's final energy use and around 30% of its direct CO<sub>2</sub> emissions (IEA, 2008a). Total CO<sub>2</sub> emissions from the global iron and steel industry were estimated to be 1.5–1.6 Gt, or about 6–7% of global anthropogenic emissions by Kim and Worrell (2002). According to the International Energy Agency (IEA), the steel industry accounted for 4–5% of global greenhouse gas (GHG) emissions in 2005. CO<sub>2</sub> emissions per tonne of steel vary widely between countries. The differences are due to the production routes used, product mix, production energy efficiency, fuel mix, carbon intensity of the fuel mix, and electricity carbon intensity. On average around 1.8 t of CO<sub>2</sub> is emitted for every t of steel cast (World Steel Association, 2011).

There is a growing consensus that action must be taken to reduce GHG emissions and lessen the impact of climate change. The Kyoto Protocol has set binding targets for 37 industrialised countries and the European Union (Annex I countries) for reducing GHG emissions by 5% against 1990 levels over 2008–12. Negotiations are ongoing to replace the Kyoto Protocol when it expires in 2012. The European Union is committed to cutting GHG emissions by 20% from 1990 levels by 2020. It has introduced an Emissions Trading Scheme, which started on 1 January 2005, and covers the steel industry. Most of the steel plants in member countries have been allocated a certain amount of CO<sub>2</sub> emissions rights, which will be decreased in the future. It is therefore important for each plant to determine the optimal solutions to reduce their CO<sub>2</sub> emissions and thereby lower costs. Other countries have introduced, or are considering, emissions trading schemes or other CO<sub>2</sub> abatement measures. Australia has recently announced that it will introduce a carbon tax on Australian businesses from July 2012, to be replaced in July 2015 with a carbon emissions trading scheme. The steel industry in Japan, the USA and elsewhere have already signed up to voluntary agreements to reduce their CO<sub>2</sub> emissions.

This report will examine ways of abating CO<sub>2</sub> emissions from iron and steel production. It begins by discussing global CO<sub>2</sub> emissions from manufacturing industry as a whole in order to set emissions from the iron and steel industry in context. Minimising energy consumption and improving energy efficiency offer the greatest scope for cutting CO<sub>2</sub> emissions in the short term, as well as lowering costs. Therefore the chapter examines energy use and potential energy savings by industry overall, before discussing energy consumption in the iron and steel industry. The principal measures for improving energy efficiency include enhancing continuous processes to reduce heat loss, increasing the recovery of waste energy and process gases, and efficient design.

The production of steel can be divided into the following processes:

- raw material preparation, that is, cokemaking and iron ore preparation;

- iron making, where the iron ore is reduced by a carbon-based agent to produce hot metal or direct reduced iron (DRI), a solid product;
- steel making, where the hot metal and DRI are converted into liquid steel;
- manufacturing steel products, where the steel is cast, reheated, rolled and finished. This is outside the scope of this report.

Measures and best available technologies (BATs) for lowering energy use and CO<sub>2</sub> emissions in cokemaking and iron ore preparation are described in Chapter 3. CO<sub>2</sub> abatement from the different iron production routes, namely blast furnaces (BFs), direct reduction processes (which produce DRI) and the smelting reduction processes (which eliminate the need for coking and iron ore sinter plants) are covered in the following three chapters.

The hot metal product from BFs and smelting reduction processes, and DRI contain unwanted elements. These are removed in the basic oxygen furnace (BOF) or electric arc furnace (EAF), producing liquid steel. CO<sub>2</sub> abatement measures and technologies for BOFs and EAFs are covered in Chapters 7 and 8, respectively. Recycling wastes generated within and outside the steelworks can help reduce overall CO<sub>2</sub> emissions per tonne of steel produced. Thus increasing the recycling rate of steel scrap will lower CO<sub>2</sub> emissions. There is still room to increase scrap recycling rates as only around 40% of the steel produced globally is recycled steel. Steel scrap is typically processed in EAFs.

Over the years the iron and steel industry has made significant efforts to reduce energy consumption and lower CO<sub>2</sub> emissions by improving energy efficiency, reducing coke and coal consumption, utilisation of by-product fuels, increasing the use of biomass and renewable energy, and other techniques. Making a tonne of steel now uses half the amount of energy than in the 1970s. But the scope for further reduction by these means is limited in state-of-the-art facilities. Further significant reductions will depend on the development of carbon capture and storage (CCS) technologies, the subject of Chapter 9. One of the largest source of CO<sub>2</sub> emissions is from the use of carbon-based agents to reduce the iron ore to iron. New technologies, currently at the research stage, that avoid carbon-based reductants are reviewed in Chapter 10.

The production of steel is a complex process incorporating a variety of process technologies with different plant layouts. These processes interact with one another and a change in one process can affect other upstream or downstream processes. A systematic study of the steelworks as a whole should first be carried out to assess the energy balance and CO<sub>2</sub> emissions before any abatement measures are introduced. This includes an energy audit to identify points of energy loss and how to minimise them. The effect of the proposed measures on the whole steelworks then needs to be assessed to determine any adverse outcomes before the change is implemented. Not all of the BATs are necessarily suitable for all installations or can be retrofitted, and the cost-effectiveness of the technologies will vary from plant to plant. Since costs are site-specific, economic factors are only covered in general terms.

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## 2 CO<sub>2</sub> emissions and energy use

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Global greenhouse gas (GHG) emissions due to human activities have grown since pre-industrial times, increasing by 70% between 1970 and 2004, with the fastest growth occurring in the last ten years. CO<sub>2</sub> is the most important of the anthropogenic greenhouse gases. In 2004, 49 Gt of CO<sub>2</sub> equivalent (CO<sub>2</sub>-e) emissions were released, of which 77% was CO<sub>2</sub> (Pachauri and Reisinger, 2008). About 69% of all CO<sub>2</sub> emissions and 60% of all GHG emissions are energy related (IEA, 2008b). World CO<sub>2</sub> emissions from energy use have more than doubled since 1971, from 14.1 Gt in 1971 to 29.4 Gt in 2008 (IEA, 2010a); they were 26.3 Gt in 2004. From 1990 to 2000, the average annual increase in CO<sub>2</sub> emissions from fuel use was 1.1%. Between 2000 and 2005, growth accelerated to 2.9% per year, despite the increased focus on climatic change. High economic growth, notably in coal-based economies, and higher oil and gas prices (which have led to an increase in coal-based power generation) are the main reasons for the increase. Emissions from coal use increased by 1%/y between 1990 and 2000, but they rose by 4.4%/y between 2000 and 2005 (IEA, 2008a). In 2005, the USA was the largest emitter of CO<sub>2</sub>, followed by China and then Russia. In 2007 this changed, with China overtaking the USA to become the world's leading producer of CO<sub>2</sub>.

The largest source of CO<sub>2</sub> emissions is the electricity and heat generation sector, followed by transport and then industry. These three sectors account for the majority of CO<sub>2</sub> emitted, with direct emissions from industry currently accounting for about 20% of the world's energy-related CO<sub>2</sub> emissions. Over the years the share from industry has generally decreased, whilst the share from the other two sectors has increased. With world demand for electricity expected to continue to grow, the power sector is likely to remain the predominant source of CO<sub>2</sub> emissions. This chapter discusses the contribution of manufacturing industries to global CO<sub>2</sub> emissions in order to set emissions from the iron and steel industry in context. Improving energy efficiency offers the greatest scope for cutting CO<sub>2</sub> emissions. Therefore energy use and potential energy savings by industry are described. Energy consumption and CO<sub>2</sub> emissions from the iron and steel industry are then examined.

Statistics quoted in the literature concerning the energy consumption and CO<sub>2</sub> emissions from the different industrial sub-sectors differ. One reason for this is the different definition of the system boundaries employed. For instance, electricity generated on-site from process offgases may be allocated to the relevant industrial sub-sector or to the energy sector. Direct emissions may or may not include the process emissions. For consistency, the following discussion on the industrial energy consumption and CO<sub>2</sub> emissions uses data principally from IEA publications.

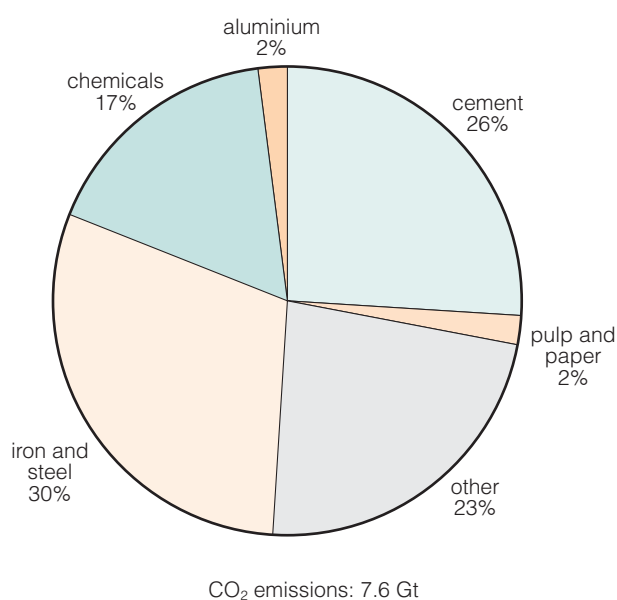
### 2.1 Industrial CO<sub>2</sub> emissions

CO<sub>2</sub> is emitted at a variety of points in industrial production processes, including:

- direct emissions from on-site combustion of fossil fuels;
- process-related (that is, non-energy) emissions. These emissions are often included with the direct emissions; and
- indirect emissions from electricity consumed during the production process.

According to the International Energy Agency (IEA, 2008a,b), total CO<sub>2</sub> emissions from industry were 9.86 Gt in 2005, equivalent to ~37% of total global CO<sub>2</sub> emissions from fossil fuel combustion (which were 27.1 Gt). Direct and process emissions were 6.66 Gt (of which 1.05 Gt were process emissions), about 25% of worldwide CO<sub>2</sub> emissions. Of the 9.86 Gt, the iron and steel sector accounted for 27% or 2.66 Gt, equivalent to 10% of world CO<sub>2</sub> emissions from energy use (IEA, 2008b). Using the Intergovernmental Panel on Climate Change (IPCC) figure of 49 Gt of GHG (CO<sub>2</sub>-e) emitted in 2004, then the iron and steel industry was responsible for around 5% of the world's GHG emissions.

	Brazil	Canada	China	France	Germany	India	Italy
<b>Chemical and petrochemical</b>	18	18	183	24	26	39	13
of which: process emissions	4	13	30	8	12	22	4
<b>Iron and steel</b>	47	18	835	26	53	120	26
of which: process emissions	4	1	41	2	4	4	2
<b>Non-metallic minerals</b>	25	10	791	18	27	111	40
of which: process emissions	15	7	384	9	12	63	18
<b>Paper, pulp and print</b>	4	7	40	4	7	6	5
<b>Food and tobacco</b>	4	0	57	8	8	25	7
<b>Non-ferrous metals</b>	8	3	42	1	3	3	1
<b>Machinery</b>	0	0	55	3	6	2	8
<b>Textile and leather</b>	1	0	46	3	1	5	4
<b>Mining and quarrying</b>	7	20	20	0	1	3	0
<b>Construction</b>	0	4	28	4	2	0	0
<b>Transport equipment</b>	0	0	19	2	3	0	0
<b>Wood and wood products</b>	0	2	9	0	1	0	0
<b>Non-specified</b>	6	21	38	2	3	34	3
<b>Total</b>	121	102	2163	97	142	348	106
of which: process emissions	19	8	425	11	16	67	21



**Figure 1 Industrial direct CO<sub>2</sub> emissions by sector in 2007 (IEA, 2010b)**

iron and steel sector (as they are in all the IEA statistics quoted in this chapter). The iron and steel industry is the largest producer of CO<sub>2</sub> (30%), followed by non-metallic minerals (mainly cement production), and chemicals. These three sectors account for over 70% of industrial CO<sub>2</sub> emissions.

By 2007, total industrial CO<sub>2</sub> emissions rose to 11.5 Gt, equivalent to about 40% of total worldwide CO<sub>2</sub> emissions from fossil fuel use (which was 29 Gt). Direct CO<sub>2</sub> emissions amounted to 7.6 Gt (IEA, 2010b). The iron and steel industry was still the largest industrial source of direct CO<sub>2</sub> emissions (2.3 Gt), accounting for around 8% of the world's CO<sub>2</sub> emissions. This is lower than in 2005, due to the global recession.

Figure 1 provides a breakdown of industrial direct CO<sub>2</sub> emissions by sector for 2007. Upstream CO<sub>2</sub> emissions from the production of electricity (which are allocated to the electricity sector in IEA statistics) and downstream emissions from the incineration of synthetic organic products are excluded from the data, as are emissions from petroleum refineries. Emissions from coke ovens and blast furnaces are included in the



Table 1 continued						
Japan	Mexico	Russia	South Africa	UK	USA	World
70	14	75	8	13	209	1086
14	7	51	6	4	64	439
178	15	124	25	20	91	1992
11	1	7	1	1	7	111
56	21	45	12	11	115	1770
32	16	20	6	5	47	940
13	2	1	0	3	66	189
9	3	4	0	6	60	243
2	0	0	0	1	15	110
7	0	2	0	3	27	129
0	0	0	0	2	10	96
1	3	7	8	1	0	98
12	1	3	1	1	5	96
0	0	2	0	2	14	49
0	0	1	0	0	11	27
42	14	3	10	19	37	775
390	73	269	64	81	659	6660
43	17	26	7	6	54	1051

A breakdown of direct CO<sub>2</sub> emissions from each of the industrial sectors by world regions and from the G8 countries and five leading emerging countries (Brazil, China, India, Mexico and South Africa) for 2005 is included in the IEA publication, *Energy technology perspectives 2008* (IEA, 2008a). Of these countries, the largest industrial emitter of CO<sub>2</sub> was China, followed by the USA, Japan, India and Russia (*see* Table 1), whilst the 27 countries of the European Union (EU27) emitted 834 Mt. The table also gives the direct and process-related CO<sub>2</sub> emissions from the countries' iron and steel industries. Here, the process-related emissions are those from limestone and dolomite, used as fluxes in the iron making process. This shows a different ranking to the overall industrial emissions. The five countries with the

highest direct CO<sub>2</sub> emissions were China, followed by Japan, Russia, India and the USA. The EU27 countries emitted 247 Mt (of which 17 Mt were process emissions).

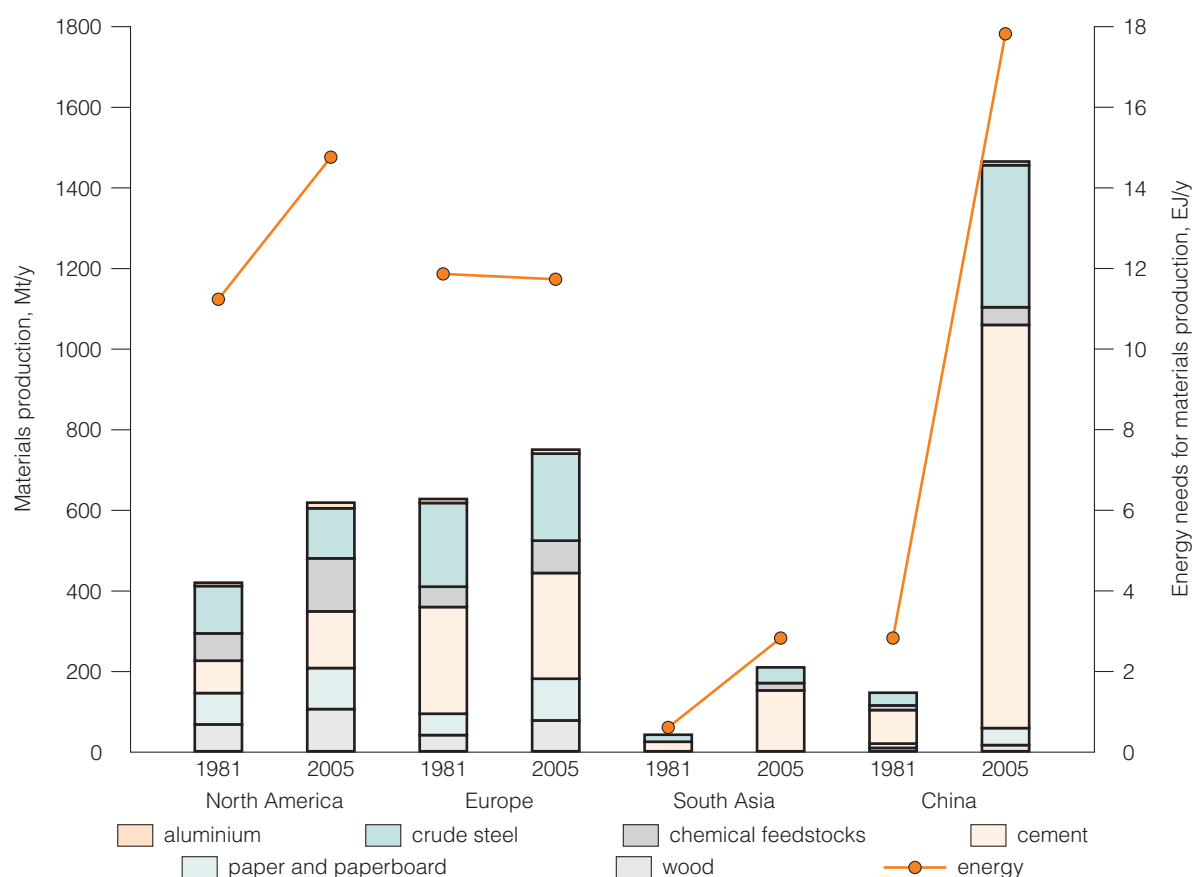
## 2.2 Industrial energy use

Manufacturing industries accounted for nearly one-third of the world's primary energy use in 2005 (IEA, 2008a). Total final energy use by industry was 2763 Mtoe (116 EJ). This figure includes petrochemical feedstocks, and conversion losses from electricity and heat supply, but excludes the approximately 1000 Mt of wood and biomass feedstock used by industry, equivalent to 380 to 430 Mtoe (15.9 to 18 EJ) of biomass. Most industrial energy use is for raw materials production. This accounted for 68% of total final industrial energy use, with the chemical and petrochemical industry alone accounting for 29% and the iron and steel industry for 20%.

Overall, industrial energy use has been growing strongly in recent decades. Between 1971 and 2005 it increased by 65%, an average annual growth of 1.5%, to reach 116 EJ (IEA, 2008a). In 2007, total final energy use by industry had risen to 3015 Mtoe or 126 EJ (IEA, 2010b). The rate of growth varied significantly between the different industries. For instance, energy and feedstock use has doubled in the chemical and petrochemical sector, whilst energy use for iron and steel production has been relatively flat despite strong growth in global production. Global energy use, though, is likely to have fallen in 2009, for the first time since 1981 on any significant scale, as a result of the financial and economic crisis. But it is expected to resume its long-term upward trend once the economic recovery is under way.

Much of the growth in industrial energy demand has been in emerging economies, and this is likely to

Table 2 Industrial final energy use in 2005, Mtoe (IEA, 2008a)							
	Brazil	Canada	China	France	Germany	India	Italy
Chemical and petrochemical	16	19	116	18	31	24	11
Iron and steel	19	6	209	7	15	27	8
Non-metallic minerals	6	1	109	4	6	11	9
Paper, pulp and print	8	17	16	3	5	1	3
Food and tobacco	18	0	20	5	5	8	4
Non-ferrous metals	5	6	25	1	3	1	1
Machinery	0	0	29	2	3	1	5
Textile and leather	1	0	23	2	1	1	2
Mining and quarrying	3	11	10	0	1	1	0
Construction	0	1	10	1	1	0	0
Transport equipment	0	0	8	1	3	0	0
Wood and wood products	0	0	3	1	1	0	0
Non-specified	6	10	19	2	12	56	3
Total	82	71	596	49	85	131	47



Note: North America includes Canada, Mexico and the USA. Europe includes EU27 excluding the three Baltic States, and including Albania, Bosnia, Croatia, Iceland, Former Yugoslav Republic of Macedonia, Norway, Serbia, Switzerland and Turkey.

Figure 2 Materials production energy needs, 1981-2005 (IEA, 2007)

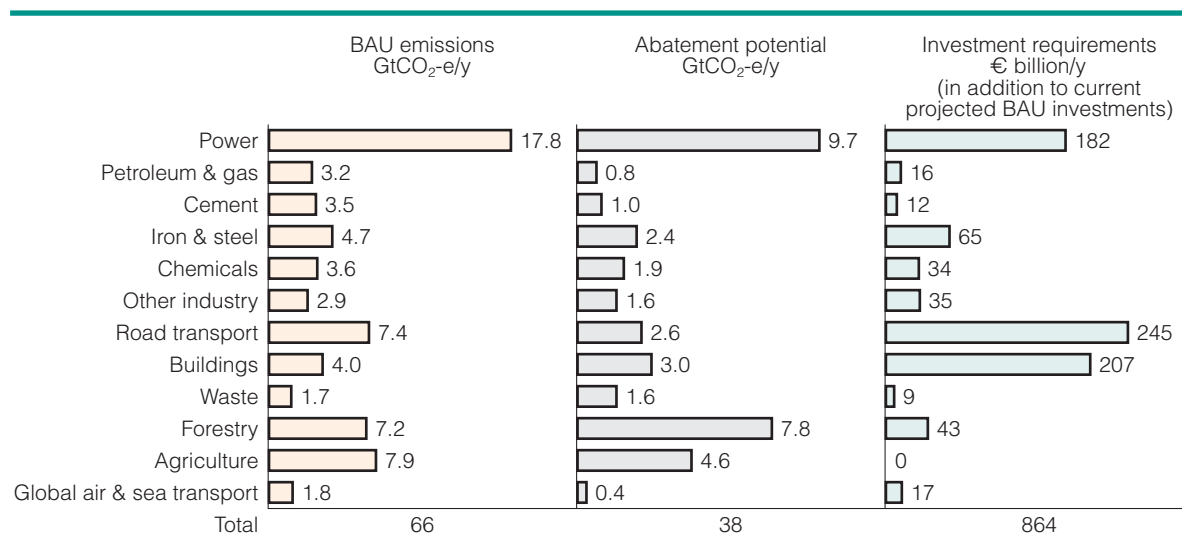
Table 2 continued						
Japan	Mexico	Russia	South Africa	UK	USA	World
53	11	49	3	13	177	809
45	5	55	7	5	31	560
8	2	14	2	3	25	263
9	1	2	0	2	55	154
4	2	8	0	4	30	143
2	0	0	2	1	13	87
9	0	6	0	3	21	97
0	0	1	0	1	6	53
0	2	6	5	0	2	53
4	0	3	0	1	2	35
0	0	4	0	1	9	34
0	0	6	0	0	12	32
17	11	6	6	9	13	443
151	35	160	25	42	397	2763

continue. Regional differences in industry energy use are shown in Figure 2. China alone accounts for about 80% of the growth in industrial production over the period 1981 to 2005, and for a similar share in industrial energy demand growth for materials production, about 16 EJ or 382.4 Mtoe (IEA, 2007). Today, China is the largest producer of commodities, such as iron and steel, and cement. The energy efficiency of production in China is, on average, lower than in developed countries and, being largely coal based, is also more carbon-intensive. However, China has some of the most efficient iron and steel making plants in the world due to the construction of new plants; these tend to be more efficient than old ones.

Efficiency has improved substantially in all the energy-intensive manufacturing industries over the last twenty-five years in every region. This reflects the adoption of cutting-edge technology in enterprises where the cost of energy is a major factor. The trend towards larger plants is also usually an advantage for energy efficiency. In general, Japan and Korea have the highest levels of manufacturing industry energy efficiency, followed by Europe and North America. This reflects differences in natural resources, national circumstances, energy prices, average age of plant, and energy and environmental policy measures (IEA, 2007).

Two-thirds of industrial final energy use in 2005 can be attributed to thirteen countries (the G8 nations and the five leading emerging economies, namely Brazil, China, India, Mexico and South Africa). Final energy use by industry for each of these countries is listed in Table 2. The data do not include energy use for transportation of raw materials and finished industrial products, which can be significant. China has the highest energy use (25 EJ) followed by the USA (16.6 EJ), Russia (6.7 EJ), Japan (6.32 EJ) and India (5.48 EJ). These five countries are also the largest industrial CO<sub>2</sub> emitters (*see* Section 2.1). The final energy use for the EU27 countries was 17.7 EJ.

Reducing energy consumption lowers CO<sub>2</sub> emissions. An analysis by the IEA (IEA, 2007), using 2004 as the reference year, found that by utilising best available technologies (BAT) and practices, manufacturing industry can improve its energy efficiency by 18 to 26%, while reducing the sector's CO<sub>2</sub> emissions by 19 to 32%. This equates to an energy saving of 600 to 900 Mtoe/y (25.1 to 37.7 EJ/y), and a reduction of 1.9 to 3.2 GtCO<sub>2</sub>/y (about 7% to 12% of global CO<sub>2</sub> emissions). The largest energy reduction potential is in the chemicals/petrochemicals industry (5–6.5 EJ/y or 120–155 Mtoe/y), followed by the iron and steel (2.3–4.5 EJ/y or 55–108 Mtoe/y), cement (2.5–3 EJ/y or 60–72 Mtoe/y), pulp and paper (1.3–1.5 EJ/y or 31–36 Mtoe/y) and aluminium (0.3–0.4 EJ/y or 7–10 Mtoe/y) industries. However, the potential CO<sub>2</sub> savings give a different order, with the highest savings in the cement industry (480–520 Mt/y), followed by the chemicals/petrochemicals (370–470 Mt/y), iron and steel (220–360 Mt/y), pulp and paper (52–105 Mt/y) and aluminium (20–30 Mt/y) industries.



**Figure 3 BAU direct CO<sub>2</sub>-e emissions in 2030 by sector** (Enkvist and others, 2010)

Enkvist and others (2010) have projected that global direct GHG emissions will reach 66 GtCO<sub>2</sub>-e in 2030 under a business as usual (BAU) scenario for all sectors, not just industry (*see* Figure 3). The projection takes into account the financial downturn. A total abatement potential of 38 GtCO<sub>2</sub>-e (58%) was identified through implementing technical measures costing below 80 €/tCO<sub>2</sub>-e. An additional 8 GtCO<sub>2</sub>-e could be saved if more expensive technical measures, as well as changes in behaviour, are included. This would result in a total reduction potential of more than 70% from BAU emissions. Investments of €864 billion per year, in addition to current projected BAU investments, would be required to meet the 38 GtCO<sub>2</sub>-e potential. The power industry has the largest potential abatement (26%), followed by forestry (21%). The iron and steel industry could potentially abate 6% of the global CO<sub>2</sub>-e emissions at a cost of €65 billion per year, plus current projected BAU investments.

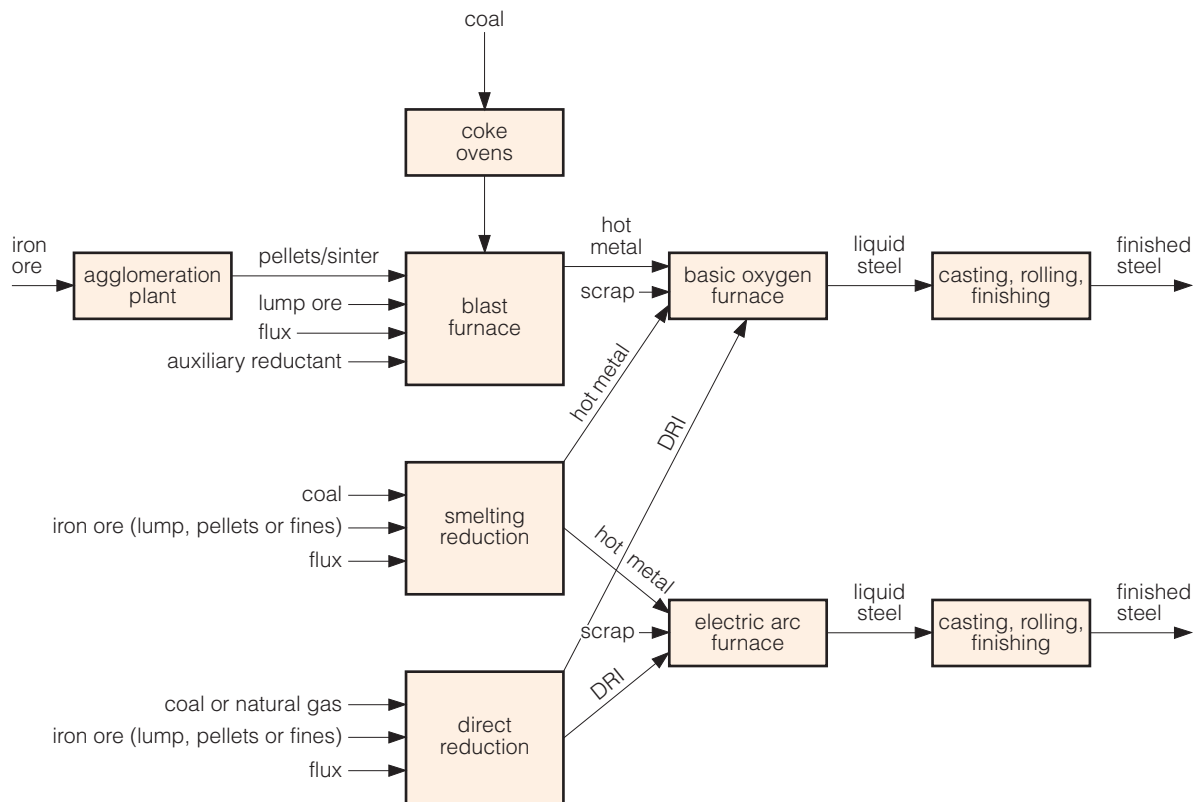
## 2.3 Iron and steel industry

Manufacturing steel is an energy- and CO<sub>2</sub>-intensive process that requires a large amount of natural resources. In 2005, the iron and steel industry consumed 560 Mtoe (23.4 EJ) and released 1.99 Gt of CO<sub>2</sub> (IEA, 2008a), whilst producing 1144 Mt of steel (World Steel Association, 2011). Two years later, energy consumption had risen to 616 Mtoe (25.8 EJ), and direct CO<sub>2</sub> emissions to 2.3 Gt (IEA, 2010b), when 1347 Mt of steel were produced. The high CO<sub>2</sub> emissions are due to the energy intensity of steel production, its reliance on coal as the main energy source and the large volume of steel produced. The four largest producers (China, EU, Japan and USA) accounted for 67% of the steel industry's CO<sub>2</sub> emissions in 2005 (IEA, 2008a).

Steel is produced via a dozen or so processing steps which are carried out in various configurations depending on product mixes, available raw materials, energy supply and investment capital. Two manufacturing routes (*see* Figure 4) dominate steel production:

- integrated steel mills based on the blast furnace-basic oxygen furnace (BF-BOF) process. Iron ore is reduced with coke in a BF and the resultant hot metal (also termed pig iron) is then converted (with up to 30% steel scrap) in a BOF to produce liquid steel; and
- mini-mills based on the electric arc furnace (EAF) process where the iron input is typically in the form of scrap, direct reduced iron (DRI) and cast iron.

Smelting reduction processes (*see* Chapter 6), such as Corex®, are a newer iron making technology, which currently account for <1% of world steel production; only a few commercial plants are currently in operation. These processes mostly use iron ore and the hot metal product can be sent to



**Figure 4 The major iron and steel production routes**

either a BOF or EAF. Around 2% of steel is produced via open-hearth furnaces (OHFs), principally in Ukraine, Russia and India. It is considered to be an outdated technology, and so will not be covered in this report.

The liquid steel from the BOF and EAF is further purified and treated to create the desired chemical composition. This is followed by casting (solidifying the molten steel) and shaping into the desired physical form.

Over the last three decades, EAF production has grown, whilst BF-BOF production has held steady. The latter integrated route is still the most widely used process, largely due to limitations on scrap availability. The BF-BOF and EAF routes accounted for about 70% and 29%, respectively, of world crude steel production in 2010 (World Steel Association, 2011). However, EAF steel making is the dominant route in some countries, for example, accounting for almost 61% of US steel production and all steel production in Saudi Arabia and Venezuela in 2010 (*see* Table 3). This table gives steel production figures for selected countries and regions in 2010, and the percentage that is produced by the BOF and EAF routes. The amounts of hot metal and DRI produced are also included. The data are compiled from the World Steel Association (2011) publication *World steel in figures 2011*. China is clearly the largest crude steel producer (500.5 Mt), followed by Japan (109.6 Mt), the USA (80.5 Mt), India (68.3 Mt) and Russia (66.9 Mt).

Energy consumption and CO<sub>2</sub> emissions of the different iron and steel making processes vary and will influence the amount of CO<sub>2</sub> that can be abated by each country. For example, recycling scrap reduces energy needs and direct CO<sub>2</sub> emissions by a factor of 2 to 4 (Gielen and others, 2008). EAF steel making is much higher in the USA and Europe (*see* Table 3), where scrap is available, than elsewhere. This difference should gradually disappear as other economies mature, and scrap becomes available. China, where steel production has quadrupled since 2000, currently has little scrap reserves. EAF accounted for only 9% of Chinese steel making in 2008. Overall, scrap recycling as a proportion of total world steel production has declined from 47% in 2000 to 36% in 2007 (IEA, 2009a). DRI/EAF

<b>Table 3 World crude steel (by process), hot metal and DRI production in 2010 (World Steel Association, 2011)</b>						
	Crude steel production, Mt	BOF, %	EAF, %	OHF, %	Hot metal, Mt*	DRI, Mt
Austria	7.2	91.2	8.8	–	5.6	–
Belgium	8	64.9	35.1	–	4.7	–
Bulgaria	0.7	–	100	–	–	–
Czech Republic	5.2	91.9	8.1	–	4	–
Finland	4	31.4	68.6	–	2.6	–
France	15.4	63.7	36.3	–	10.1	–
Germany	43.8	69.8	30.2	–	28.6	0.4
Greece	1.8	–	100	–	–	–
Hungary	1.7	94.6	5.4	–	1.3	–
Italy	25.8	33.3	66.7	–	8.6	–
Latvia <sup>e</sup>	0.7	–	–	100	–	–
Luxembourg	2.5	–	100	–	–	–
Netherlands	6.7	98.1	1.9	–	5.8	–
Poland	8	50	50	–	3.6	–
Portugal <sup>e</sup>	1.4	–	100	–	–	–
Romania	3.7	53.5	46.5	–	1.7	–
Slovak Republic	4.6	92.7	7.3	–	3.6	–
Slovenia	0.6	–	100	–	–	–
Spain	16.3	23.5	76.5	–	3.6	–
Sweden	4.8	68.7	31.3	–	3.4	0.1
UK	9.7	75.4	24.6	–	7.2	–
<b>EU27</b>	<b>172.6</b>	<b>57.7</b>	<b>41.9</b>	<b>0.4</b>	<b>94.5</b>	<b>0.5</b>
Turkey	29.1	28.3	71.7	–	7.7	–
<b>Other Europe†</b>	<b>32.6</b>	<b>29.1</b>	<b>70.9</b>	<b>–</b>	<b>10.9</b>	<b>–</b>
Russia	66.9	63.4	26.9	9.8	47.9	4.5
Ukraine	33.4	69.3	4.5	26.2	27.3	–
<b>CIS†</b>	<b>108.9</b>	<b>64.1</b>	<b>21.1</b>	<b>14.8</b>	<b>77.9</b>	<b>4.5</b>
Canada	13	57.7	42.3	–	7.7	0.6
Mexico	16.7	30.8	69.2	–	4.6	5.4
USA	80.5	38.7	61.3	–	26.8	–
<b>NAFTA</b>	<b>110.2</b>	<b>39.8</b>	<b>60.2</b>	<b>–</b>	<b>39.1</b>	<b>6</b>
Argentina	5.1	50.7	49.3	–	2.5	1.6
Brazil	32.9	76.2	23.8	–	31	–
Chile	1	64	36	–	0.6	–
Venezuela	2.2	–	100	–	–	3.8

<b>Table 3 continued</b>						
	Crude steel production, Mt	BOF, %	EAF, %	OHF, %	Hot metal, Mt*	DRI, Mt
<b>Central and South America†</b>	44.8	64.1	35.9	–	34.5	7.2
Egypt <sup>e</sup>	6.7	9	91	–	0.6	3
South Africa	7.6	57.3	42.7	–	5.3	1.1
<b>Africa†</b>	16.5	33.5	66.5	–	6.6	5.4
Iran <sup>e</sup>	12	20	80	–	2.5	9.4
Saudi Arabia	5	–	100	–	–	4.9
<b>Middle East†</b>	19.3	12.4	87.6	–	2.5	17.6
China	626.7	90.2	9.8	–	590.2	0.1
India <sup>e</sup>	68.3	38.1	60.5	1.5	38.7	26.3
Japan	109.6	78.2	21.8	–	82.3	–
South Korea	58.4	58.4	41.6	–	35.1	–
Taiwan	19.8	52.6	47.4	–	9.4	–
<b>Asia†</b>	898.5	80.3	19.6	0.1	756.9	30.1
Australia	7.3	83.1	16.9	–	6	–
New Zealand <sup>e</sup>	0.9	72.7	27.3	–	0.7	–
<b>Total of above countries</b>	1411.6	70	28.8	1.3	1029.6	71.3
e estimated * includes both hot metal (pig iron) for steelmaking and foundry iron † includes other countries in the region The countries in this table accounted for over 99% of world crude steel production in 2010						

steel making is widespread in the Middle East, South America, India (the largest DRI producer) and Mexico. Most DRI production is based on cheap, stranded natural gas, except in India, where around 70% of its DRI production is coal-based (Riley and others, 2009). Thus whilst the majority of steel tonnage in India comes from EAFs, the proportion of iron coming from coal-based reduction is similar to other emerging economies.

Various values are quoted in the literature concerning the energy consumption and CO<sub>2</sub> emissions of the different processing steps, individual plants and countries. The differences can be explained by factors such as variations in the quality of the raw materials and the chosen boundary conditions. Steel plants that buy pellets, coke, DRI, oxygen, steam and electricity and other products will have lower energy consumption and CO<sub>2</sub> emissions than plants that generate them on-site, but will increase CO<sub>2</sub> emissions elsewhere. Selling by-products, such as BF slag as a cement clinker substitute, and coke oven and BF gases to power producers, reduces CO<sub>2</sub> emissions elsewhere but not at the site. This is discussed in the IEA (2007) publication which provides values on the energy and CO<sub>2</sub> emission impacts of system boundaries. For example, buying coke can save a steel plant 1–1.5 GJ per tonne of crude steel (tcs) and lower CO<sub>2</sub> emissions by 0.05–0.1 t/tcs. The definition for crude steel usually includes casting, but excludes rolling and finishing. A study by Tanaka (2008) showed that the specific energy consumption of crude steel production in Japan can range from 16 to 21 GJ/t, depending on the system boundaries set for the analysis and the conversion coefficient used for electricity production. Electricity produced from coal generates higher CO<sub>2</sub> emissions than that produced from

natural gas, which in turn, has higher CO<sub>2</sub> emissions than hydropower. Uniform boundaries are needed for proper comparison purposes.

In addition, the specific CO<sub>2</sub> emissions value for power generation varies from country to country as it is based on the different ratios of thermal, nuclear and hydroelectric power generation employed in the country. India and China, for example, have a high specific emission value of 1.3 and 1.071 kgCO<sub>2</sub>/kWh, respectively, due to the high use of coal. Sweden, on the other hand, has a low value of 0.057 kgCO<sub>2</sub>/kWh since most of its power is generated in hydroelectric plants (Böhm and others, 2004). The nationwide specific CO<sub>2</sub> emissions are often used when calculating indirect CO<sub>2</sub> emissions. This is one reason why CO<sub>2</sub> emissions from steelworks using basically the same process steps can vary from country to country.

Benchmarking provides a means of comparing energy use and CO<sub>2</sub> emissions within a company or plant to that of other facilities producing similar products. This approach can be used to compare plants, processes or systems. A benchmarking study of the energy efficiency of four integrated steel plants and eight EAFs in Canada in 2002 were compared with the Ecotech model plant, as defined by the World Steel Association. The average efficiency improvement potential for the Canadian plants was found to be 25–30%. The study concluded that the BFs and EAFs are close to the Ecotech plant level of efficiency. The coke oven efficiency was relatively low, but improvements would not be economic. Key areas for efficiency improvements were identified (Natural Resources Canada, 2007).

The World Steel Association has developed a database containing CO<sub>2</sub> emissions data from individual steel plants in all the major steel-producing countries. Data collection has been designed to ensure that steel plants report emissions on a comparable basis. Unfortunately, the data on individual plants are confidential and the database is only available to member companies of the World Steel Association.

The Asia Pacific Partnership for Clean Development and Climate (APPCDC) also collects energy efficiency data for individual steel plants in its member countries. The IEA Greenhouse Gas R&D Programme (IEAGHG) has a database on CO<sub>2</sub> emissions from large stationary sources, which includes iron and steel plants. The database is available on application to the IEAGHG.

An EAF uses about 1.6 GJ of electricity/t steel for a 100% scrap feed. In actual operation, however, EAF energy use is somewhat higher. To be truly comparable to the BF/BOF process, the electricity needs to be expressed in primary energy terms. With electricity generation efficiency ranging from 35% to more than 50%, EAF primary energy was calculated to be in the range 4–6 GJ/t of liquid steel (t<sub>ls</sub>). The scrap/EAF route consumes less energy than the BF/BOF route which consumes 13–14 GJ/t<sub>ls</sub> (IEA, 2008a). This is because there is no need to reduce iron ore to iron, and it eliminates the need for the iron ore agglomeration, coking and iron making steps. EAF energy consumption will increase when DRI is added to the scrap feed due to reduction of the iron oxides.

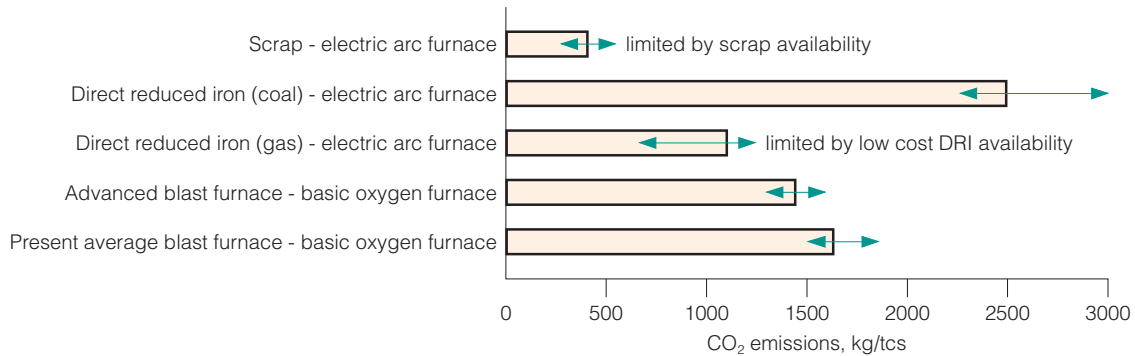
**Table 4 Ranges of primary energy intensities of key iron and steel making processes (Price and others, 2001)**

Process	Primary energy intensity range, GJ/t steel
Iron making – hot metal (pig iron)	12.7–18.6
Iron making – smelting reduction	13–18
Iron making – DRI	10.9–16.9
Steel making – BOF	0.7–1
Steel making – DRI + EAF	4–6.7
Steel making – scrap + EAF	4–6.5
Casting – ingot casting	1.2–3.2
Casting – continuous casting	0.1–0.3
Casting – thin slab casting	0.6–0.9
Rolling – hot rolling	2.3–5.4
Rolling – cold rolling	1.6–2.8
Note: iron making includes energy used for ore preparation and cokemaking iron making – DRI and steel making – DRI + EAF assumes 80% DRI and 20% scrap	



Most of the energy consumption in the BF/BOF route is related to the BF process at about 10–13 GJ/tcs, including the hot stoves. Other big consumers of energy are sintering (2–3 GJ/tcs), cokemaking (0.75–2 GJ/tcs) and steel rolling (1.5–3 GJ/tcs). Ladle metallurgy and casting consume around 0–1 GJ/t steel. Production of DRI using natural gas requires about 12 GJ/tcs (IEA, 2007). Table 4 gives the energy intensities of key iron and steel making processes compiled by Price and others (2001). It includes the newer smelting reduction processes.

The scrap/EAF route also yields lower CO<sub>2</sub> emissions than the DRI/EAF and BF/BOF routes (*see* Figure 5). The largest emitter of CO<sub>2</sub> emissions is the coal-based DRI/EAF route. The green arrows in



Note: The high and low-end ranges indicate CO<sub>2</sub>-free and coal-based electricity, and account for country average differences based on IEA statistics. The range is even wider for plant based data. The product is crude steel, which excludes rolling and finishing.

Figure 5 CO<sub>2</sub> emissions per tonne of crude steel (IEA, 2007)

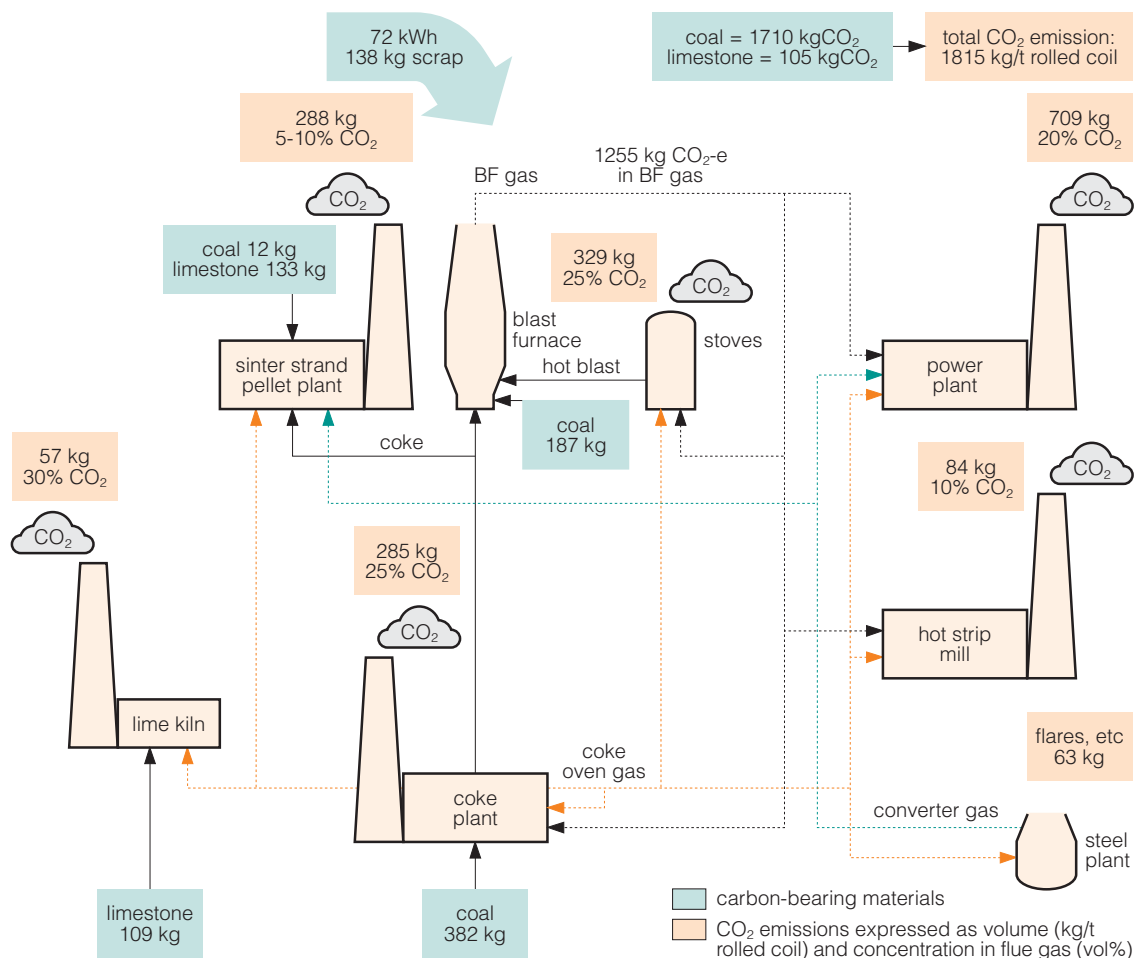


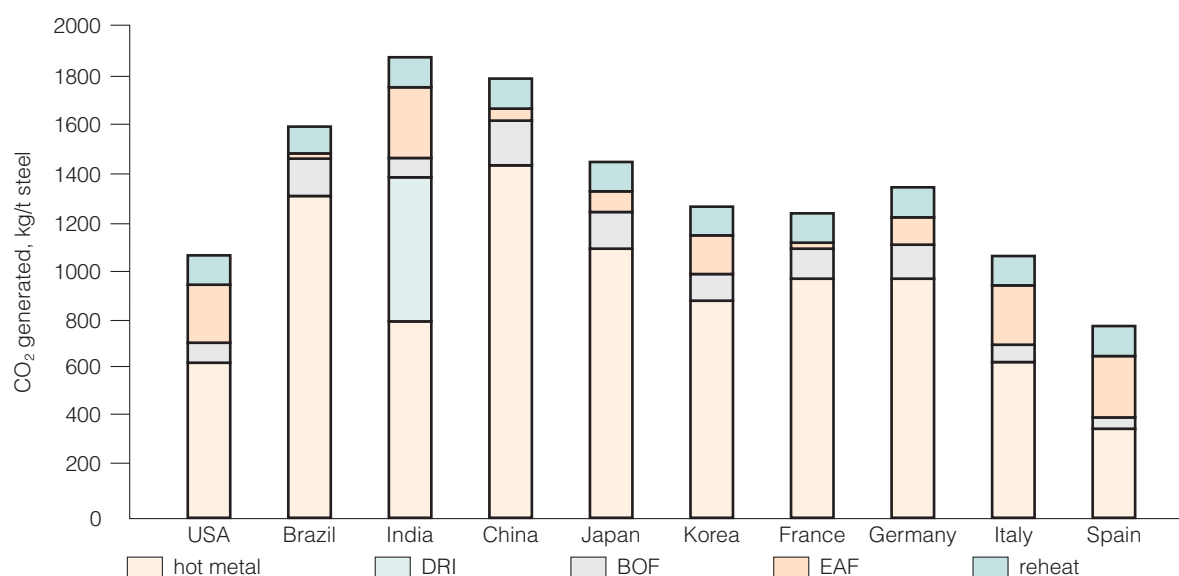
Figure 6 CO<sub>2</sub> emissions from a typical steel mill (Birat, 2010a)

the figure indicate the amount of emissions from the electricity, where the low-end and high-end indicate CO<sub>2</sub>-free and coal-based electricity, respectively. Around 30–80% of CO<sub>2</sub> emissions can potentially be reduced, excluding any reductions that might be achieved through CO<sub>2</sub> capture from the BF or elsewhere. However, this assumes that the processes are interchangeable, which does not take into account actual available options; for example, the limited availability of scrap and low carbon fuels (IEA, 2007). Using natural gas rather than coal and coke can lower CO<sub>2</sub> emissions in DRI production. But this depends on the use of low cost stranded gas which is only accessible in certain parts of the world, such as the Middle East.

Wang and others (2009) quote a 1999 report by De Beer and others that provides a breakdown of CO<sub>2</sub> emissions within an integrated steel plant. BFs are the largest producers (1.14–1.4 tCO<sub>2</sub>/t), CO<sub>2</sub> emissions from the rest of the processes (in tCO<sub>2</sub>/t) are 0.06–0.07 from the coking plant, 0.03 from iron ore pelletising, 0.1–0.11 from the sinter plant, –0.04–0.04 from the BOF, 0.01 from continuous casting, 0.2–0.29 from rolling and finishing, and 0.12–0.21 from the oxygen and power plants. Figure 6 gives a simplified carbon balance for a typical integrated steel mill producing hot rolled coil (HRC). The major carbon sources are coal and limestone, and the CO<sub>2</sub> stack emissions are expressed in volume (kg/t of HRC) and concentration in the flue gas (volume %). The CO<sub>2</sub> stream from the BF accounts for 69% of all steel mill emissions to the atmosphere (Birat, 2010a). But the BF gas never ends up directly in a stack, as the energy within it is recovered in an on-site power plant and elsewhere in the steel mill. The figure also shows where COG and BOF gases are utilised within the steel mill.

Riley and others (2009) estimated the CO<sub>2</sub> emissions/t steel for various countries, broken down by the production process (see Figure 7). They included CO<sub>2</sub> emissions from electricity generation, using factors of 0.95 kg/kWh, 0.87 kg/kWh and 0.6 kg/kWh for coal-, oil- and natural gas-based power generation, respectively. Zero CO<sub>2</sub> emissions for nuclear, hydro/renewable sources were assumed. The figure shows that, despite the differences in how iron, steel and electricity are produced in each of the listed country, BF iron making is the predominant source of steel mill CO<sub>2</sub>. Reheating of steel slabs before rolling and finishing is also a significant source of CO<sub>2</sub>. It also indicates which countries have the highest CO<sub>2</sub> emissions/t steel and hence where CO<sub>2</sub> abatement technologies could have the greatest impact.

There is considerable difference in the energy efficiency of primary steel production among countries and even individual plants. Energy efficiency tends to be lower in countries with low energy prices. For the BF-BOF process, the gap in energy efficiency between the top and bottom country is about



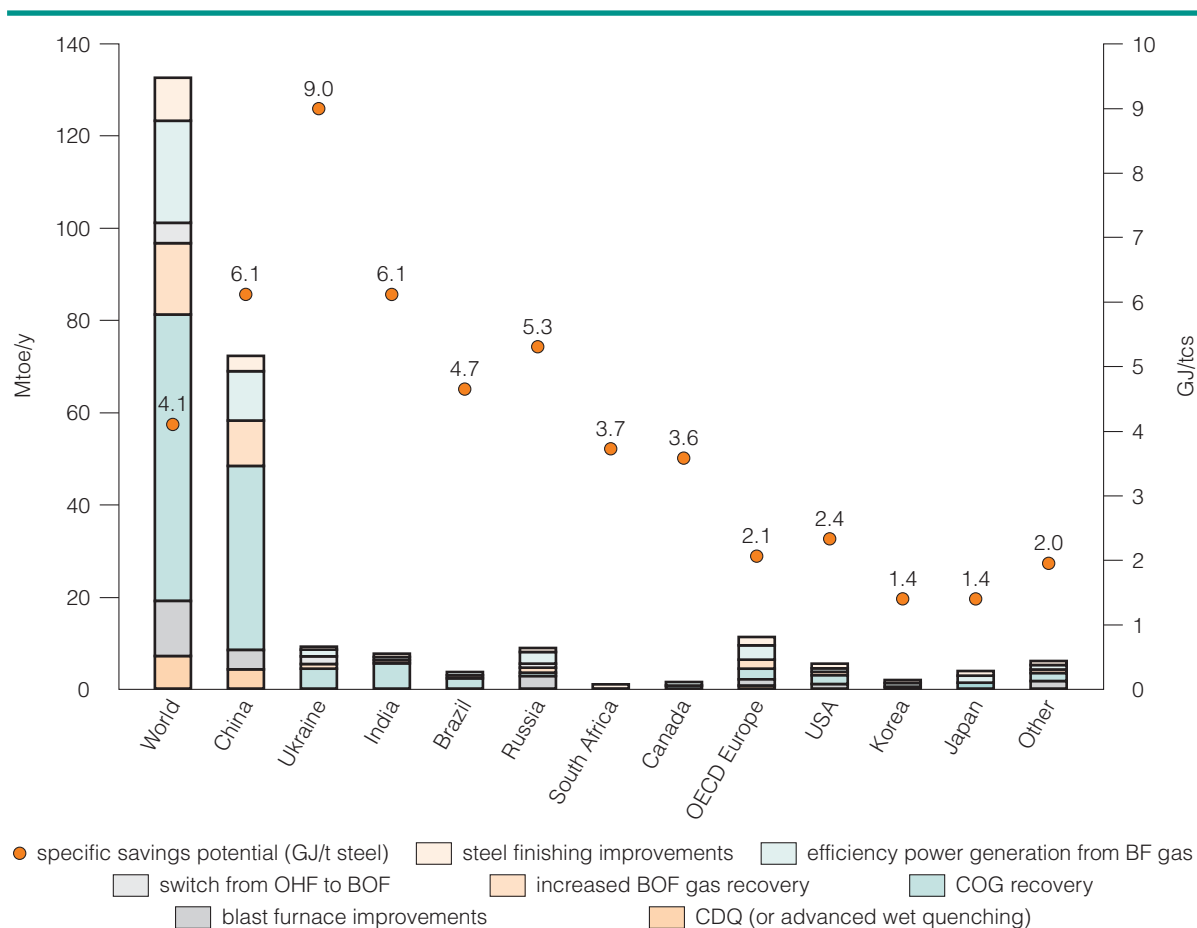
**Figure 7** Estimated CO<sub>2</sub> emissions/t steel for selected countries (Riley and others, 2009)

50%. This is due to variations in plant size, level of waste energy recovery, quality of iron ore and quality control (IEA, 2007). Waste energy recovery is more common in countries with high energy prices, where the waste heat is used for power generation. Nevertheless, overall the global iron and steel industry has achieved significant energy efficiency gains, and consequently lower CO<sub>2</sub> emissions, over the last 30 years or so. Increased scrap recycling and higher efficiency of energy and materials use has helped achieve this. In Japan, for example, the energy efficiency of the iron and steel industry improved by about 20% from the 1970s to 1990; but this growth slowed to 7% between 1990 and 2005 (IEA, 2007). This trend can be explained by the fact that major energy efficient technologies, such as large scale waste energy recovery, had been deployed before 1990. The Japan Iron and Steel Federation has set up a voluntary action plan to reduce energy consumption by 10% in the 2010 financial year compared to the 1990 financial year, assuming annual crude steel production is 100 Mt. This would reduce CO<sub>2</sub> emissions by around 9%, and would be achieved mainly by stepping up energy conservation (Kojima, 2009). Japan is one of the most energy-efficient steel making nations today.

According to the IEA (2007) publication, which quotes the American Iron and Steel Institute, energy efficiency of BF-BOF steel production in the USA improved at 1.5% per year from 21.2 GJ/t in 2002 to 20.3 GJ/t in 2005. Over the same time period, energy efficiency in EAF plants improved from 5.2 GJ/t to 4.9 GJ/t. EAF production growth was faster, contributing to an average gain of 12% during this period. In 2008 hot metal production was 30% lower than in 2000 and 32% below 1990. CO<sub>2</sub> emissions from iron and steel production (including coke production) decreased by 33% (33.6 MtCO<sub>2</sub>-e) from 1990 to 2008 due to restructuring of the industry, technological improvements, and increased scrap steel utilisation (EPA, 2010a).

Nevertheless, the world energy efficiency average has not improved substantially over the last 30 years due to increased steel production in China, which has a relatively low average efficiency of ~0.71–0.74 t of coal equivalent (tce) (20.8–21.7 GJ)/tcs. The efficiency of a steel plant is closely linked to several elements including technology, plant size and quality of raw materials. New plants are also more efficient than old ones. This partly explains why the average efficiency of the iron and steel industries in China, India, Ukraine and the Russian Federation are lower than those in OECD countries (IEA, 2007). These four countries accounted for nearly half of global iron production and more than half of global CO<sub>2</sub> emissions from iron and steel production in 2005. China itself produced 419 Mt of steel in 2006 (about 34% of the world's production), at a cost of 9.8 EJ of energy (335 Mtoe or 235 Mtoe) or 15% of the nation's total energy consumption (Xu and Cang, 2010). China has some of the most energy efficient steel plants but also some of the worst. According to the China Iron and Steel Association, energy consumption of the large and medium steel companies in 2004 was 0.705 tce (20.7 GJ)/t steel. This is 7.5% higher than that of Japanese steel companies (0.656 tce (19.23 GJ)/t steel). The energy consumption of the small Chinese production units was considerably higher at 1.045 tce (30.6 GJ)/t steel (Wang and others, 2007). Other authors have given the energy consumption/t steel in China as 10–20% higher than the best international level (Rong and others, 2010; Zeng and others, 2009). The overall low energy efficiency in China is mainly due to the high share of these small-scale units, as well as limited or low levels of heat recovery and inefficient use of residual gases, and low quality ore. In its first Climate Change Plan published in June 2007, China has committed to enhance energy efficiency and requires the steel industry to adopt energy saving technologies on its large BFs (Xu and Cang, 2010). It is also closing its small-scale units.

Although the specific energy consumption of the Indian iron and steel industry has declined by over 15% over the last 10 years, its consumption was 28.9 GJ in 2008, well above the world average of 18.8 GJ (Jain, 2010). New, but energy inefficient technologies, such as coal-based DRI iron production, play an important role in India. Coal-based DRI can take advantage of the local low-quality coal resources and can be developed on a small scale, but has high CO<sub>2</sub> emissions. India is the world's largest producer of DRI. Outdated technologies, such as OHFs, are still in use in Ukraine and Russia. The energy intensity of OHFs is about 3.9–5 GJ/t steel compared to 0.7–1 GJ/t steel for BOFs (Price and others, 2001).



**Figure 8 Energy savings potential in 2007 based on BATs (IEA, 2010b)**

The potential for energy efficiency improvement at steel plants will vary depending on the production route employed, product mix, energy and carbon intensities of fuel and electricity, and the boundaries chosen for the evaluation. The IEA estimated that the global iron and steel industry could potentially save ~133 Mtoe (5.57 EJ), based on the steel production volume in 2007 (IEA, 2010b). If achieved, this would result in 421 MtCO<sub>2</sub> avoided. Figure 8 shows the potential energy savings broken down by country and BAT. China accounts for around half of the potential energy saving (it is the largest steel producer). However, in terms of specific savings potential, Ukraine has the highest potential at 9 GJ/t steel, followed by China and India, and then Russia.

Focussing on best technological practice and diffusing it to the world under international cooperation will be one of the most effective measures for saving energy and abating CO<sub>2</sub> emissions. The following chapters will examine BATs and other measures for reducing CO<sub>2</sub> emissions and energy consumption for the different iron and steel production processes. The biggest CO<sub>2</sub> abatement potential lies in old installations, but every installation has some abatement potential, and even the most modern installations could improve their efficiency. Not all new steel plants have adopted the BATs. The amount that state-of-the-art integrated steel mills can improve efficiency is limited as processes are approaching their thermodynamic limits. Replacing inefficient motors with modern efficient ones is one way of lowering both energy consumption and CO<sub>2</sub> emissions but will not be discussed; it is covered in IEA (2007).

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## 3 Raw material preparation

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This chapter looks at how to lower energy consumption and CO<sub>2</sub> emissions from cokemaking and iron ore agglomeration (sintering and pelletising). It discusses the BATs and whether these can be retrofitted, and both short- and long-term solutions. It should be noted that not all integrated steel mills have coking plants on-site. Pelletising is only covered briefly since iron ore pellets are typically produced at the mine.

Lime is used as a flux reagent in iron and steel making to capture impurities and this lime may be produced on-site. The lime production process involves the calcination of calcium carbonate in limestone or dolomite to produce calcium oxide. Around 57 kgCO<sub>2</sub>/t HRC is released in the flue gas from lime kilns (Birat, 2010a). CO<sub>2</sub> emissions also result from the use of lime in the sinter plants, BFs and elsewhere. Globally, around 111 Mt of CO<sub>2</sub> was emitted in 2005 from limestone and dolomite use in BFs (IEA, 2008a). CO<sub>2</sub> abatement at lime kilns is covered by Zhu (2011).

### 3.1 Cokemaking

Coke is produced from metallurgical grade coal (coking coals). It is the primary reducing agent in the BF where its combustion provides the reducing gases to reduce the iron ore, and the heat to melt the iron ore and slag and to drive the endothermic processes. In addition, coke physically supports the iron burden and provides a permeable matrix through which the gases and liquid iron and slag can flow. There is no other satisfactory reductant that can yet fulfil this last physical role and so it is not possible to replace all the coke in large BFs.

The cokemaking process consists of heating a batch of crushed coal (usually a blend of coals) in a coke oven to around 1000–1100°C in the absence of air (O<sub>2</sub>-deficient atmosphere) to drive off the volatile compounds. The process takes about 12–36 h. The resultant coke is then pushed from the oven and cooled either with water or inert gas. Coke production is discussed in the IEA Clean Coal Centre report by Couch (2001). Direct CO<sub>2</sub> emissions result from the fuel used to heat the coke ovens and process emissions.

There are two general types of coke ovens:

- by-product (usually slot) ovens, where chemical by-products (tar, ammonia and light oils) in the coke oven gas (COG) are recovered and the remaining COG is cleaned and utilised within the steel plant to heat the coke ovens, and generate steam and/or electricity (*see* Section 3.1.4);
- non-recovery (usually beehive) ovens, where the by-products are not recovered and the raw COG and other products are combusted in the oven. The energy use and specific CO<sub>2</sub> emissions are about one and a half times those of a conventional by-product oven (IEA, 2007). Modern non-recovery ovens (heat recovery ovens) recover the sensible heat from the offgases in a waste heat boiler to generate steam or electricity that can be used within the plant. Non-recovery ovens are less commonly used and so will not be covered.

One tonne of coal yields about 0.75–0.8 t of coke, 45–90 kg of coke breeze (large particles from coke breakage utilised in the iron ore sintering plant) and 285–345 m<sup>3</sup> of COG (Couch, 2001). The differing proportions of high and low volatile coals in the blend used affects both the coke and COG yields. COG production is often maximised in areas where energy is expensive since it can be utilised as a fuel. The composition of the crude COG depends on the coking time and coal blend composition. It has a relatively high calorific value (17.4–20 MJ/m<sup>3</sup>), and contains around 1–3 vol% of CO<sub>2</sub> and 4–7% of CO (European IPPC Bureau, 2011).

Cokemaking is an energy intensive process, consuming around 3.5–5 GJ/t coke or 0.75–2 GJ/tcs

(IEA, 2007). The theoretical minimum energy needed for cokemaking is about 2 GJ/t coke or 0.8 GJ/t steel (with 100% natural gas as the energy source and a coke output of 0.768 t/t coal). This indicates a large potential for energy efficiency improvements. The theoretical minimum and actual CO<sub>2</sub> emissions are 0.11 and 0.3–0.34 kg CO<sub>2</sub>/t coke, respectively (Fruehan and others, 2000).

The energy balance (input and output) for a typical coking plant with an annual production of 1.4 Mt is given in Figure 9. It shows the important role COG plays in the energy supply and management in an integrated steelworks. One measure for reducing energy consumption is the recovery of the sensible heat in the discharged hot coke, COG and coking waste gases, and the chemical energy in the COG. Table 5 shows the amount of energy that could potentially be recovered from these streams and various other products and gases for an integrated 10 Mt/y plant. If the waste heat and energy from all the streams could be effectively recovered, then 14.7 GJ/t steel could be saved and a large amount of CO<sub>2</sub> would be avoided. Recovering the chemical energy from the COG, blast furnace gas (BFG) and BOF gas has the largest effect (60.2% of the total), followed by sensible heat recovery from the hot products (sinter, coke and bloom steel at 14.46%) and from the offgases and waste gases (coking, sinter and BOF waste gases, COG, and BFG at 13.81%). The following sections discuss ways of recovering waste energy from the discharged coke (dry quenching), COG and waste gases. The use of COG, coal moisture control, use of biomass and wastes in the coking coal blend and briefly, innovative processes are then examined.

The control and optimisation of both the battery and individual coke ovens is essential for energy efficient operation. Retrofitting computer-based automatic monitoring and control systems can help achieve this. For example, the use of programmed heating, instead of conventional constant heating, can help optimise the fuel gas supply to the ovens during the coking process. It could save 10% of the fuel, or ~0.17 GJ/t of coke (Worrell and others, 2010).

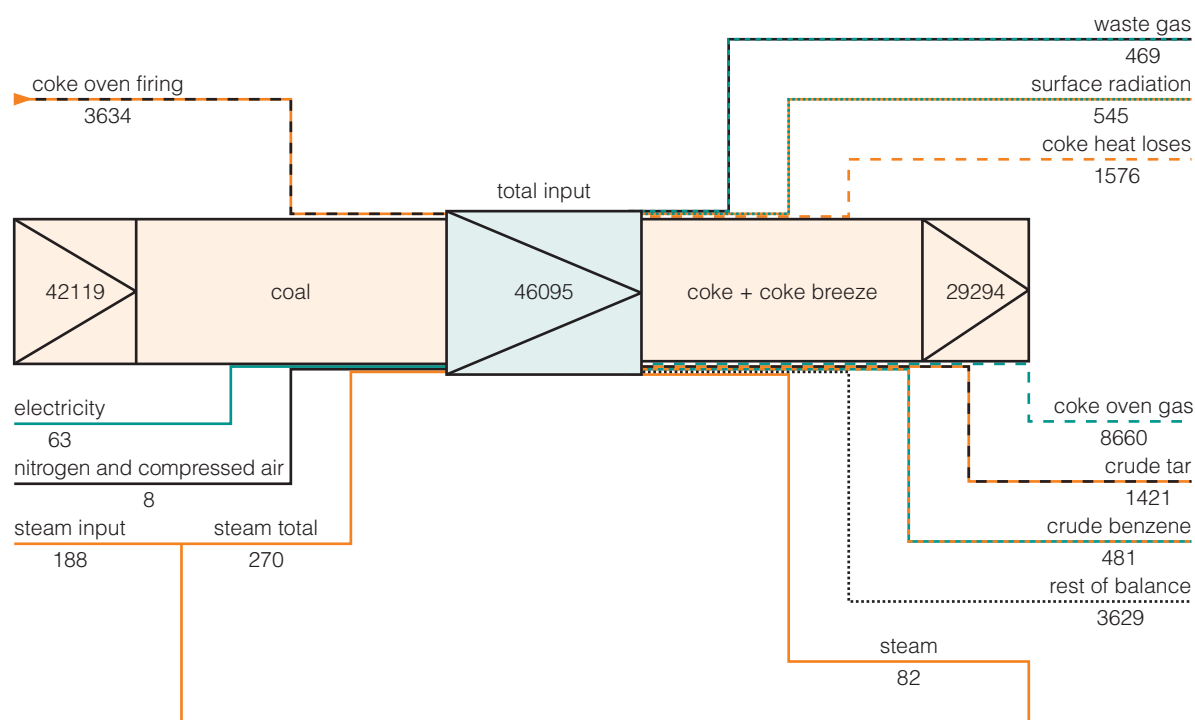
### 3.1.1 Coke dry quenching

The hot coke is pushed out from the coke oven into a ‘coke quenching car’ and transported to the quenching tower. The sensible heat of hot coke contains ~35–40% of the total amount of heat consumed in the coking process. Instead of quenching coke with water, where the sensible heat is lost to the atmosphere as steam, coke dry quenching (CDQ) recovers about 80% of the coke sensible heat as steam (Guo and Fu, 2010), with consequent energy benefits. However, the energy benefits of CDQ compared to advanced wet quenching systems are not so clear. Advanced wet quenching cools the coke from top and bottom, which leads to much more rapid cooling. This does not result in energy recovery, but it does produce a high quality coke that can generate energy savings in the BF (Gielen and Taylor, 2009).

In CDQ, coke enters the quenching chamber at ~1000°C and is cooled by the counter flowing inert gas (for instance, nitrogen) to ~180–200°C over 4–5 h. The inert gas, which is recycled by a blower, exits the chamber at a temperature of 750–860°C and is utilised in a waste heat boiler for steam generation. The steam can, in turn, be used for power generation or used elsewhere in the steelworks.

About 0.5 t steam (480°C, 6 MPa)/t coke, corresponding to 1.5 GJ/t coke, can be recovered. An electric efficiency of 30% was achieved at the Kimitsu steelworks in Japan with the CDQ process when the steam was used for power generation (IEA, 2007). Operational data concerning the use of a CDQ at an integrated steelworks gave a steam production level of 120 t/h (10.5 MPa, 550°C) on the basis of 200 t/h of hot coke. The steam is utilised both in the works and for generating electricity and this has led to energy savings of the order of 1439 MJ/t dry coke, although this value includes a contribution from the small degree of coke combustion which inevitably occurs in the process (Cairns and others, 1998). The combustion of coke will release a small amount of CO<sub>2</sub>.

A typical modern CDQ system generates 150 kWh/t coke and brings several co-benefits such as lower



Note: values are in MJ/t coke (dry) and correspond to an annual production of 1.4 Mt.

**Figure 9 Annual energy balance of a coking plant (European IPPC Bureau, 2011)**

Table 5 Typical sensible heat and chemical energy produced (Li and others, 2010)				
		Temperature, °C	Energy, GJ/t steel	Ratio, %
Sensible heat from product	Sinter	800	0.94	6.39
	Coke	1000	0.59	3.99
	Bloom steel	900	0.6	4.08
Sensible heat from slag	BF slag	1500	0.59	3.99
	BOF slag	1550	0.15	1.02
Sensible heat from gas	Coking waste gas	200	0.19	1.29
	COG	700	0.17	1.16
	Sinter waste gas	300	0.69	4.69
	BFG	200	0.77	5.24
	BOF waste gas	1600	0.21	1.43
Sensible heat from cooling water	BF cooling water	40	0.95	6.46
Chemical energy from offgas	COG	–	2.58	17.55
	BFG	–	5.42	36.87
	BOF gas	–	0.85	5.78
Total			14.7	100

Note: based on annual production of 10 Mt steel

water consumption, decreased dust emissions and enhanced coke quality (Guo and Fu, 2010; Oda and others, 2007). The improvement in coke quality increases productivity and reduces coke consumption in the BF by about 2%, that is, 0.6 GJ/t coke is saved (IEA, 2007). For a modern BF with pulverised coal/oil injection, consuming 350 kg of coke/t of hot metal (thm), the overall energy saving with CDQ is ~10–14 kg of coal equivalent (~290–410 MJ)/tcs, which may lead to a reduction in CO<sub>2</sub> emissions of 3.04 t/tcs (Xu and Cang, 2010). Li and others (2010) calculated that for an integrated steelworks with a capacity of 10 Mt/y, CDQ (9.5 MPa, 540°C) could generate 160 kWh/t coke in a combined heat and power plant, thereby abating 0.52 MtCO<sub>2</sub>.

In principle, CDQ can be retrofitted to existing plants (provided there is space). Worldwide, over 60 coking plants employ CDQ including Japan, China, South Korea, Russia, The European Union and South America (European IPPC Bureau, 2011; IEA, 2007; Zeng and others, 2009). However, it is not applied in the USA or Canada or Australia. Economics may be one reason for the low rate of CDQ use in North America and elsewhere. The overall economics of operating a CDQ system are heavily dependent on the value of the heat/power produced. Investment and operation costs are high. Investment costs of a CDQ system with an annual processing capacity of 2 Mt coke are around €100 million (of which equipment costs are expected to be around €70 million (€ year not given)), although it depends on the site conditions, market conditions and other factors (European IPPC Bureau, 2011). New plant costs have been estimated to be 110 US\$/t coke (\$ year 2008) and retrofit costs can be as high as 112–144 \$/GJ saved (EPA, 2010b). Retrofit costs depend strongly on the layout of the coke plant. In China, CDQ costs 150–300 million yuan (Cai, 2008). It is only where investment and operational costs are balanced by high electricity prices and 10% rates of return are applied, that CDQ makes sense (IEA, 2007).

One promising opportunity for the iron and steel industry in emerging economies to obtain the necessary capital and technology to improve energy efficiency, and thereby reduce CO<sub>2</sub> emissions, is through the clean development mechanism (CDM) set out in the Kyoto Protocol. This allows the transfer of CO<sub>2</sub> emission certificates to the foreign investor. Among the Chinese registered CDQ power generation projects under the CDM are two at the Anshan Iron and Steel Group providing 137,586 and 132,303 tCO<sub>2</sub>-e/y (certified emission reduction credits) at the Anshan and Yingkou sites, respectively. Details of the CDM projects can be found on the <http://cdm.unfccc.int> website.

Given about 300 Mt coke production without CDQ and a saving of 600 gCO<sub>2</sub>/kWh, the IEA estimated that about 25 MtCO<sub>2</sub> (and 0.2–0.3 EJ/y) could potentially be saved globally by using CDQ processes (IEA, 2007).

### 3.1.2 Sensible heat recovery of COG

The temperature of the crude COG entering the ascension pipes above the coke oven is ~650–1000°C, which is sufficiently high to allow recovery of its sensible heat. The recovered heat could be used on-site for preheating the coal or fuel gas or off-site as district heating. Heat recovery is rarely carried out since it poses both installation and operational problems relating to the high levels of tars and other by-product components condensing at the lower temperatures, leading to corrosion and clogging of the ductwork (Cairns and others, 1998), and their buildup on heat exchanger surfaces (BCS, 2008). There is also the question of whether there is space for retrofitting the equipment in existing coke plants.

Facilities in Japan have successfully applied heat recovery through the use of heat exchangers in the ascension pipes (Couch, 2001). In general, the minimum allowable temperature for the COG in the heat exchanger is 450°C. Cooling to this temperature only enables around one-third of the sensible heat to be recovered (BCS, 2008). It is estimated that COG heat recovery systems could recover up to ~0.3 GJ/t dry coke of steam (Cairns and others, 1998) or ~0.24 GJ/t rolled steel (IEA, 2007) or 0.17 GJ/t steel when the COG has a temperature of 700°C (Li and others, 2010).



### 3.1.3 Sensible heat recovery of waste gas

Another source of sensible heat loss in coke ovens is the waste gases from the combustion of recycled COG or fuel gas used as a fuel in the heating flues. The hot exhaust gases commonly pass through a regenerator to transfer heat to the incoming combustion air and/or fuel (BCS, 2008). Waste gases exit the regenerator at  $\sim 200^{\circ}\text{C}$ , a temperature sufficiently high to allow recovery of waste heat as steam or via a suitable heat exchanger. However, the dew point of the gases is  $\sim 150^{\circ}\text{C}$ , which limits the temperature drop to  $\sim 50^{\circ}\text{C}$ . It has been estimated that around 0.1 GJ/t dry coke could be recovered from the waste gases (Cairns and others, 1998) or 0.19 GJ/t steel (Li and others, 2010).

### 3.1.4 Use of COG

<b>Table 6 Raw COG yield and composition</b> (European IPPC Bureau, 2011)	
Raw COG	Value
Yield, m <sup>3</sup> /t coal	280–450
Density, kg/m <sup>3</sup>	0.42–0.65
Net calorific value, MJ/m <sup>3</sup>	17.4–20
Composition, vol %	
H <sub>2</sub>	39–65
CH <sub>4</sub>	20–42
C <sub>x</sub> H <sub>y</sub>	2–8.5
CO	4–7
CO <sub>2</sub>	1–3
Also contains H <sub>2</sub> S (4–12 g/m <sup>3</sup> ), benzene, toluene and xylene (20–30 g/m <sup>3</sup> ), ammonia (6–8 g/m <sup>3</sup> ), polycyclic aromatic hydrocarbons, other hydrocarbons, oxygen, nitrogen, nitrogen compounds (such as HCN), other sulphur compounds (such as COS) and water vapour	

Large amounts of COG are produced, around 280–600 m<sup>3</sup>/t coal. If the gas is flared then  $\sim 390$  kg CO<sub>2</sub>/t is emitted (European IPPC Bureau, 2011). Instead of flaring, the majority of integrated steel plants utilise the COG (although there are occasions when the COG may have to be flared off). Raw COG has a relatively high calorific value (CV) due to the presence of hydrogen, methane, carbon monoxide and hydrocarbons (*see* Table 6), and contains economically valuable by-products, such as tar and light oils. The by-products are recovered from the COG and sold. The cleaned COG can be used as a raw material in the chemical synthesis of methanol or to produce hydrogen. There are about ten methanol production installations in China with capacities of 70–200,000 t/y (European IPPC Bureau, 2011). Another option is to use the COG as a reducing agent in BFs, in the production of DRI or hot briquetted iron, or as a fuel.

Most steel plants utilise the COG as a fuel to heat the coke ovens, hot blast stoves, BFs, sinter plant furnaces, reheat furnaces and to fuel equipment such as boilers. The boilers supply steam for electricity generation, turbine-driven equipment, such as pumps and fans, and for process heat. The overall efficiency can be improved if the coke oven is fired with BFG, which has a lower CV ( $\sim 3.5$  MJ/m<sup>3</sup>), and the COG is put to a higher quality use, such as power generation. While COG-fired steam cycles achieve about 30% efficiency, combined cycles can reach more than 42% electric efficiency. Overall, about 70% of COG is used in iron and steel production processes, 15% to heat coke ovens and 15% for power generation (IEA, 2007).

The Nikkei Business Daily reported that Nippon Steel Corp would be upgrading the power facilities at its Kimitsu, Oita and Muroran works in Japan to utilise the waste heat and gas generated from the coke ovens and BFs. Power capacity at the works will be raised by 15% to 30% which will help reduce CO<sub>2</sub> emissions by 440 Mt annually. The total investment cost is estimated to be 80 billion yen (US\$882.3 million) (Reuters, 2010).

In China, one-third of coke production in 2005 was in integrated steel plants where 97% of the COG is recovered. COG is still flared from some coke ovens. The other two-thirds were produced by cokemaking enterprises that are located close to coal mines. Only 24% of the COG was recovered at

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these plants. This leaves 250 PJ of COG that could be recovered and used, a savings potential of 25 MtCO<sub>2</sub> (IEA, 2007). There are a number of projects in China where the waste gases will be recovered for power generation. For instance, the Jinan Iron and Steel Works in Shandong Province has installed a 544 MW combined-cycle power plant that utilises waste gases from the coke ovens and BFs. This CDM project will generate 2,295,000 MWh/y, saving 2,089,883 tCO<sub>2</sub>-e/y by displacing power that would otherwise be taken from the local grid (UNFCCC, 2006a).

### 3.1.5 Coal moisture control

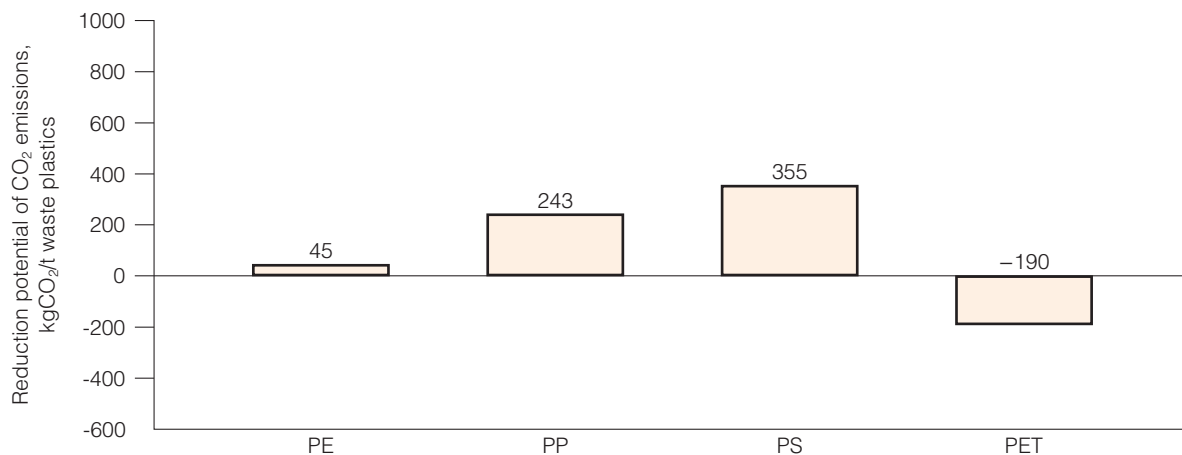
Preheating coal to reduce its moisture from ~8–12% to ~4–6% lowers the energy consumption of coke ovens by ~94–151 MJ/t dry coke/% moisture, and improves coke quality. The coal can be dried by using the heat content of COG or other waste heat sources. However, the additional energy required for coal preheating equates to ~64–105 MJ/t dry coke/% moisture reduction, depending on the process used. Thus coal preheating may not save energy directly, but will lower the specific energy requirement of the process through productivity enhancements of 4.5–7% (Cairns and others, 1998). The authors provide operational information for three plants utilising COG, waste gas and hot coke sensible heat for coal moisture control, including thermal balances for the systems. Worrell and others (2010b) quote a potential reduction of 6.7 kgCO<sub>2</sub>/t coke and fuel savings of 0.3 GJ/t coke if coal moisture control is applied.

It may be difficult to find space on existing plants for the steam heated coal drying units. It is always easier to incorporate such equipment in plants where coal drying is part of the design. However, many facilities have been built with a fairly generous allowance of space around them, including coal stocking areas (Couch, 2001). Coking plants in Japan, South Korea and China are among those utilising, or have retrofitted, this technology. Coal moisture costs for a plant in Japan were 21.9 US\$/t steel (\$ year not given) (APPCDC, 2010).

### 3.1.6 Use of biomass and waste materials

Biomass feedstock is considered to be ‘CO<sub>2</sub> neutral’ since its CO<sub>2</sub> emissions from combustion are offset by the absorption of atmospheric CO<sub>2</sub> during plant photosynthesis. Adding biomass to coking coal blends could therefore mitigate CO<sub>2</sub> emissions from coke ovens and BFs, if renewable and sustainable biomass is used. However, there is a limit to the amount that can be added due to the adverse effect on coke quality. Charcoal addition has the benefit of enhancing coke reactivity, thus lowering the thermal reserve zone temperature in the BF. This decreases the amount of carbon required in the BF and therefore CO<sub>2</sub> generation. Raw wood wastes and charcoal are limited to around 1–3% (Hanrot and others, 2009; Ng and others, 2008; Ota and others, 2006).

Reducing the mineral matter content in charcoal produced from trees is one way for more of the material to be used. If 10% of charcoal could be added to the coking coal blend without detrimental effects on the resultant coke quality, then CO<sub>2</sub> emissions from BFs can be reduced by 56 m<sup>3</sup>/thm, which corresponds to a 31% reduction (Ng and others, 2008). In Canada, the steel industry annually uses 3.7 Mt coke in BFs, equivalent to 13 MtCO<sub>2</sub>. Replacing 10% of coke by charcoal would reduce CO<sub>2</sub> emissions by 1.3 Mt/y (MacPhee and others, 2009). The requisite amount of charcoal would be available from Canadian sources although this is not the case for many countries in the developed world. Biomass sustainability, availability and productivity, as well as its conversion into charcoal, is being investigated as part of the European ULCOS (Ultra-Low CO<sub>2</sub> Steelmaking) project (see [www.ulcos.org](http://www.ulcos.org)). This has progressively focused on charcoal supply from tropical eucalyptus plantations (Fallot and others, 2008). While the global potential for biomass production is large, there is only a finite area of land available without compromising food production. In addition, the price of biomass is likely to rise as the power and other industries utilise it for CO<sub>2</sub> abatement.



**Figure 10 CO<sub>2</sub> emissions reduction potential with 1 t waste plastics** (Sekine and others, 2009)

The addition of waste plastics to the coking coal blend not only reduces energy consumption and hence CO<sub>2</sub> emissions from BFs, but also allows recycling of a waste that may otherwise be landfilled or incinerated. Adding 2 wt% waste plastics to coke mitigates BF CO<sub>2</sub> emissions by 2% (Hanrot and others, 2009). The main downside is the cost of the collection and treatment of the material. The recycling of waste plastics in coke ovens uses existing equipment. However, waste processing equipment will be needed unless suitably treated waste plastics can be bought.

Again, like wood wastes, the amount of waste plastics that can be added to the coking coal blend is currently limited to less than 2 wt% due to detrimental effects on coke quality. Just 1 wt% waste plastic is added to the coke ovens at the Japanese steelworks. In addition, the relative proportions of the different plastic types (polyolefins to polystyrene (PS) and polyethylene terephthalate (PET)) in municipal waste plastics is a critical factor (Diez and others, 2007). It has been found that chlorine does not cause problems as most of the chlorine from the waste plastics is removed by the ammoniacal liquor used for flushing the COG when it exits the coke oven (Kato and others, 2006). New processes are being developed to increase the amount of waste plastics that can be added (Liao and others, 2006).

Sekine and others (2009) calculated the reduction potential of CO<sub>2</sub> emissions when polyethylene (PE), polypropylene (PP), PS and PET are added to the coking coal blend. The system boundary in the life cycle inventory included the pretreatment of the waste plastics, the processes within the steelworks that are affected by waste plastics usage (such as the coke oven and BF), and the associated power plant (where the surplus gas is utilised). PS had the highest CO<sub>2</sub> reduction potential, followed by PP and PE (see Figure 10), whilst PET increases CO<sub>2</sub> emissions. The differences were attributed to differences in the calorific values and coke product yields of each plastic type.

### 3.1.7 Innovative processes

The SCOPE21 (Super Coke Oven for Productivity and Environment enhancement towards the 21st century) project was implemented in Japan in 1996 with the aim to increase energy efficiency and productivity, decrease environmental pollution, whilst expanding the choice of coals. The coal blend is rapidly heated in a fluidised bed dryer before carbonisation in a compact coke oven at 850°C (instead of 1200°C in a conventional coke oven). The resultant coke is reheated to 1000°C in a CDQ unit to complete the processing (Couch, 2001; Worrell and others, 2010). Energy is saved by recovering the sensible heat from the generated and waste gases. A plant has been installed at the Nippon Steel Corp's Oita steelworks. It is expected to consume 21% less energy and emit 0.4 Mt/y less CO<sub>2</sub> than a conventional coking plant (Kojima, 2009).

Carbonyx Inc has developed a coke substitute synthesis process to produce Cokonyx carbon alloy material from non-coking coals. Other pre-specified carbonaceous materials can also be included. Coal is combined with a binder and shaped into briquettes. These are heated to drive off the volatiles and to harden the resultant product in a continuous process. The by-product gases can be recovered and recycled back into the process as fuel and/or utilised to generate electricity (US Steel News, 2008). The process is claimed to achieve both lower emissions and energy consumption (hence lower CO<sub>2</sub> emissions) than conventional coke ovens. In 2010, United States Steel applied for a permit to construct four Cokonyx plants at its Gary Works in Indiana (IDEM, 2010).

## 3.2 Iron ore agglomeration

Iron ore in its natural state occurs as lump ore or fine ore. Lump ore is crushed and screened before shipment from the mine. It must meet certain quality restrictions (>62% iron) and physical characteristics in terms of size and handling since it is fed directly into the BF. The energy needs of the BF depend to some extent on the quality of the ore. The higher the metal content, the lower the energy consumption. Variations in the ore chemical composition can make a difference of about 10–15% in BF energy use. Lump ore is more expensive than ore fines. About 25% of all iron ore is used directly, without agglomeration (IEA, 2007).

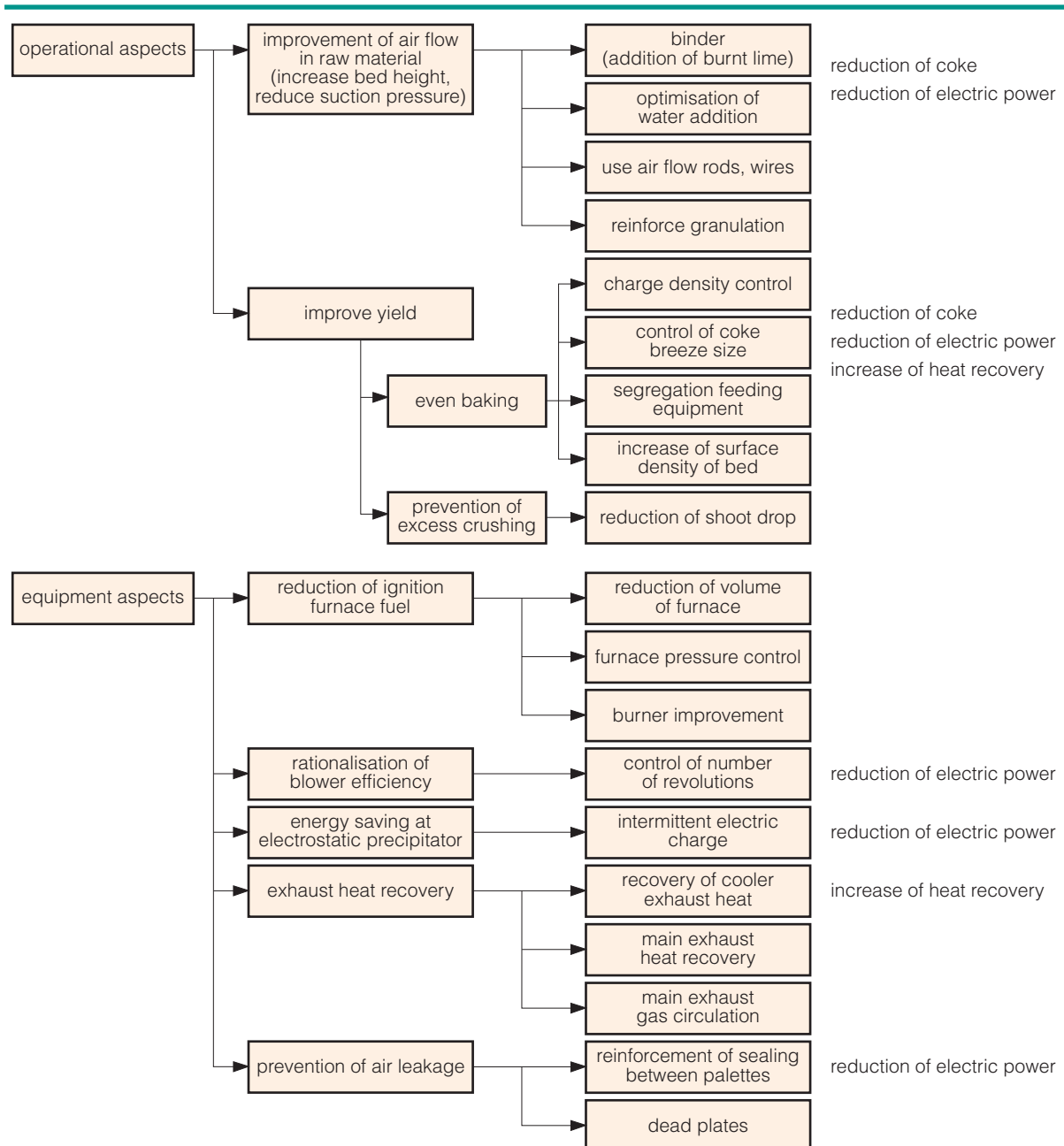
Fine ore must be converted into larger aggregates for use in BFs. These aggregates are often a better feedstock than lump ore (IEA, 2007). The two common ore agglomeration processes are sintering and pelletising. New iron reduction processes that can consume fine ore directly (such as Finex®, *see* Section 6.3) have an important cost advantage since they avoid the cost of agglomeration (and its CO<sub>2</sub> emissions) and the more expensive lump ore.

### 3.2.1 Sintering

More than 50% of all iron ore is converted into sinter (IEA, 2007). Sintering involves heating the fine ore, without melting, causing it to agglomerate into larger granules. Iron ore, coke breeze (coke with particle sizes of <5 mm), and flux (such as lime or limestone) are fed onto a continuous travelling grate and ignited. Air is drawn through the feed to burn the mixture. The bed temperature reaches 1300–1480°C, which is sufficient to fuse the fine ore particles together. The porous fused sinter mass is cooled, crushed and screened, and sent to the BF. The offgas is cleaned before being emitted or utilised. Sintering also allows the steelworks to recycle iron-rich waste materials (such as collected dust, sludge from BFG cleaning, mill scale and recycled sinter from sinter screening), turning them into valuable iron sources, since they can be added to the iron ore mixture.

Direct CO<sub>2</sub> emissions result from the fuel used in the sintering process, from the recycling of waste materials, and from limestone calcination and other process emissions. The incorporation of flux in the sinter saves fuel in the BF. Around 201 kg of coke can be saved for each tonne of limestone fed into the sinter plant instead of into the BF (IEA, 2007). However, CO<sub>2</sub> emissions at the sinter plant will increase with greater amounts of limestone. In addition, CO<sub>2</sub> emissions are higher when carbonate iron ores, such as siderite, are sintered. CO<sub>2</sub> emissions from European plants using non-carbonate iron ores, such as magnetite and haematite, were 161–368 kg/t sinter whereas those plants using carbonate ores were nearly twice as high (European IPPC Bureau, 2011). A higher ore alumina content also results in a higher coke breeze (fuel) consumption. With iron ore quality decreasing, CO<sub>2</sub> emissions are likely to increase.

Energy consumption of sinter plants and their CO<sub>2</sub> emissions are larger than coking plants within an integrated steelworks (*see* Section 2.3). Therefore reducing these factors at the sinter plant could potentially have a larger influence on the overall CO<sub>2</sub> emissions from steelworks. Typically, the sintering process consumes around 1.5–2 GJ/t sinter or 2–3 GJ/tcs. The theoretical minimum energy



**Figure 11 Energy saving measures in the sintering process (APPCDC, 2007)**

needed for ore agglomeration is 1.2 GJ/t output or 1.6 GJ/t steel (Fruehan and others, 2000). This suggests there is potential for reducing the energy consumption of sinter plants and, indirectly, CO<sub>2</sub> emissions. Some of the techniques available are widely applicable and relatively low cost, and are widely used at many sinter plants. Others are more limited in application, due to plant configuration, economics and level of development. Some of the operational and equipment aspects for energy savings are summarised in Figure 11.

Improved process control could save 2–5% of energy use. A 2% saving equates to a primary energy saving of ~0.05 GJ/t sinter and a reduction of 5 kgCO<sub>2</sub>/t sinter. Increasing the bed depth in the sinter plant can lower fuel consumption by 0.3 kg coke/t sinter per 10 mm bed thickness increase and may achieve electricity savings of 0.06 kWh/t (0.002 GJ/t) sinter (EPA, 2010b; Worrell and others, 2010). Reducing air leakage lowers fan power consumption by ~0.011–0.014 GJ/t sinter and CO<sub>2</sub> emissions by 2 kg/t sinter (EPA, 2010b). Large fuel reductions can be achieved by improving the ignition efficiency. Introducing efficient ignition of the sintering furnace in a Chinese steelworks was

**Table 7 Energy efficiency technologies and measures applied to sinter plants in the USA**  
(EPA, 2010b; Worrell and others, 1999, 2010)

	Emissions reduction, kgCO <sub>2</sub> /thm	Fuel savings, GJ/thm	Electricity savings, GJ/thm	Annual operating costs, US\$/thm	Retrofit capital costs, US\$/thm	Payback time, y
Sinter plant heat recovery	57.2	0.55	0	0	4.7	2.8
Reduction of air leakage	2	0	0	0	0.14	1.3
Increasing bed depth	9.9	0.09	0	0	0	0
Improved process control	5	0.05	0	0	0.21	1.4
Use of waste fuels (such as lubricants)	19.5	0.18	0	0	0.29	0.5

calculated to save 8374 GJ (200 toe) of energy/y (Kaneko and others, 2006). Utilising multi-slit burners in the ignition furnace could save ~10–15 kgCO<sub>2</sub>/t sinter (Singhal, 2009) and lower ignition energy by ~30% (Worrell and others, 2010). Ignition furnaces consume about 6% of the total primary energy at the sinter plant (Cairns and others, 1998). The estimated CO<sub>2</sub> and fuel savings when applying energy efficiency techniques on US sinter plants are summarised in Table 7 (\$ year 2008).

JFE Steel installed SuperSINTER™ (Secondary-fuel Injection Technology for Energy Reduction) at its Keihin sinter plant. In this process natural gas is injected into the sintering strand, making the process more energy efficient, and lowering carbon consumption by replacing some of the coke breeze, thereby reducing CO<sub>2</sub> emissions (JFE Holdings, 2009; Takeda and others, 2011).

### Waste heat recovery

The heat consumed in the sintering process is about 33% of the total heat input to the plant, with about 49% released to the atmosphere (IEA, 2007). Waste heat recovery is therefore a key strategy for improved energy efficiency. There are two places where waste heat is discharged from the sinter plant and could potentially be recovered:

- the sensible heat from the main exhaust gas from the sinter strand, around 0.23 GJ/t rolled steel (IEA, 2007);
- the sensible heat of the cooling air from the sinter cooler. Although the temperature and specific heat capacity of sinter are about half that of hot coke, the overall energy content is large owing to the very high sinter production levels. Therefore energy recovery from this source can contribute significantly to the reduction in energy consumption, and hence CO<sub>2</sub> emissions, of a steelworks (Cairns and others, 1998). The sensible heat from the sinter cooling gas is around 0.97 GJ/t rolled steel compared to 0.24 GJ/t rolled steel for CDQ (IEA, 2007).

The temperature of the exhaust gas leaving the sinter strand varies along the length of the strand. In places where it is below 150°C, it is too low to recover heat effectively in a waste heat boiler. However, the temperature leaving the later stages of the sinter strand can be as high as 500°C, which if separated from the earlier stages of the strand, is sufficiently high to allow effective heat recovery, for instance in a waste heat boiler. Such a system, though, would require significant modifications to existing plants (Cairns and others, 1998), and corrosion and condensation problems can occur when using heat exchangers.

Sinter leaves the crusher at the end of the strand at a temperature of ~500–700°C and is air cooled to ~100–150°C. The energy in the cooling air is commonly recovered and used in a number of ways,

including steam generation in a waste heat boiler for use in the steelworks (~0.25 GJ/t sinter (Worrell and others, 2010)) or for electricity generation (~20 kWh/t sinter), hot water generation for district heating, preheating combustion air in the sinter plant, and preheating the sinter mixture. After cooling, the waste gas can be recycled to the sinter cooler and used again for sintered ore cooling. Waste heat recovery from the sinter cooler can lower CO<sub>2</sub> emissions by ~35–40 kg/t sinter (Singhal, 2009).

The sensible heat can additionally be recovered by recirculating the hot waste gas (from the sinter strand and sinter cooler) to the sintering process, either directly or after heat recovery in a waste heat boiler. Partial recycling of the waste gas is a common practice in some countries. Processes that recycle portions of the sinter strand include Emission Optimised Sintering (EOS®), Low Emission and Energy optimised sintering Process (LEEP) and Environmental Process Optimised SINTERing (EPOSINT) or VAI Selective Waste Gas Recirculation System. All these processes decrease coke breeze consumption (up to ~15%) due to the recirculated heat and combustion of the CO in the waste gas, lower energy consumption, decrease CO<sub>2</sub> emissions by around 10%, and increase sinter productivity, as well as reducing dust and gaseous emissions.

The amount of waste heat recovered is influenced by the design of the sinter plant and the heat recovery system. The heat recovery efficiency is 60% for waste gas from the cooler and 34% for waste gas from the sinter strand when the two gas streams are passed through separate waste heat recovery boilers and recirculated back to the sinter bed and cooler (JP Steel Plantech, 2010). Examples of steelworks employing waste heat recovery are discussed in APPCDC (2010), Cairns and others (1998) and European IPPC Bureau (2011). The latter reference includes investment costs for some cases. Costs are also given in Table 7.

Heat recovery is typically provided in new sinter plants. In principle, heat recovery can be retrofitted to existing plants if there is enough space. It is widely practised in Asia (especially Japan and South Korea) and Europe. But it is not practised in sinter plants in the USA (Park, 2008). One reason for this may be economics. As energy costs climb, retrofitting heat recovery may become more attractive.

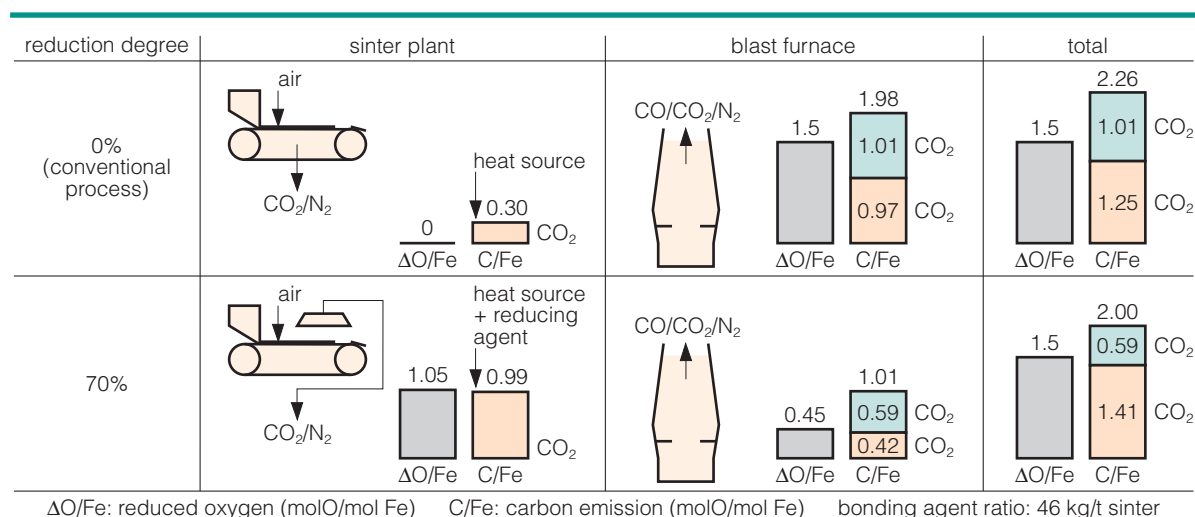
There are a number CDM projects that provide capital and technology for installing waste heat recovery systems in the emerging economies countries (*see* <http://cdm.unfccc.int>). One of these involves JP Steel Plantech (Japan) installing a sinter cooler waste heat recovery system at the Rashitirya Ispat Nigam Ltd/Visakhapatnam Steel plant in India. The system will generate about 20 MW of electricity, equivalent to an annual reduction of 117,000 tCO<sub>2</sub> (JP Steel Plantech, 2009). Calculations by Zeng and others (2009) suggest a potential annual energy saving of about 0.26 EJ (9 Mtce) if the Chinese iron and steel industry utilised the sinter plant waste heat for power generation. It is already employed in some key Chinese enterprises. Around 196 tCO<sub>2</sub>/y could be saved in an integrated 10 Mt/y capacity Chinese steel plant by generating 20 kWh/t sinter (Li and others, 2010).

### Pre-reduced agglomerates

A new sintering process is being developed in Japan in which the iron ore is partially reduced and agglomerated in a conventional sinter strand. Fine iron ore and fine coke breeze are first formed into quasi-particles and coated with fine coke. The internal carbon material acts as a reductant and the carbon coating as a heat source in the sintering strand (Ariyama and Sato, 2006). Although CO<sub>2</sub> emissions from the sinter plant will increase, CO<sub>2</sub> emissions from the BF decrease since less carbon is required for reduction and energy consumption is lowered. Figure 12 compares the carbon emissions from the sintering plant and BF when conventional sinter and 70% pre-reduced agglomerates are utilised. Overall, carbon emissions are reduced by over 10% with pre-reduced agglomerates (Machida and others, 2006).

### Use of biomass and waste fuels

Replacing part of the coke breeze with CO<sub>2</sub> neutral biomass (charcoal) lowers CO<sub>2</sub> emissions, as well as sulphur dioxide and nitrogen oxide emissions, and increases sinter production rates since charcoal reacts faster than coke (APPCDC, 2010; Lovel and others, 2007). The amount of charcoal that can be



**Figure 12 Relationship between carbon emissions and reduction degree of pre-reduced agglomerates** (Machida and others, 2006)

added is limited. Bench-scale experiments indicated that optimum performance in terms of productivity is achieved when 20% of the coke breeze is replaced by wood charcoal (Ooi and others, 2011). This technology is not yet in commercial operation.

Utilising waste materials with a suitable CV content, such as lubricants and waste oils from the cold rolling mills, can reduce the energy demand (*see* Table 7 on page 30). Energy savings of ~0.18 GJ/t sinter, equivalent to CO<sub>2</sub> reduction of 19.5 kg/t sinter, can be achieved depending on the quality and composition of the waste fuels (EPA, 2010b).

### 3.2.2 Pelletising

About 25% of all iron ore is processed into pellets. Most of the production serves as feed for BFs and about one-third of the pellets are used in DRI production (IEA, 2007). The consumption of pellets in BFs is about three times lower compared to sinter. Iron ore pellets are generally made from one well-defined iron ore or concentrate at the mine and are transported in this form. Some steel companies, though, have their own pelletising plants. In a Life Cycle Assessment (LCA), CO<sub>2</sub> emissions from mine pelletising plants should be allocated to the steel making process.

Pelletising converts iron ore into small spheres (9–16 mm) while upgrading its iron content. The wet or dry iron ore is crushed and ground, and the resultant slurry is mixed with binding agents before passing through the balling machine. The green balls produced are fed into the induration strand where they are dried and heated to at least 1250°C. The pellets are then cooled and screened, and the undersized or broken pellets are recycled.

CO<sub>2</sub> emissions from and energy consumption at pelletising plants vary mainly due to differences in design, the type of ore processed, and whether the sensible heat in the gas flows is utilised. Three pellet plants in EU25 emitted around 17–193 kg CO<sub>2</sub>/t pellets (European IPPC Bureau, 2011). Energy consumption at integrated steelworks processing haematite ores is ~1262 MJ/t pellets (Cairns and others, 1998). In 2005, the specific energy consumption in European plants (mainly stand alone pelletising plants) had decreased to 186–662 MJ/t pellets (European IPPC Bureau, 2011). Induration strands utilising the grate kiln process predominantly use coal whilst the travelling grate process uses oil or gas. At most pelletising plants, carbon-bearing additives in the pellets provide part of the heat required in the induration strand. External energy consumption at these plants is at the higher end of the quoted range. Plants processing magnetite ores have an energy consumption at the lower end of the range because the oxidation of magnetite to haematite releases energy and thereby acts as a



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carbon-free fuel. Magnetite oxidation supplies around 60% of the thermal energy in the induration strand. This means that iron ore pellets produced from magnetite ore are significantly more CO<sub>2</sub>-efficient than iron ore pellets from other types of ores.

Improved process control, better sealing of the process to prevent ambient air ingress into the gas streams, and fuel switching from coal or oil to natural gas could help lower CO<sub>2</sub> emissions. The use of biomass in the future may be a viable option but requires more research and development (Hooey, 2010).

### Waste heat recovery

As at sinter plants, the sensible heat in the gas flows can be recovered. For example, the hot air from the primary cooling section in the induration strand can be used as secondary combustion air in the firing section. In turn, the heat from the firing section, and heat from the secondary cooling section, is utilised in the drying section of the induration strand.

In integrated steelworks, the cooling section can generate more sensible heat than can be used in the induration strand. This heat can be utilised to dry the ore prior to grinding by recirculating the hot air (250°C) in a 'hot air recirculation duct' to the drying and grinding unit in the steelworks. The gross energy consumption at a plant practising this technology was ~1.4 GJ/t pellet. About 0.7 GJ/t pellet is supplied by means of heat recuperation, whereas ~0.7 GJ/t pellet is introduced via the fuel. The 'hot air recirculation duct' accounts for an energy recovery of ~0.067 GJ/t pellet, around 4% of gross energy consumption (European IPPC Bureau, 2011). It can be retrofitted at existing plants with an appropriate design and a sufficient supply of sensible heat.

## 4 Blast furnaces

Iron making is the process of reducing iron ore (solid oxidised iron) into iron through the removal of the oxygen. It is the most energy-intensive stage of the steel process and is the largest producer of CO<sub>2</sub>. This chapter examines how to reduce the energy consumption and CO<sub>2</sub> emissions from BFs, and the following two chapters covers DRI and the newer smelting reduction processes.

Essentially all primary iron and steel production processes are based on the same chemical reactions. However, the material and energy flows within integrated steelworks and mini-mills are very different. In iron ore reduction processes, a reducing agent, based on carbon and/or hydrogen, removes the oxygen from the iron oxides. CO<sub>2</sub> is inevitably produced during reduction, and is emitted with the offgas from the reduction vessel. Oxygen removal can take place either above or below the melting point (1530°C) of the ore and the reduced iron. Reduction above the melting point results in molten hot metal. Most of the gangue materials segregate from the liquid iron and float upon it. Because of the high temperature and the liquid state of the iron, carbon readily dissolves in the hot metal. The hot metal also contains impurities such as sulphur, phosphorus, silicon and manganese that are removed in the subsequent steel making processes. Hot metal is produced in BFs and by alternative smelting reduction processes. Reduction of iron ore below its melting point results in DRI.

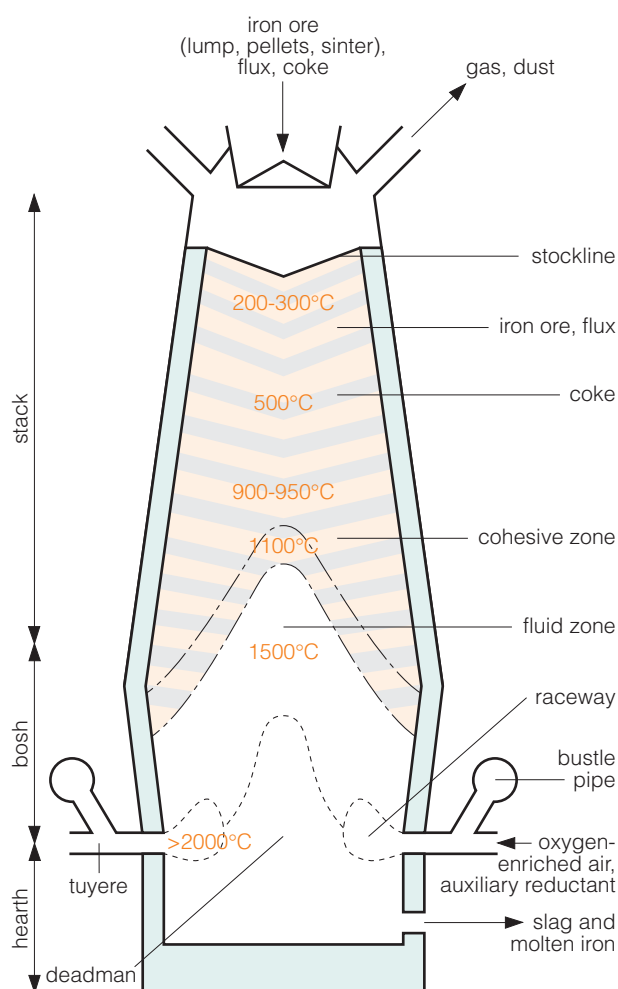


Figure 13 Blast furnace cross section

The most common method of producing iron, accounting for more than 90% of world iron production, involves the BF. Prepared iron ore (lump ore, pellets, sinter), coke and limestone are charged into the top of the BF (see Figure 13). A hot air blast (commonly enriched with oxygen) and often an auxiliary reductant (such as coal) are blown through the tuyeres near the bottom of the furnace. The hot air blast reacts with the coke in the burden (and any auxiliary reductant) to form reducing gases (carbon monoxide and hydrogen) which flow countercurrent to the descending burden. The raw materials take six to eight hours to descend to the bottom of the furnace where they become liquid slag and liquid iron. The hot metal is tapped and if the sulphur content of the hot metal is too high, processed in a desulphurisation unit. It is then transported to the BOF for refining (see Chapter 7).

Slag from the BF is tapped, cooled and either sold or landfilled. Another product is the hot gas which exits the top of the BF. The BF gas (BFG, also termed top gas or BF offgas) contains around 17–25% of CO<sub>2</sub> (see Section 4.3). It is cleaned, cooled and commonly burnt as a fuel in the hot blast stoves which are used to preheat the air entering the BF. Any excess gas is utilised to generate steam and electricity for on-site use or sold.

The production of 1 t of hot metal generates ~1.5 t of CO<sub>2</sub>. Only about half of this is produced directly by the BF. The rest is produced by combustion of the CO in the BFG (Riley and others, 2009).

Measures for lowering CO<sub>2</sub> emissions from BFs (Ribbenhed and others, 2008) include:

- utilising higher quality raw materials;
- changing to a reductant (injectant) with a lower CO<sub>2</sub> emission factor;
- decreasing the amount of reductant used, for example, by increasing the blast temperature;
- changing the fuel mix (including fuels in addition to those used as reductant), by using fuels with a low CO<sub>2</sub> emission factor;
- decreasing flaring of generated BFG by utilising the gas on-site or selling it;
- recirculating BOF slag to the BF, resulting in a decreased demand for limestone and thereby less CO<sub>2</sub> would be emitted. But if the slag contains compounds such as vanadium and phosphorous oxides, these can adversely affect the BF process;
- improving yields.

The iron making process consumes more energy compared with other processes within an integrated steelworks, with consequently greater energy savings potential. Although the BF is an energy efficient process, it still consumes 25–30% more energy than the absolute theoretical minimum of 9.8 GJ/thm (Fruehan and others, 2000). The practical minimum energy, though, is 10.4 GJ/thm, which is the sum of the chemical energy, the carbon content of the hot metal (5% C), the energy in the hot metal and the energy needed for limestone calcination, if limestone is added (Fruehan and others, 2000; IEA, 2007). Calcination of limestone consumes ~4.7 GJ/t CaO and releases ~0.79 tCO<sub>2</sub>. The potential energy saving at individual plants is dependent on the technologies already in use and those that can be retrofitted. State-of-the-art BFs are already operating near the ideal process conditions and therefore there is relatively little scope for further reductions in energy consumption at these plants.

The principal techniques (BATs) for reducing energy consumption (if they are not already in use) are:

- direct injection of auxiliary reductants;
- energy recovery from BFG;
- energy savings at the hot stoves;
- energy recovery from the top gas pressure (in a top pressure recovery turbine);
- sensible heat recovery from the slag.

Size affects BF efficiency, with smaller furnaces in China emitting up to 25% more CO<sub>2</sub> than large ones. The CO<sub>2</sub> intensity for Chinese BFs with a capacity >3000 m<sup>3</sup> is 1.09 tCO<sub>2</sub>/t compared to 1.31 tCO<sub>2</sub>/t for those with a capacity of 300–999 m<sup>3</sup> (Wang and others, 2007). A larger BF is usually more efficient because the heat losses are lower (larger surface/volume ratio) and it is usually more economical to install energy efficient equipment. For BFs of a certain size the energy efficiency is independent of the production capacity. There are many energy-efficient mid-size BFs producing 3500–6500 t/d. In China and India there is a trend to use mini-BFs to feed EAFs. This allows small-scale steel production, which is better adjusted to local market circumstances and requires less capital. However, this results in lower energy efficiency. The IEA has estimated that CO<sub>2</sub> emissions in China can be reduced by 37 Mt/y, if all furnaces were as efficient as the largest ones that are currently in operation (IEA, 2007). The Chinese Government is closing its smaller BFs (<380 m<sup>3</sup> capacity).

Using BATs on BFs and given an average savings potential of 75 kg coal and coke/thm, iron and steel manufacturing has an energy efficiency improvement potential of 1.5 EJ/y and could reduce CO<sub>2</sub> emissions by 150 MtCO<sub>2</sub>/y (IEA, 2007). This includes the BATs measures listed earlier, as well as the closure of inefficient small-scale BFs. It excludes the CO<sub>2</sub> benefits of switching to waste plastic or charcoal. BATs and other measures for reducing CO<sub>2</sub> emissions and energy consumption are discussed in the following sections. The estimated CO<sub>2</sub> and fuel savings from their application on US BFs are given in Table 8.

**Table 8 Energy efficiency technologies and measures applied to BFs in the USA (EPA, 2010b; Worrell and others, 1999, 2010)**

	Emissions reduction, kgCO <sub>2</sub> /thm	Fuel savings, GJ/thm	Electricity savings, GJ/thm	Annual operating costs, US\$/thm	Retrofit capital costs, US\$/thm	Payback time, y
PCI to 130 kg/t iron	47	0.77	0	-3.1	11	2
PCI to 225 kg/t iron	34.7	0.57	0	-1.6	8.1	2.4
Natural gas injection to 140 kg/t iron	54.9	0.9	0	-3.1	7.8	1.3
Top pressure recovery turbines (wet type)	17.6	0	0.11	0	31.3	29.8
Recovery of BFG	4	0.07	0	0	0.47	2.3
Hot blast stove automation	22.6	0.37	0	0	0.47	0.4
Recuperator on hot blast stove	4.9	0.08	0	0	2.2	8.7
Improved BF control systems	24.4	0.4	0	0	0.56	0.4

## 4.1 Raw materials

The quality of the raw materials added to the top of the BF influences both energy and reductant consumption, and consequently CO<sub>2</sub> emissions. BF operation is still largely based on experience, and therefore the impact of raw material quality on process operation cannot easily be transferred from one BF to another.

### 4.1.1 Iron ore and other iron-bearing materials

Variations in the chemical composition of ore can make a difference of around 10–15% in BF energy use (IEA, 2007). The higher the metal content of the iron burden material, the lower the energy and reductant consumption. Less slag is produced and smaller amounts of limestone are required, and hence less energy is needed to heat and melt the gangue and CaO.

If the iron content of the feedstock improves by 1%, coke use decreases by 1.5–2%. The use of prepared burden (sinter and pellets which have a higher iron content than lump ore) reduces the coke ratio substantially. Data for European BFs suggest that an increase in the prepared burden ratio from 65 to 95% lowered the coke ratio from 410 to 330 kg/thm. For mini-BFs, an increase in the iron content of the ore from 50 to 55% decreased reductant use from 750 to 600 kg/thm, a 20% saving. An increase in daily furnace productivity from 1 to 1.5 t/m<sup>3</sup> reduces the reductant rate from 750 to 600 kg/thm (IEA, 2007).

The addition of small amounts of scrap, DRI and hot briquetted iron (HBI) to the feedstock increases the metallic iron input to the BF (and increases productivity). For each 10% of the iron feedstock that is metallic, the reductant consumption decreases by 7% and furnace productivity increases by 8% (Hunter, 2009). CO<sub>2</sub> emissions are reduced by 200 kg/t HBI (1000 kg minus 800 kg for HBI production and transport) (Whipp, 2008). The amount of tramp (unwanted) elements in the scrap limits the amount that can be added; typically to less than 30%. The decrease in reductant requirement

is a relatively linear relationship up to 20–30% scrap addition (Wang and others, 2009). The use of pre-reduced or metallic charge material can only yield benefits if the CO<sub>2</sub> emissions associated with the production of such materials are lower (*see* Chapter 5).

However, adding scrap or DRI/HBI to the BF may not be the best strategy to reduce CO<sub>2</sub> emissions at an integrated plant as scrap is also charged to the BOF, where it acts as a coolant (*see* Chapter 7). There is an optimum distribution between scrap charging to the BF and BOF for different amounts of scrap. Using a mixed integer linear programming model, it was shown that at moderate scrap rates, lower direct CO<sub>2</sub> emissions are favoured by scrap addition to the BOF. That is, it is more beneficial to allow higher coke consumption in the BF and higher silicon content in the hot metal to gain a higher scrap melting capacity in the BOF (Ryman and Larsson, 2006; Wang and others, 2009). When the scrap addition rate is over 100 t/h, then the scrap is distributed between the BF and BOF for minimum CO<sub>2</sub> emissions with scrap preferentially added to the BOF until the heat capacity of the bath is balanced. Further work showed that although the use of scrap in the BF-BOF system generally lowers CO<sub>2</sub> emissions and energy consumption, it is more expensive. Using iron ore pellets generally leads to lower costs, but higher energy use and direct CO<sub>2</sub> emissions (Wang and others, 2009). The trade-offs between the objectives of cost and CO<sub>2</sub> could provide useful information for decision makers at steelworks to generate strategies under CO<sub>2</sub> emission trading schemes. Similar results would be obtained if DRI/HBI were utilised instead of scrap.

Increasing the reactivity of the iron source also lowers reductant consumption and can improve the energy efficiency of the BF. This can be achieved by utilising composite carbon-iron ore agglomerates, whereby coke or coal is added to the iron ore (Kamijo and others, 2009; Ueda and others, 2009a). The addition of catalysts, such as biomass char, can further decrease the reductant rate (Ueda and others, 2009b).

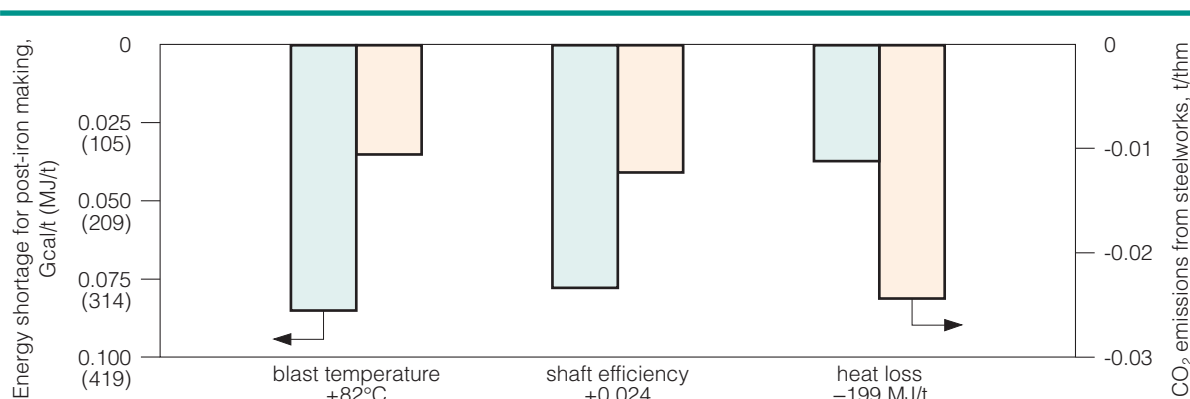
#### 4.1.2 Coke

As most of the CO<sub>2</sub> emissions arise from combustion of reducing agents in the BF, abatement measures regarding the reductants are important. Decreasing coke consumption by 10 kg/thm would reduce CO<sub>2</sub> emissions by ~29 kg/thm (Ribbenhed and others, 2008). This can be achieved by improving coke quality, lowering energy consumption and changing operating parameters. The effect of these measures on maintaining the energy balance of iron making and downstream processes must be investigated before implementation. Lowering coke consumption additionally results in less energy use for cokemaking, and consequently lower CO<sub>2</sub> emissions from coking plants.

Coke quality is of fundamental importance in the operation of BFs, especially its strength and reactivity. This is because coke breakdown within the furnace leads to the accumulation of fines and the loss of permeability for both gases and liquids. This, in turn, leads to increased energy consumption, as well as unstable operation and lower productivity. The quality of coke is more stringent with higher rates of auxiliary reductant injection, which lowers the coke rate. Coke quality is largely dictated by the parent coal properties.

Improving the reactivity of coke, whilst maintaining its strength, can lower coke consumption. Using a calcium-rich coke (where calcium acts as a catalyst) in the Muroran BF2 in Japan decreased the reductant agent rate (coke and coal) by 10 kg/thm (Nomura and others, 2006). The coke is produced by adding a calcium-rich non-caking coal to the coking coal blend.

Low ash coke is preferred as a high ash content means additional flux and higher slag volumes to be removed, and hence increased energy consumption and lower productivity. A 1% increase in coke ash raises the slag rate by 10–12 kg/thm, and results in a 2% increase of coke use, that is, ~1 kg/thm (Carpenter, 2006; IEA, 2007). The energy demand for every 10 kg/thm of slag is ~63 MJ/thm (Kumar and Mukherjee, 2004).



**Figure 14** Changes in CO<sub>2</sub> emissions and supplied energy with a 10 kg/thm reductant rate decrease (Sato and others, 2006)

Oxygen enrichment of the hot blast, increasing blast temperature, improving shaft efficiency and decreasing heat loss from the BF walls can lower CO<sub>2</sub> emissions. Figure 14 shows the changes in CO<sub>2</sub> emissions and supplied energy from the iron making process when the reductant rate (coke and coal) is decreased by 10 kg/thm via three of these measures. Suppressing the peripheral gas flow in the BF reduces heat loss and improves shaft efficiency (which has the largest impact on CO<sub>2</sub> emissions). But whether this can be achieved depends on the quality of the raw materials used and the changes in the supplied energy to downstream processes (Sato and others, 2006). The reduction in supplied energy is largest for the increased blast temperature case due to higher energy consumption in the hot stoves.

In general, coke consumption decreases by 10 kg/thm for every increase of 40°C in blast temperature (Poveromo, 2004). Limitations in existing equipment (principally the hot stoves) may mean that blast temperatures cannot be improved. Reductant (coke and coal) consumption was decreased by ~8 kg/thm in a Swedish steel plant by increasing the blast temperature, using high reducing nut coke and utilising energy waste oxide briquettes in the iron ore pellet layers. No investment was needed for this measure (Ribbenhed and others, 2008). Less energy, though, is available for downstream processes since more BFG is consumed in the hot gas stoves. Minimisation of BFG production also lowers CO<sub>2</sub> emissions but may not be possible at plants where utilisation of the BFG is important, for instance, to ensure power supply to other works areas.

### 4.1.3 Charcoal

Replacing coke in the BF with charcoal, whilst not resulting in any energy efficiency gains, reduces CO<sub>2</sub> emissions substantially if the charcoal is produced in a sustainable manner. LCAs of charcoal and steel production have indicated that GHG reductions of up to 55% may be possible if all the coke is replaced by charcoal (Lund and others, 2008). Another LCA study found that substituting 100% and 20% coke with charcoal lowered CO<sub>2</sub> emissions by 4.5 and 1.2 kg/kg steel, respectively, over the base case (Norgate and Langberg, 2009). These values include credits for electricity and eucalypts oil co-products from charcoal production using Mallee eucalypts. Without these credits, the CO<sub>2</sub> emission reductions are 1.3 and 0.3 kg/kg steel for 100% and 20% coke substitution, respectively. With costs of charcoal and coal in the order of 386 US\$/t and 90 US\$/t respectively, charcoal is not competitive with coal. However, the introduction of carbon trading schemes or carbon taxes can be expected to improve its competitiveness. A carbon tax in the order of 30–35 US\$/tCO<sub>2</sub> would be required for the overall charcoal and coal costs to be roughly equal. Without the charcoal co-product credits, this increases to about 95–115 US\$/tCO<sub>2</sub>. A more appropriate comparison would be to compare charcoal with coke, which it is replacing. Coke is more expensive than coal, making charcoal more competitive. The price of both coal and coke has risen considerably since the study was published.

However, the low strength and low abrasion resistance of charcoal limits its use in large BFs to below 20% (Norgate and Langberg, 2009). A processed type of charcoal with better mechanical properties, termed 'biocoal', is under development. Otherwise charging a small amount of charcoal through the top of a BF, where it is consumed in the upper part of the furnace, reduces coke consumption without impairing permeability. Charging 20 kg of charcoal lowered coke consumption by ~30 kg/thm, but BFG production would also be reduced (Hanrot and others, 2009).

Charcoal can replace 100% coke in smaller furnaces (Gupta and Sahajwalla, 2005). These smaller furnaces can operate with lump iron ore alone and so no ore preparation is needed, thus eliminating CO<sub>2</sub> emissions from sintering plants. Charcoal has lower ash, sulphur and phosphorus contents and higher volatile matter content than coke. The slag rate in charcoal BFs is usually <150 kg/thm, and a typical charcoal rate is below 500 kg/thm. Less lime is required (Nogami and others, 2004), and consequently CO<sub>2</sub> emissions from the lime kilns are lower. The offgas from charcoal-based BFs has a higher CV (4–4.2 MJ/m<sup>3</sup>) compared to coke-based furnaces (Gupta, 2003). The advantages and limitations of biomass (woodchar) use are reviewed by Gupta (2003).

Charcoal is used in iron production only in South America, notably in Brazil. In 2005, one third of Brazilian iron was produced using charcoal. Just over half of the charcoal came from planted forests and the remainder from native forest. The average CO<sub>2</sub> emissions in Brazil, using charcoal produced from native forests, was 0.3–0.55 t/t steel (IEA, 2007). One challenge if more BFs use charcoal will be to sustain sufficient forests to manufacture the required charcoal. Producing 500 Mt of hot metal a year requires over 40,000 hectares (400 km<sup>2</sup>) of forest (IISI, 2005). Biomass sustainability, availability and productivity is reviewed by Fallot and others (2008) as part of the European ULCOS (Ultra-Low CO<sub>2</sub> Steelmaking) project (*see* [www.ulcos.org](http://www.ulcos.org)).

## 4.2 Injectants

The injection of auxiliary reducing agents through the tuyeres is a well-established practice, that can be retrofitted to BFs (provided there is space). It decreases coke consumption in the BF, thereby lowering CO<sub>2</sub> emissions and the energy demand of the coking plant. In addition, H<sub>2</sub>-rich reducing agents can promote H<sub>2</sub> reduction, resulting in lower CO<sub>2</sub> emissions from the BF (the H<sub>2</sub> content of coke is only ~0.5%). Energy consumption also tends to decrease because of lower heat demand by the direct reduction, solution loss and silicon transfer reactions. Injecting reductants usually has the benefit of increasing furnace productivity and can save costs by replacing more expensive coke. The injectant, though, cannot replace coke as coke is needed to physically support the iron ore.

Injectants include coal, heavy fuel oils, oil residues, natural gas, COG, BOF gas, waste plastics, charcoal and animal fats. Praxair is developing a process which injects H<sub>2</sub> into the BF and recovers CO<sub>2</sub> from the BFG (Riley and others, 2009). Technology to use H<sub>2</sub>, produced by reforming COG, as an injectant is being investigated in Japan under the COURSE50 programme (Kojima, 2009). This section will examine the effect of some of these injectants on CO<sub>2</sub> emissions. Injecting BFG is covered in Section 4.3.1.

### 4.2.1 Coal

Coal is the most commonly used injectant. The net energy savings of pulverised coal injection (PCI) have been calculated as ~3.76 GJ/t coal injected. At an injection rate of 180 kg/thm, energy savings amount to 0.68 GJ/thm or 3.6% of the gross energy consumption of the BF. Higher input rates should enable bigger energy savings (European IPPC Bureau, 2011). The fuel savings and CO<sub>2</sub> reductions for two different rates of PCI for US BFs are indicated in Table 8 (on page 36), which shows the opposite effect – higher CO<sub>2</sub> reductions and fuel savings for the lower PCI rate. Fuel injection, however, does require energy for oxygen and coal injection, electricity and equipment for grinding the coal.

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For every kg of coal injected, ~0.8–1 kg of coke is replaced, depending on energy and carbon content of the coal and the injection rate (Carpenter, 2006), or ~0.9–1.1 GJ coal replaces 1 GJ of coke (Cairns and others, 1998). Low volatile coal replaces more coke than high volatile ones. For instance, 150 kg of low volatile coal reduces coke consumption by 18–26 kg more than the same amount of high volatile coal (IEA, 2007). Lower ash coals are preferred. For each percentage increase in the ash content of injected coal, ~1.5–6 kg/thm of extra coke is consumed (IEA, 2007; Poveromo, 2004), increasing the carbon input and therefore, CO<sub>2</sub> emissions.

The theoretical maximum for coal injection is thought to be ~270 kg/thm (Ribbenhed and others, 2008). This limit is set by the carrying capacity of the coke and thermochemical conditions in the BF. According to the World Steel Association, an increase of coal injection above 180 kg/thm does not reduce the coke amount, and the additional coal is just gasified to produce more BFG. Nevertheless, Geerdes and others (2011) discuss how PCI rates of 300 kg/thm could be achieved with high O<sub>2</sub> enrichment, reducing CO<sub>2</sub> emissions when the BFG is used for power generation (*see* Section 4.3).

Trials have shown that coal injection can replace up to half the coke now used in BFs. Assuming that coal and coke have the same energy content, that half of all coke is replaced by injected coal, and that the energy used in coke production is 2–4 GJ/t coke, the potential for coal savings in cokemaking would amount to 12 Mtoe/y (0.5 EJ/y), equivalent to 50 Mt/y of CO<sub>2</sub> (IEA, 2008a). PCI is discussed in an earlier IEA Clean Coal Centre report (Carpenter, 2006).

## 4.2.2 Natural gas

Natural gas is another common injectant and, according to EPA (2010b), it is typically applicable only to medium-sized furnaces having production rates of 1.3–2.3 Mt/y. 1 GJ natural gas emits ~56.5 kgCO<sub>2</sub>, whilst 1 GJ coke produces ~103 kg (Ribbenhed and others, 2008). Natural gas has a higher replacement rate than coal of ~0.9–1.15 kg/kg coke or 1.3 GJ natural gas replaces 1 GJ coke (Cairns and others, 1998). Maximum injection rates, though, are lower due to technical reasons related to furnace temperature; natural gas has a larger cooling effect on the flame temperature than coal and heavy oil, and so requires more O<sub>2</sub> enrichment. Hence total coke replacement rates are lower with natural gas, affecting CO<sub>2</sub> savings from the coking plant. However, natural gas enriches the BF with H<sub>2</sub>. H<sub>2</sub> reduction does not produce CO<sub>2</sub> thus helping to reduce CO<sub>2</sub> emissions from the BF.

Injecting up to 140 kg natural gas/t iron is estimated to save 0.9 GJ/thm and 54.9 kgCO<sub>2</sub>/thm (*see* Table 8 on page 36). The resulting BFG has a higher CV (influencing CO<sub>2</sub> emissions from its use in downstream processes). CO<sub>2</sub> emissions can be lowered by replacing coal or fuel oil injectants with natural gas or by injecting natural gas simultaneously with coal. The complete substitution of coal and fuel oil by natural gas would reduce net GHG emissions by 10% compared to the average EU15 emission level of 1650 kgCO<sub>2</sub>/thm (Croezen and Korteland, 2010). Natural gas injection is limited to steelworks with easy access to cheap natural gas supplies.

## 4.2.3 COG

About 1 kg of COG replaces 0.98 kg of coke. Trial operations of COG injection at two BFs in Linz, Austria, achieved a 4.5% reduction in BF CO<sub>2</sub> emissions (Buegler and Skoeld, 2007). Although injecting COG lowers CO<sub>2</sub> emissions from the BF, overall CO<sub>2</sub> emissions from the integrated steelworks will only decrease if low-CO<sub>2</sub> electricity or other low CO<sub>2</sub>-energy can be purchased to compensate for the input of COG into the BF. COG injection requires a compressor unit which consumes ~0.73 GJ (204 kWh)/t COG (European IPPC Bureau, 2011). The utilisation of COG for injection is highly dependent upon the availability of the gas that may be used effectively as a fuel elsewhere in the steelworks (*see* Section 3.1.4). Maximum level of COG injection is thought to be 100 kg/thm, set by thermochemical conditions in the furnace (European IPPC Bureau, 2011).



#### 4.2.4 Charcoal

Replacing part or all of the fossil fuel (coal, oil, natural gas) injectant with charcoal can lower CO<sub>2</sub> emissions. The lower strength of charcoal, which limits its use as a lump coke replacement (see Section 4.1.3), becomes redundant when used as an injectant. Injecting charcoal through the tuyeres also has the advantage of using current BF facilities, without large modifications and investment and, hence, a faster industrial application. Charcoal fines are currently injected at rates of 100 to 150 kg/thm in small charcoal BFs in Brazil (Babich and others, 2010).

Numerical modelling by Ng and others (2008) showed that CO<sub>2</sub> emissions from the BF iron making process (coking plant, BF and hot stoves) are reduced by nearly 25% (from 890 m<sup>3</sup>/thm to 671 m<sup>3</sup>/thm) when the coal injectant (at 140 kg/thm) is replaced by charcoal. This equates to a GHG emission reduction from 13.7 to 10.5 Mt/y for the Canadian iron making industry (excluding CO<sub>2</sub> emissions from charcoal production), based on the production of 9.04 Mthm in 2008 (Ng and others, 2010a). The raw biomass required could be met by roadside residues produced by the forest industry. Charcoal injection at a higher rate (200 kg/thm) reduces CO<sub>2</sub> emissions by 28% (to ~1300 kg/t HRC) compared to a BF injecting coal at the same rate (Hanrot and others, 2009). Studies have shown that most of the CO<sub>2</sub> directly released from BFs injecting charcoal at this rate is absorbed by the forest that is planted for charcoal production (Nogami and others, 2004).

Besides the positive environmental effect, the use of charcoal can also provide economic advantages in the form of better quality of metal and the possibility of higher productivity due to its low sulphur, phosphorus and ash content. However, the volume and CV of BFG decreases affecting downstream processes. The change in coke rate, furnace productivity and operational parameters when replacing pulverised coal with charcoal is dependent on the charcoal ash content and composition (Babich and others, 2010). A study by Helle and others (2009) found that biomass injection may be economical if its price is below a certain share of the coal (or coke) price, and this critical ratio increases with the CO<sub>2</sub> emission price.

#### 4.2.5 Waste plastics

Injecting waste plastics, which have a higher CV than coal, decreases BF coke and energy consumption and can lower CO<sub>2</sub> emissions by about 30% in comparison to coal and coke (Ogaki and others, 2001). An advantage of waste plastics is their low sulphur and alkali content, but the chlorine content (due to PVC) may lead to dioxin formation. Like natural gas injection, injecting waste plastics increases the amount of H<sub>2</sub> in the BF. Waste plastics injection is currently practised in Austria, Germany and Japan.

Delgado and others (2007) estimated that injecting 1 t of an average non-chlorinated thermoplastic (average 800 g C/kg) reduces CO<sub>2</sub> by 113 kg. Replacing 25% of the heavy oil injectant with waste plastics at the Linz works in Austria will cut CO<sub>2</sub> emissions by 400,000 t/y (voestalpine, 2007). Life cycle methodology used by Narita and others (2001) estimated the CO<sub>2</sub> reduction effects of coal and waste plastics injection to be 0.07 and 0.16 kgCO<sub>2</sub>, respectively, at an injection rate of 0.1 kg/kg of hot metal. A LCA study by Inaba and others (2005) showed that the CO<sub>2</sub> reduction potential for waste plastics is dependent on whether they replace the coke or pulverised coal (or other injectant). Injecting 1 kg of waste plastics replaces ~0.75 kg of coke, 1.3 kg of coal or 1 kg of heavy oil (Carpenter, 2010).

A life cycle inventory study by Sekine and others (2009) found CO<sub>2</sub> emissions would vary between 398 to 580 kgCO<sub>2</sub>/t of injected waste plastics taken from seven Japanese cities. This was mainly due to differences in the amount of impurities (ash and water) in the municipal waste plastics. The European IPPC Bureau (2011) quotes a limit of 70 kg/thm due to thermodynamic and kinetic conditions in the raceway. Calculations by Asanuma and others (2000) indicated that the maximum injection rate is 250 kg/thm for 3.1 mm-sized agglomerated waste plastics.

Instead of injecting waste plastics directly, they could be gasified to produce a syngas for injection into a BF. A 7% reduction in CO<sub>2</sub> emissions could be achieved using a circulating fluidised bed gasification process (Hanrot and others, 2009). More information about the injection of coal and waste plastics into BFs can be found in Carpenter (2010).

### 4.3 BFG use and recycling

About 35–40% of the energy content of the reducing agents is converted into BFG. The gas contains about 20–28% CO, 1–5% H<sub>2</sub>, 17–25% CO<sub>2</sub>, 50–55% N<sub>2</sub>, sulphur and cyanide compounds, and dust. Higher H<sub>2</sub> contents of up to 10% are produced with natural gas or COG injectants. The CV is low, ~2.7–4 MJ/m<sup>3</sup>, depending on its CO content. Nevertheless the large amounts of BFG generated (~1200–2000 m<sup>3</sup>/thm) mean the energy recovery potential is high and consequently, the potential to reduce CO<sub>2</sub> emissions. Total export from the BF is ~5 GJ/thm, which equals 30% of the BF gross energy consumption (European IPPC Bureau, 2011). The high CO<sub>2</sub> content means that minimising BFG production will lower CO<sub>2</sub> emissions or the CO<sub>2</sub> could be captured and stored (*see* Chapter 9).

The low CV limits the use of BFG as a fuel and therefore it is often enriched with natural gas, COG or BOF gas, which have higher CVs. BFG is used mainly for blast heating (*see* Section 4.6), coke oven heating (*see* Section 3.1.4), power production, combined heat and power production, in hot mill reheating furnaces or is recycled to the BF (*see* Section 4.3.1). Using O<sub>2</sub> injection instead of an air blast increases the CV of the BFG, which can then be used as a fuel in a combined cycle power plant (Liu and Gallagher, 2010). But O<sub>2</sub> injection has not yet been proven. In addition, combustion of BFG generates CO<sub>2</sub>. Significant amounts of BFG are still flared during periods when supply exceeds demand. Installing larger storage systems can help minimise flaring.

Combined cycle power generation with enriched BFG has a higher electric efficiency (>41%) than conventional power generation (<30%). Hence combined cycle power generation leads to lower CO<sub>2</sub> emissions. As a result, there are a number of CDM projects building combined cycle power plants utilising BFG, details of which can be found on the UNFCCC website (<http://cdm.unfccc.int/projects>). One project is the construction of a 300 MW combined cycle power plant at Anshan Iron and Steel Group's Anshan works using surplus BFG and COG that would otherwise be flared. About 1890 GWh/y would be generated, replacing electricity that would otherwise be bought from the coal-fired power dominated power grid. Emission reductions of 1,739,716 tCO<sub>2</sub>-e/y are projected (UNFCCC, 2008a). A similar project at the Yingkou works would save 871,346 tCO<sub>2</sub>-e/y by installing a 150 MW combined cycle power plant generating 945 GWh/y (UNFCCC, 2008b). A 480 MW net combined cycle power plant, with an efficiency of over 45%, has been incorporated in ThyssenKrupp Companhia Siderúrgica do Altântico's new steelworks at Santa Cruz in Brazil. Some of the BFG gas from the two BFs is used as the only fuel in the two specially designed gas turbines, and steam from the coking plant and steel mill is utilised in the steam turbines. The power plant supplies 200 MW for consumption within the steel complex, and the rest is sold to the Brazilian grid (PEI, 2010).

#### 4.3.1 Top gas recycling

Recycling BFG to the BF, commonly termed top gas recycling (TGR), has been suggested as a method for lowering the fuel rate. However, this means that BFG is unavailable for downstream processes. The BFG would have to be replaced by another fuel, with its associated CO<sub>2</sub> emissions. So although TGR is an effective method for reducing CO<sub>2</sub> emissions from the BF, it will not necessarily reduce overall CO<sub>2</sub> emissions from the steelworks, although the need for coke will decrease. TGR can be retrofitted.

Various TGR processes have been suggested, numerically evaluated or practically applied, including (Chu and others, 2004) recycling:

- with or without CO<sub>2</sub> removal from the BFG;
- with or without preheating the BFG before injection;
- via injection through the tuyeres and/or shaft (stack).

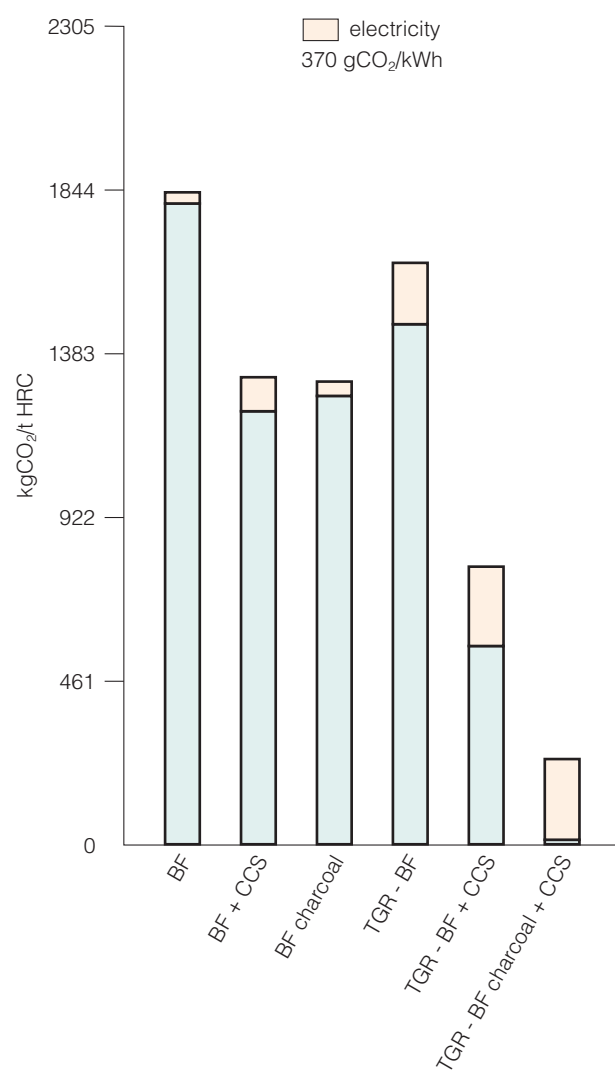
Replacing the normal blast gases, with or without O<sub>2</sub> enrichment, decreases productivity and increases fuel rates due to the cooling effect of the CO<sub>2</sub> in the top gas (Austin and others, 1998; Sharma and others, 2004). Consequently, CO<sub>2</sub> emissions will rise. Removing CO<sub>2</sub> leaves a gas rich in CO and H<sub>2</sub>. Injecting this CO<sub>2</sub>-stripped BFG promotes the indirect reduction of the iron oxides, lowering the demand for coke, and increases productivity. Field tests at RPA Toulachermet in Russia in the 1980s, with preheated CO<sub>2</sub>-stripped BFG and O<sub>2</sub> injection, achieved a 28–30% reduction in the coke rate, whilst improving the BF productivity by 25–30% (Sharma and others, 2004; Tseitlin and others, 1994).

If BFs were redesigned for TGR with O<sub>2</sub> injection instead of enriched air, then BF CO<sub>2</sub> emissions would reduce by 20–25%. Storing the captured CO<sub>2</sub> could result in a 85–95% reduction in CO<sub>2</sub> emissions (IEA, 2008a). Zhang and others (2010) calculated that injecting CO<sub>2</sub>-stripped BFG could decrease BF CO<sub>2</sub> emissions by 213 kg/thm. Some of the BFG is still used to heat the hot blast. Rootzén and others (2009) estimated that if all the 74 BFs in the 33 integrated steelworks in the EU countries were retrofitted with this technology than 106 MtCO<sub>2</sub>/y could be saved. A net reduction in energy consumption with TGR will not be achieved as the reduced coke consumption is balanced by an increase in electric power requirement for CO<sub>2</sub> separation (Croezen and Korteland, 2010).

Injecting O<sub>2</sub> instead of enriched air avoids the accumulation of nitrogen (from the air) due to recycling, and increases the CO<sub>2</sub> content in the top gas, enabling its capture with physical absorbents (*see* Chapter 9). However BFs with O<sub>2</sub> injection has not been proven yet, and retrofitting to conventional BFs may require major modifications to the furnace. One programme developing this technology is ULCOS (*see* [www.ulcos.org](http://www.ulcos.org)). As part of the project, two versions were tested at the LKAB experimental BF in Sweden in 2007 that differed in the injection position and temperature of the CO<sub>2</sub>-stripped BFG. In one version the CO<sub>2</sub>-stripped BFG was heated to 1250°C and injected through the tuyeres with cold oxygen and coal. In the second version, part of the stripped BFG, heated to 950°C, was additionally injected through supplementary tuyeres in the lower part of the shaft. At a recycling ratio of 95%, consumption of coke and coal decreased by 24% (123 kg/thm), and CO<sub>2</sub> emissions from the BF could be reduced by up to 76% (with CO<sub>2</sub> storage). This results in a net CO<sub>2</sub> saving of 65%/t HRC, taking into account the extra energy required to compensate for the decrease in export gas (Danloy and others, 2009; Schmöle and others, 2009; Zuo and Hirsch, 2008). Injection into the shaft would involve costly constructional modifications to existing BFs. There are plans to demonstrate TGR (under the ULCOS programme) on a small scale at ArcelorMittal's Eisenhüttenstadt BF3 and, if the trials are successful, at a large scale at their Florange BF6 (Croezen and Korteland, 2010). This latter project will include CO<sub>2</sub> storage. One of the recommendations of the IEA/UNIDO CCS roadmap is for a full-scale TGR-BF demonstration by 2016 (IEA/UNIDO, 2011).

Helle and others (2010) analysed, by simulation and optimisation, the recycling of CO<sub>2</sub>-stripped BFG under massive O<sub>2</sub> enrichment, and its impact on the production economics and emissions of a steelworks. Lowest CO<sub>2</sub> emissions occurred with full TGR, at 1–1.1 tCO<sub>2</sub>/tIs. Comparisons of conventional BFs and various scenarios of TGR with O<sub>2</sub> injection (*see* Figure 15) showed that the capacity for CO<sub>2</sub> reduction is ~5–10% from TGR alone, 50–60% with CO<sub>2</sub>-stripped TGR and carbon storage (TGR-BF + CCS), and over 80% with CO<sub>2</sub>-stripped TGR in a charcoal-based BF with carbon storage (TGR-BF charcoal + CCS) (Borlée, 2007; Xu and Cang, 2010). Carbon capture and storage using physical absorbents is likely to be more cost effective than with chemical absorbents (IEA, 2008a).

Ng and others (2010b) investigated the feasibility of recycling part of the CO<sub>2</sub>-stripped BFG to the BF and the rest to a combined cycle power plant. A coal gasifier is incorporated whereby the syngas product is injected into the BF instead of pulverised coal. In addition, the syngas is sufficiently hot (~1500°C) to provide the necessary heat for reheating the CO<sub>2</sub>-stripped BFG. The power generated can meet the energy required to support the necessary units for implementation of the oxygen BF



**Figure 15 CO<sub>2</sub> emissions from BFs with and without TGR (Borleé, 2007)**

systems (APPCDC, 2010; IEA, 2007). An additional benefit of dry systems is that the gas exits the TRT at a temperature of 50–70°C. Burning the gas in stoves or boilers enables its sensible heat (~70 MJ/thm) to be recovered (Cairns and others, 1998).

TRT application is limited to those BFs with an adequate top pressure of over 80 kPa. In some circumstances, the system could be retrofitted at existing plants (European IPPC Bureau, 2011). The technology has been widely adopted. TRTs are installed on all BFs in Japan and Korea, with over 8% of the electricity consumed in Japanese steelworks being generated by TRTs. Assuming 0.5 kgCO<sub>2</sub> emission per kWh for a thermal power plant, the potential of TRTs for CO<sub>2</sub> abatement would be 20–30 kgCO<sub>2</sub>/tcs (Xu and Cang, 2010). Applying wet-type TRT turbines in the USA could save 0.11 GJ/thm and reduce CO<sub>2</sub> emissions by 17.6 kg/thm (see Table 8 on page 36). Installation of TRT at SSAB Strip Products in Sweden would generate ~90–130 GWh/y, equating to a reduction of ~80,000–120,000 tCO<sub>2</sub>/y (Johansson and Söderström, 2011). The IEA (IEA, 2007) estimated that if this technology was installed worldwide on all furnaces that are operated at elevated pressure, then CO<sub>2</sub> emissions could be reduced by 10 Mt.

Over 560 TRT units have been installed in China, with all BFs with a capacity over 2000 m<sup>3</sup> having TRTs (Dao, 2010). Chinese policy dictates that all new build BFs must install TRTs. Although there are no technical barriers for installing them, Chinese operators face both financial and operative

process. Calculations suggest that CO<sub>2</sub> emissions could be reduced by 70% compared to a conventional BF process. CO<sub>2</sub> emissions could be further lowered by substituting biofuel for coal in the gasifier.

#### 4.4 Top pressure recovery turbines

Many BFs are operated at high pressure to increase furnace productivity. The pressure in the gas exiting the BF can be utilised to drive a gas turbine to generate electricity. A top pressure recovery turbine (TRT) can produce 40–60 kWh/thm, thereby reducing fossil fuel consumption of thermal power plants (APPCDC, 2010). Energy savings of ~0.4 GJ/thm for a 15 MW turbine are possible, ~2% of gross BF energy demand (European IPPC Bureau, 2011). Around 30% of the electricity necessary for all equipment for the BF, including air blowers, can be generated by TRT technology (IEA, 2007), and CO<sub>2</sub> emission reductions of 36–48 kg/thm could be achieved (Singhal, 2009).

The amount of energy that can be recovered depends on the BFG volume, pressure gradient and temperature at the turbine inlet. The BFG must first be cleaned to avoid damage to the turbines. TRTs with dry cleaning systems save on water and electricity use, produce more power (~25–30%) and have more favourable economics than those using wet cleaning

<b>Table 9 TRT cost information (Cai, 2008)</b>				
BF capacity	≤1000 m <sup>3</sup>	≤1250 m <sup>3</sup>	≤2300 m <sup>3</sup>	≤4000 m <sup>3</sup>
Top pressure, kPa	110–120	120–150	150–200	200–250
Annual operating cost, thousand yuan				
Dry	960	1460	2360	5170
Wet	3100	4220	6750	14620
Annual recovered electricity, GWh				
Dry	24	38	64	140
Wet	17	26	44	100
Annual recovered electricity expense, million yuan				
Dry	12.79	20.26	34.12	74.63
Wet	9.06	13.86	23.45	53.31
Annual net income, million yuan				
Dry	11.83	18.8	31.76	69.46
Wet	5.96	9.64	16.7	38.69
Total investment, million yuan				
Dry	24	30.5	48	74
Wet	25.5	32	51	82
Payback time, y				
Dry	2.03	1.62	1.51	1.07
Wet	4.28	3.32	3.05	2.12
Annual energy saving, tce				
Dry	8736	13832	23296	50960
Wet	6188	9464	16016	36400
1 yuan is about US\$0.15 or €0.11 (September 2011)				

barriers. Investment costs are high (*see* Table 9), especially for smaller plants with lower profit margins. In Shandong Province, where just 11 TRTs were operating in 2006, the steelworks cannot directly use the generated electricity due to the monopoly of the electric power companies. For instance, the power grid company requires Jigang to sell its own electricity to the grid, and then to buy back the electricity it needs at a higher price (Cai, 2008). There is also a complex approval procedure for TRT electricity to go on-grid. Reform is required in the power industry. Despite these barriers, a number of CDM projects installing TRTs have been approved. For example, a 20 MW TRT is proposed for the BF7 (3200 m<sup>3</sup> capacity, top pressure 250 kPa) of Wuhan Iron and Steel Co in Wuhan City, Shandong Province. This is expected to save 94,445 tCO<sub>2</sub>-e/y by substituting power from the Central China Grid (UNFCCC, 2007a). Installing TRTs at their BF2 and BF4 will save an additional 80,888 and 88,878 tCO<sub>2</sub>-e/y, respectively.

## 4.5 Sensible heat recovery from slag

BF slag contains the residues from the iron ore, coke, injectant and the fluxing agent. Hence the

amount of slag generated depends on the quality of the raw materials used. Typically, slag production is in the range 250–300 kg/thm, or higher if high ash coals are utilised. Cooling 1 t of molten slag from 1500°C to ambient temperature releases ~1.8 GJ of sensible heat that could be recovered for use in plant applications. With a global slag production rate of 180–220 Mt, for 718 Mt of iron production (IEA, 2007), then ~324–396 PJ/y could potentially be saved, equivalent to ~24.3–29.7 MtCO<sub>2</sub>/y if coal is replaced as the energy source. The Australian steel industry alone could potentially save ~3.6 PJ (it produces over 2 Mt of slag each year), reducing Australian GHG emissions by ~0.25–0.4 Mt/y (Xie, 2010). Effective recovery of the sensible heat from the over 10 Mt of slag produced by the Korean steel industry could lower their CO<sub>2</sub> emissions by 10% (Moon and others, 2010).

Heat recovery is only possible with dry granulation as there are technical difficulties recovering heat from wet slag (wet quenching). Dry granulation processes, based on air blast, rotating drums or spinning cup, recover ~40–60% of the slag heat in the form of hot air at a temperature over 600°C (Moon and others, 2010). The hot air could be used for steam generation or other on-site uses. None of these processes have yet been applied commercially. A process being developed in Australia utilises a spinning disc granulator and heat exchanger. Preliminary techno-economic analysis suggest it could deliver cost savings in terms of both capital and operating costs. Pilot trials have been carried out, and a semi-industrial plant built. Trials at one of Australia's steel plants are planned (Xie, 2010).

BF glassy slag is commonly used to replace cement clinker. Each tonne of slag recovered reduces the energy demand of the cement process by ~4.5 GJ, as well as the limestone requirement by ~1.4 t (Cairns and others, 1998). Significant CO<sub>2</sub> savings are therefore possible, ~340 kgCO<sub>2</sub>/t slag (APPCDC, 2010). Increasing the use of BF slag as a substitute for cement clinker could lower CO<sub>2</sub> emissions by 90–135 Mt, based on 2005 data (IEA, 2007). Purwanto and others (2010) have proposed using the molten slag directly to produce cement. The recovery of the thermal exergy of the molten slag is expected to lower the total net exergy losses by up to 20% compared to the conventional BF slag cement method, and also reduce CO<sub>2</sub> emissions. The cement plant would need to be located next to the iron making plant. The use of slag, though, decreases emissions from the cement producer as burning of limestone is avoided, rather than for the steel producer. CO<sub>2</sub> emissions from the cement industry is covered in the report by Zhu (2010).

## 4.6 Hot blast stoves

Hot blast stoves (also termed cowpers) heat the air blast for the BF. Typically there are three to four stoves per furnace operating in rotation to maintain a constant preheated air blast. Each stove is built of bricks that are heated up by combustion of gases. BFG, which may be enriched with COG or natural gas, is commonly used. Once the required temperature is reached (1100–1500°C), combustion is stopped. Cold air blown through the chamber is then heated by the hot bricks to produce a blast temperature of 900–1350°C.

The majority of CO<sub>2</sub> emitted from a BF facility comes from the fuel combusted in the hot stoves, ~329–427 kg/thm from a BAT BF (Birat, 2010a; Schmöle and Lungen, 2004). Based on the production of 36.1 Mt of hot metal in 2007, and an emissions factor of 260 t of CO<sub>2</sub>/TJ for the combustion of BFG, hot stoves in the USA release ~24 MtCO<sub>2</sub>/y (EPA, 2010b). The flue gas flow rate from the stoves is ~331,400 m<sup>3</sup>/h or more and consists of ~27% CO<sub>2</sub> when firing BFG and COG (Santos, 2011). Capturing and storing this CO<sub>2</sub> (*see* Chapter 9) could lower plant CO<sub>2</sub> emissions by 18%.

Hot blast stoves also account for 10–20% of the total energy requirement of an integrated steelworks, typically 3 GJ/thm. Therefore, improving the efficiency of hot blast stoves will result in substantial energy savings. Optimising the operation of the hot stoves at BF2 enabled China Steel Corporation to improve the thermal efficiency by 2.97%. The expected energy savings equate to a CO<sub>2</sub> reduction of 7076 t/y (Lin and others, 2010).

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The principal methods for improving the energy efficiency of hot stoves include:

- preheating the fuel for the hot stoves;
- combustion improvements;
- improved hot stove control.

Typically ~18% of the total heat input into the stoves is lost through the flared flue gas (Fletcher and Martin, 2010). The sensible heat in the flue gas can be recovered and used to preheat the fuel and/or combustion air. The feasibility of this depends on the efficiency of the stoves as this determines the flue gas temperature. Waste heat recovery may not be technically or economically feasible if the flue gas temperature is below 250°C (APPCDC, 2010). Around half of the energy loss could be reclaimed. At plants that use enriched BFG, preheating the fuel could mean that enrichment would no longer be necessary. This would release COG to be used elsewhere in the steelworks, as well as reducing costs since natural gas is more expensive than BFG. Energy savings of ~0.3 GJ/thm (APPCDC, 2010; European IPPC Bureau, 2011) or fuel savings between 0.08-0.085 GJ/thm (APPCDC, 2010) could be achieved. CO<sub>2</sub> emissions reduction is ~4.9 kg/thm (*see* Table 8 on page 36). According to a paper quoted in IEA (2007), a waste heat recovery unit increases the overall stove system efficiency by up to 8 percentage points, a saving of 0.24 GJ/thm. Based on this latter figure, the global savings potential is 0.2 EJ/y, equivalent to ~20 MtCO<sub>2</sub>/y (IEA, 2007).

Various designs of heat exchangers are in use. These can be retrofitted if there is enough room. Where space constraints do not allow the installation of direct contact heat exchangers, then indirect contact systems can be employed (Colling and Pallant, 2009). The indirect systems use circulating oil or pressurised water as the heat transfer medium, and can be sited separately from the stove preheating section. Most new stoves that are built include waste heat recovery systems.

A CDM project to build a new plant at Essar Steel Hazira's steelworks at Hazira, India is expected to save 142,541 tCO<sub>2</sub>-e/y by fitting three sets of hot stoves with waste heat recovery on the 2200 m<sup>3</sup> BF (UNFCCC, 2009c). A reduction of 62,551 tCO<sub>2</sub>-e/y is forecast at Steel Authority of India Ltd's (SAIL) IISCO plant at Burnpar, India, when three sets of new hot stoves with waste heat recovery are installed. Around 492 TJ/y would be recovered, reducing coke consumption in the BF (UNFCCC, 2008d).

The use of ceramic burners in the internal combustion chamber can reduce energy losses from unburnt gases to ~0.05%, and CO emissions to 200–300 ppm (Colling and Pallant, 2009). Overall, improvement of combustion through more efficient burners and changing combustion conditions (fuel/oxygen ratio) may save 0.04 GJ/thm (European IPPC Bureau, 2011). Riley and others (2009) show how adding high purity O<sub>2</sub> to the stove combustion air and combusting it with BFG, instead of enriching the air with natural gas or another higher CV gas, can lower overall CO<sub>2</sub> emissions from BFs.

Installing computer control systems can reduce energy consumption of the stoves by running the operation more efficiently and closer to optimum conditions. Energy savings typically range between 5% and 12%, and may reach 17% (EPA, 2010b; Worrell and others, 2010). This may equate to a fuel saving of 0.37 GJ/thm and CO<sub>2</sub> reduction of 22.6 kg/thm (*see* Table 8 on page 36). Implementation of this measure could require the construction of a fourth stove in the case of BFs with three stoves (if possible) in order to maximise benefits (APPCDC, 2010; European IPPC Bureau, 2011). Four stoves allow staggered parallel operation whereby the blast temperature is controlled by mixing air from two stoves at different parts on their cycles. This is a more efficient process than mixing the hot blast with cold air, and is in common use.

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## 5 Direct reduction processes

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DRI production is the most widely used alternative to BF iron making, accounting for around 6% of the world crude steel production in 2010. The manufacture of DRI (also called sponge iron) has been steadily growing from 44.2 Mt in 2002 to 71.3 Mt in 2010 (World Steel Association, 2011). This growth seems likely to continue. The majority of DRI production (over 90%) is based on natural gas, primarily cheap stranded gas. The top six producers are India, Iran, Mexico, Saudi Arabia, Russia and Venezuela (*see* Table 3 on pages 14 and 15). India is the world's largest manufacturer, where around 70% of its DRI is generated using local low quality coal. The specific investment and operating costs of direct reduction plants are low compared to integrated steel plants, making them more suitable for many emerging economies where supplies of coking coal are limited (as is the case for India). The DRI technologies operate without coke or sinter, thereby avoiding the necessity for coking and sintering plants with their associated CO<sub>2</sub> emissions.

Direct reduction processes reduce iron ore in its solid state using natural gas or coal as the reducing agent. In the natural gas-based processes, the reducing gas, which has the composition 55–60% H<sub>2</sub>, 35–40% CO, 2–3% CO<sub>2</sub> and 1–2% CH<sub>4</sub>, is generated by reforming the natural gas. The reformed natural gas is then heated to ~900°C which is necessary for the reduction reactions to proceed (Cairns and others, 1998). For the coal-based processes, the reducing gas is generated by the combustion and gasification of coal and is composed largely of CO. Consequently, CO<sub>2</sub> emissions from the natural gas-based processes are lower than those from the coal-based ones.

The solid DRI product typically contains 88–94% metallic iron, 1–5% carbon, some residual oxygen, and gangue. Since no melting or refining occurs, all the impurities in the oxide feed become concentrated in the DRI. The DRI may be subsequently melted or made into briquettes by mechanical compression. Hot briquetted iron (HBI) reduces the danger of spontaneous combustion during storage and transport. DRI/HBI is primarily fed to EAFs for further processing.

The main characteristics of direct reduction processes based on coal as reductant, compared to natural gas-based processes, are smaller production units with lower productivity, higher specific energy consumption, higher CO<sub>2</sub> emissions, and higher reduction temperatures (Lüngen and Steffen, 2007). Energy consumption for coal-based processes is ~11.7–16 GJ/t DRI (Carpenter, 2004). Natural gas-based processes consume ~10.5–14.5 GJ/t DRI assuming 100% lump ore operation. Extra energy for pelletising is required if pellets are used (European IPPC Bureau, 2011).

The processes for producing DRI can be classified by the type of reactor employed:

- shaft furnaces, such as the natural gas-based Midrex® and HYL/Energiron and Danarex™ (formerly Arex) processes;
- rotary kilns, such as the SL/RN, DRC and Krupp CODIR processes;
- rotary hearth furnaces (RHF), for example, the coal-based Fastmet®/Fastmelt®, ITmk3®, Iron Dynamics (IDI), Inmetco™/RedIron™ and Shenwu processes;
- multiple hearth furnace, such as the coal-based Primus® process;
- fluidised bed reactors, which include the coal-based Circofer® and natural gas-based Finmet®, Circored® and Iron Carbide processes.

This chapter covers the CO<sub>2</sub> emissions and energy consumption of DRI processes, with the emphasis on commercial processes. The Primus® process will not be covered since the 80,000 t/y demonstration plant at Differdange, Luxembourg, and the 100,000 t/y plant at Dragon Steel, Taiwan, are processing EAF and BF/BOF dusts, and not iron ore. Innovative processes being developed include the coal-based Paired Straight Hearth (PSH) furnace which is expected to have a lower energy consumption than RHF and BF, and lower CO<sub>2</sub> emissions than BF (Lu, 2006), and the ULCORED process.



Measures for abating CO<sub>2</sub> emissions from DRI reactors are similar to those for BFs, listed at the beginning of Chapter 4. These include utilising the sensible heat from the offgas and changing to a reductant with a lower CO<sub>2</sub> emission factor, such as biomass. CO<sub>2</sub> emissions can be reduced by charging hot DRI into the EAF as it lowers the EAF energy consumption (*see* Section 8.5). Before discussing the processes, the influence of the quality of iron ore and reductant is described in general terms. Utilising higher quality raw materials can help lower CO<sub>2</sub> emissions.

## 5.1 Iron ore quality and reductant

Direct reduction processes require a higher quality iron ore than BFs. The iron oxide feed can be in the form of lump ore, pellets or fine ore. Some processes can also use iron-bearing wastes (dusts, slags, sludges and scale) from steel making plants. CO<sub>2</sub> emissions from the pelletising plants are discussed in Section 3.2.2. The chemical, physical and metallurgical properties of the iron ore influence the performance, including energy consumption, and economics of the direct reduction processes and subsequent steel making processes. The properties of the coal also influence, either directly or indirectly, CO<sub>2</sub> emissions.

Direct reduction processes reduce the iron ore in the solid state and so the gangue constituents remain in the solid product and will increase in concentration due to the removal of oxygen from the ore. In coal-based processes, the DRI also includes ash and sulphur from the coal. The amount and composition of the gangue directly affects the energy consumption of EAFs (*see* Section 8.1), with higher gangue contents and residual oxygen leading to increased power consumption in the EAF. For good quality DRI, the iron ore used must have low levels of impurities (gangue). Processed ores below 65% iron are usually considered unsuitable (APPCDC, 2010; Carpenter, 2004). Lower ash coals and those with a sulphur content of less than 1% are usually preferred (Carpenter, 2004). Natural gas-based processes (shaft furnaces) typically have a chemical pretreatment stage to remove sulphur compounds from the natural gas before its conversion into a reducing gas in a reformer. Therefore its composition has little affect on the composition of the DRI product. Commercial processes, such as Circofer®, have introduced an additional stage whereby the DRI is melted in a furnace, with fluxes, to remove the gangue minerals. The resultant hot metal is then directly fed into the EAF.

The metallurgical properties of the iron oxide feed, particularly its inherent reducibility, influences the amount of coal or natural gas consumed, and hence CO<sub>2</sub> emissions. A higher reducible iron ore consumes less reductant.

The effect of the coal properties on CO<sub>2</sub> emissions is not straightforward. Coal volatile matter contributes to the generation of heat and to the reducing conditions in the reactor. Highly volatile coals can generate more reductant gas than can be used in the reduction process. This would lead to an unnecessary increase in the temperature and volume of the offgas (potential CO<sub>2</sub> emissions) and higher fuel consumption. Although more coal is required as the volatile matter increases, less fuel is then required for the burners in RHF processes as the combustion of the evolved coal volatiles and CO produces heat. However, this contribution has to be offset against an increase in ash and sulphur in the product due to the increased coal rate. On the other hand, low volatile coals may not be able to meet the heat requirements in some of the processes. They also have a lower reactivity and therefore a lower productivity is achieved. The influence of the quality of iron ores and coal on the performance and productivity of the direct reduction processes, including coal consumption, is discussed in Carpenter (2004).

DRI processes can reduce CO<sub>2</sub> emissions by using natural gas instead of coal due to the replacement of carbon reductant by hydrogen from the methane. But this is generally only possible in regions with cheap and abundant natural gas supplies, such as the Middle East. Substituting charcoal for coal in the iron ore pellets could lower CO<sub>2</sub> emissions from rotary kilns and RHF, provided the charcoal is produced in a sustainable manner. Charcoal would also enable the reactors to operate at a lower

<b>Table 10 Comparison of direct reduction processes</b> (Carpenter, 2004; Duarte and others, 2008; IEA, 2007; Plaul and others, 2009; Tanaka and others, 2008; Voest-Alpine, 2001)				
	Midrex®	HYL/Energiron	SL/RN	Fastmet®/Fastmelt®
Company	Midrex Technologies/ Kobe Steel	Tenova HYL/Danieli		Kobe Steel/Midrex Technologies
Reactor	shaft furnace with external reformer	shaft furnace (self-reforming)	rotary kiln	rotary hearth
Feed	lump ore or pellets or both	lump ore or pellets or both	lump ore or pellets	pellets (iron ore fines/waste oxides + coal + binder)
Reducing temperature, °C	750–1000	930–1050	1050–1100	1250–1350
Residence time, min	>360		600	6–12 (10–20 for wastes)
Coal consumption	–	–	630–1200 kg/t DRI	420 kg/t DRI
Natural gas use, GJ/t	9.6	9.4–10	–	–
Melting stage	–	–	–	electric furnace (Fastmelt®)
Product	DRI/HBI	DRI/HBI	DRI/HBI	DRI/HBI (Fastmet®) hot metal (Fastmelt®)
Typical product analysis*, %	Fe <sub>tot</sub> 90–94 Fe <sub>met</sub> 83–80 C 1–2.5 S 0.001–0.03 P 0.005–0.09 gangue 2.8–6	Fe <sub>tot</sub> 87–93 Fe <sub>met</sub> 80–88 C 1.5–5.5	Fe <sub>tot</sub> 94.7 Fe <sub>met</sub> 88 C 0.1 S 0.025 gangue 3.3	Fastmet® Fe <sub>tot</sub> 86–91.6 Fe <sub>met</sub> 79.4–85.6 C 1.7–4.2 S <0.19 gangue 4.1–7.6  Fastmelt® Fe <sub>met</sub> 96–98 C 2–4 S <0.05 P <0.05
Export gas (potential electricity generation)	–	–	low CV (400–609 kWh)	low CV (100–313 kWh)
Energy consumption	10.4 GJ/t DRI	9.4–11.2 GJ/t DRI	14.9 GJ/t DRI	Fastmet® >10 GJ/t DRI  Fastmelt® 14.5–20 GJ/thm
Fe <sub>tot</sub> = total iron; Fe <sub>met</sub> = metallic iron * phosphorus content is principally determined by iron oxide feed				

temperature and achieve a higher throughput. A process combining a RHF with a smelter, such as HIs melt® (see Section 6.4) could reduce CO<sub>2</sub> emissions by 70–95% by using sustainable charcoal (Fruehan, 2004a,b). The iron ore-wood charcoal pellets are reduced to ~70–80% metallisation in the RHF before being added to the coal-based smelter for final reduction and gangue separation. The

**Table 10 continued**

ITmk3®	Circofer®	Finmet®
Kobe Steel/Midrex Technologies	Outotec	Fior/Voest Alpine
rotary hearth	two fluidised beds	four fluidised beds with external steam reformer
pellets (iron ore fines/waste oxides + coal + binder)	fine ore	fine ore
1350	950 (CFB) + 850 (BFB)	450–800
10	20–30 (CFB) + 45–240 (BFB)	
460 kg/t iron nuggets	323 kg/t HBI	–
–	–	12.4
in RHF	–	–
iron nuggets	DRI/HBI	HBI
Fe <sub>met</sub> 96–97 C 2.5–3 S 0.05–0.07 P 0.01 gangue-free	Fe <sub>tot</sub> 93.2 Fe <sub>met</sub> 86.7 C 1.6 S 0.035 gangue 3.3	Fe <sub>tot</sub> 91–94 Fe <sub>met</sub> 84–86 C 1–2 S <0.03 P <0.09 gangue <3
low CV (234 kWh)	–	–
16.1–18.9 GJ/t iron nuggets	11.7 GJ/t HBI	14 MJ/t HBI

gases in the lower part of the shaft. The DRI can also be discharged hot (~700°C) and fed to a briquetting machine for the production of HBI or fed directly into the EAF (*see* Chapter 8). Table 10 summarises the main features of the principal direct reduction commercial processes. All the figures in the table are dependent on the properties of the reductant, iron ore feed and operating conditions,

smelter offgas replaces natural gas in the RHF. Energy consumption would decrease and productivity increase by ~30–50%.

## 5.2 Shaft furnaces

The Midrex® process is the most widely used direct reduction process, accounting for about 60% of the world's DRI production in 2010, followed by HYL/Energiron at 14%. Other gas-based processes (such as Finmet®) accounted for 0.5% and coal-based DRI processes for about 26%. There were 62 Midrex® and 26 HYL/Energiron modules installed in 2010 (nine of which were idled). The largest Midrex® module in operation has a capacity of 1.76 Mt/y, about half that of a standard size BF, and the largest HYL/Energiron module is 1.6 Mt/y. Larger capacity plants are currently under construction, the 1.8 Mt/y Midrex® unit of Jindal Steel and Power in India, and the 1.95 Mt/y HYL/Energiron plant of Suez Steel in Egypt (Midrex Technologies, 2011).

In the shaft furnace processes, lump iron ore, iron ore pellets or a combination of the two are fed into the top of the vertical shaft and reduced by a counterflowing reduction gas. In Midrex®, the reducing gas is produced by reforming natural gas and recycled reduction gas from the shaft furnace in an external reformer at ~900°C. The natural gas is first desulphurised to avoid poisoning the reformer catalyst and adversely affecting product quality. In HYL/Energiron, the natural gas is reformed in situ in the shaft furnace by taking advantage of the catalytic effects of metallic iron. The furnace operates at a pressure of ~0.15 MPa (Midrex®) or ~0.6 MPa (Energiron). The DRI product typically contains 90–94% iron. For production of cold DRI the reduced iron is cooled and carburised by counterflowing cooling

	DRI production, t/h	Reducing gas temperature, °C	O <sub>2</sub> addition, m <sup>3</sup> /t	Natural gas, m <sup>3</sup> /t	Electricity, kWh/t	Total final energy, GJ/t	Total primary energy, GJ/t
Original practice: 1970s (100% pellets)	88.8	780	0	268.6	135	10.2	10.9
Practice using lump ore: 1980s	100.3	850	0	262.3	120	9.9	10.5
Practice using coated iron oxide feed: 1990s	110.2	918	0	257.9	109	9.7	10.3
O <sub>2</sub> injection practice: late 1990s	121.5	1050	17.5	260.3	99	9.7	10.3
OXY+ practice: 2000s	129.2	961	30.2	265.8	93	9.9	10.4
Combined practice with O <sub>2</sub> injection and OXY+ (future)	133.6	1050	41.2	264.6	90	9.9	10.4

Note: Total final and primary energy intensity calculated using energy-specific conversion factors

and so are only indicative. More information about the Midrex® and HYL/Energiron processes can be found on the websites [www.midrex.com](http://www.midrex.com) and [www.energiron.com](http://www.energiron.com), respectively.

State-of-the-art plants are energy efficient, with natural gas consumption of Midrex® plants as low as 9.6 net GJ/t DRI and electricity consumption of <99 kWh/t DRI (Griscom and others, 2000; Midrex Technologies, 2010). Energy consumption at Energiron plants is 9.42–10.05 GJ/t DRI of natural gas and 60–80 kWh/t DRI of electricity when producing hot discharged DRI (Duarte and others, 2008). In some cases, Midrex®/EAF facilities emit only one-third of the carbon emissions/t steel as a BF/BOF steelworks (Midrex Technologies, 2010).

The energy efficiency of Midrex® is partly achieved by utilising a heat recovery system which recovers the sensible heat from the reformer flue gas and the reformed gas stream. This heat is used to preheat the feed gas mixture, the burner combustion air, the natural gas feed and, depending on the economics, the fuel gas. It is also utilised to generate high pressure steam to drive the reformed gas compressors and other equipment. Part of the offgas from the shaft furnace provides fuel for the burners in the reformer (the rest is recycled back to the furnace via the reformer). Technology developments have contributed by increasing productivity and lowering electricity consumption. These include the introduction in the 1990s of iron oxide pellets coated with CaO or CaO/MgO, enabling an increase in the reduction gas temperature to ~900°C and thus the reduction rate. A 10°C increase in the reducing gas temperature improves productivity by 1.5–2% (Harada and others, 2005). The reduction temperature was further increased to ~1000°C in the late 1990s by adding high purity oxygen to the hot reducing gas. The addition of an OXY+ unit after the reformer has also raised the productivity. This unit generates additional reducing gas by the partial oxidation of natural gas by oxygen. Table 11 compares the energy use and productivity of these different technologies. CO<sub>2</sub> emissions from the production of the coated pellets and oxygen generation will need to be taken into account in a LCA analysis.

In Energiron ZR (HYL ZR), natural gas and oxygen are fed into the reducing gas section of the shaft furnace. The overall energy efficiency is optimised by the high reducing temperature (>1050°C) and reforming inside the shaft furnace, as well as by a lower utilisation of thermal equipment in the plant (Duarte and others, 2010a). The partial combustion of the natural gas generates the H<sub>2</sub> and CO reducing gases and also provides the additional energy required for in situ natural gas reforming and

carburisation of the metallic iron. The sensible heat of the offgas (which leaves the furnace at 400°C) is recovered by producing steam or alternatively, utilised to preheat the reducing gas stream. After the offgas is cleaned, compressed and the CO<sub>2</sub> removed, it is mixed with the reducing gas and recycled to the furnace. A version of Energiron with an external reformer for natural gas is available but this version will not be covered since it is similar to Midrex®. It consumes slightly more natural gas but less power than the self-reformer scheme (Becerra and Martinis, 2008).

CO<sub>2</sub> emissions from the DRI-EAF route, including an iron ore production plant and incorporating Energiron, were calculated to be 1082 kgCO<sub>2</sub>/tIs via cold DRI and 984 kgCO<sub>2</sub>/tIs with hot DRI. This is a 6% and 10% reduction respectively, compared to a conventional DRI-EAF route, where 1147 kg/tIs (cold DRI) and 1082 kg/tIs (hot DRI) of CO<sub>2</sub> are emitted. CO<sub>2</sub> emissions for a BF/BOF plant were calculated to be 1557 kg/t HRC compared to 1080 kg/t HRC for an Energiron ZR/EAF plant without CO<sub>2</sub> storage, and 810 kg/t HRC with CO<sub>2</sub> storage (Duarte and others, 2008, 2010a). The BF/BOF facility is a net exporter of electricity due to power generation from the COG, BFG and BOF gases, whereas the Energiron ZR/EAF route is a net importer. CO<sub>2</sub> emissions for power generation were assigned as 0.74 kg/kWh in all cases.

Capturing and storing the CO<sub>2</sub> from the shaft furnace offgas before it is recycled to the shaft would lower CO<sub>2</sub> emissions. Energiron already captures up to 50% of the total CO<sub>2</sub> generated as part of the reduction process via a chemical absorption process. Up to 90% could be recovered by incorporating a physical absorption system. This results in a H<sub>2</sub>-rich fuel for the process gas heater leading to essentially carbon-free emissions from its stack (Duarte and others, 2010b). As part of the Masdar CCS project in Abu Dhabi, United Arab Emirates, the 0.8 Mt of CO<sub>2</sub> captured from the DRI plant will be transported via a pipeline for enhanced oil recovery in the offshore oil fields (Nader, 2009).

Midrex Technologies has developed a system employing an amine-type system to capture the CO<sub>2</sub> from the shaft furnace offgas. The resultant gas is then preheated, with part of it added to the reformed gas and the remainder used as a fuel in the reformer burners. This is expected to reduce CO<sub>2</sub> emissions from the reformer stack by 50% (from 500 to 250 kg/t DRI). In addition, natural gas use drops by 5% but electricity consumption increases by 20 kWh/t DRI. Stripping CO<sub>2</sub> from the reformer flue gas as well is possible, but would increase capital and operating costs significantly compared to Midrex® plants without any CO<sub>2</sub> capture systems (Metius and Kopfle, 2010).

When credits for power generation in integrated steelworks are poor, then COG could be utilised, after cleaning, as a reducing gas in Midrex® or Energiron plants. The DRI could then be processed in an EAF or in the BOF. This could lower overall CO<sub>2</sub> emissions if the CO<sub>2</sub> removed in the Energiron plant is stored (Becerra and Martinis, 2008).

In areas where natural gas is unavailable or in short supply and coal is abundant, then syngas from a coal gasifier could be used as the reducing gas. Offgas from the Corex® melter-gasifier is already utilised in a shaft furnace at a South African steel making plant (*see* Section 6.2). Jindal Steel & Power is building a 1.8 Mt/y Mycol™ plant (a Midrex® shaft furnace combined with a coal gasifier) in Angul, Orissa, India. The Lurgi fixed bed gasifier utilises high ash domestic coal. The syngas is cleaned, cooled and depressurised before it is mixed with recycle offgas. An external reformer is not required. CO<sub>2</sub> is removed from the offgas in a Lurgi Rectisol® unit in order to maintain a high reductant (H<sub>2</sub> + CO) to oxidant (H<sub>2</sub>O + CO<sub>2</sub>) ratio. Thus the captured CO<sub>2</sub> could be stored to lower emissions. If the syngas flowrate is high enough, it may be economical to use a turbine generator to depressurise the syngas so as to recover energy as electricity. Electricity consumption is predicted to be 175 kWh for a 1.8 t/y facility (Lurgi gasifier) producing hot DRI (Cheeley and Leu, 2010). An Energiron plant would require ~700 m<sup>3</sup> (or ~9.5 GJ)/t DRI of syngas (Becerra and Martinis, 2008). The electricity requirements will be higher (at 70–90 kWh/t DRI) than a natural gas-based facility (60–80 kWh/t DRI) (Scarnati, 2008). Syngas from the gasification of biomass, either alone or with coal, could also be utilised, lowering CO<sub>2</sub> emissions, provided the biomass is produced sustainably (Buegler and Di Donato, 2008).

In China, Baosteel and Lunan Chemicals Industry has developed the BL-DR process in which syngas from a Texaco gasifier is used for direct reduction in a shaft furnace. A pilot plant has been built (Liu and Gallagher, 2010). The ULCORED process, part of the ULCOS project, produces DRI in a shaft furnace, either from coal gasification or natural gas, using 100% O<sub>2</sub>. Offgas from the shaft is recycled to the process after the capture of CO<sub>2</sub> (which can then be stored). The use of a coal gasifier and a shift reactor for the shaft offgas makes it possible to by-pass some of the syngas directly to the shifter, producing excess CO<sub>2</sub>-free gas that can be used as a fuel elsewhere in the steelworks, lowering overall CO<sub>2</sub> emissions. Having a single CO<sub>2</sub> source makes it possible to basically capture and store all CO<sub>2</sub> generated in the steel making system (Bergman and Larsson, 2008; Knop and others, 2008). The utilisation of H<sub>2</sub> as a reductant in shaft furnaces is also being investigated as a way of avoiding CO<sub>2</sub> generation (*see* Section 10.1).

### 5.3 Rotary kilns

Around 350–400 rotary kilns are operating in the world, almost all of which are in India, with a few in South Africa and Peru (Midrex Technologies, 2011). The majority use the SL/RN process.

In the SL/RN process, lump ore or pellets, coal and limestone or dolomite are fed into the top of a heated, rotating inclined kiln. The iron ore is reduced as it passes down the kiln by the countercurrent flowing gases (CO and H<sub>2</sub>) produced by gasification of the coal. The DRI is discharged hot or cold (when it is passed through a rotary cooler). Typical retention time in the kiln is around 10 h.

Energy consumption and productivity is influenced by the quality of the coal and, to a lesser extent, the reducibility of the iron ore (*see* Section 5.1). India utilises local low quality coal; typically these plants consume 1.2–1.5 t coal/t DRI, and emit 1.8–1.2 tCO<sub>2</sub>. Advanced plants use 1.05–1.2 t low quality coal/t DRI, which equates to 20–25 GJ/t DRI (IEA, 2007). Kilns employing higher quality coals (CV 31 GJ/t dry coal) consume 19.5 GJ and 100 kWh of electricity per tonne of DRI. Power production from the waste heat is estimated as 609 kWh/t DRI, giving a net energy consumption of 14.9 GJ/t DRI (Cairns and others, 1998). The energy efficiency of individual plants depends on the efficient use of the large amounts of offgas. Coal consumption is higher than for a BF and the fuel rates are about twice those of other DRI routes (Cairns and others, 1998).

The fuel economy of the kiln can be improved by enriching the process air with oxygen, lowering the heat loss in the offgas as hot nitrogen. Proper distribution of the oxygen throughout the kiln is important in order to avoid any problems. Enriching the air to contain 23% oxygen can lower coal rates by 3.5% and increase productivity by over 10%. The drop in coal rates corresponds to a CO<sub>2</sub> reduction of ~20 kg/t DRI (Riley and others, 2009). Replacing wet gas cleaning systems with dry ones (electrostatic precipitators) will also lower energy consumption, saving ~30–40 units/t DRI (Pandit and others, 2002). Utilising charcoal as the iron ore reductant would reduce CO<sub>2</sub> emissions.

Since a rotary kiln is not well suited for heat exchange, only ~60% of the heat is used in the reduction process and 40% is discharged with the kiln waste gases and kiln (char) materials, depending on the quality of coal (Pandit and others, 2002). The hot (850–900°C), low CV offgas and char thus contain considerable energy saving potential. The offgases can be used to preheat the iron ore charge, for electricity generation or for drying the coal.

Ore preheating can reduce the coal consumption by 25% (IEA, 2007). Power consumption in Indian kilns has been reduced from 110–130 kWh/t DRI to 80–90 kWh/t DRI by utilising the sensible heat of the offgas for power generation. After deducting the internal power consumption, between 400–500 kWh/t DRI is generated, depending on the reductant used (IEA, 2007; Pandit and others, 2002).

Around 0.25–0.35 t of non-magnetic kiln discharge (char) per tonne of DRI is produced (IEA, 2007).

By burning the char, coal fines and coal washery rejects in a fluidised bed boiler, steam can be generated that, in turn, can be used for power generation (Pandit and others, 2002). But CO<sub>2</sub> will be emitted from the boiler.

Power generation from kiln offgas is eligible for credits under the Clean Development Mechanism of the Kyoto Protocol and can be highly profitable. As a result, there are a number of CDM projects installing waste heat recovery based power plants, details of which can be found on the UNFCCC website (<http://cdm.unfccc.int>). One example is at Godawari Power and Ispat Ltd's plant at Raipur, Chattisgarh, India. Offgas from a 350 t/d kiln (producing ~75,000 m<sup>3</sup>/h offgas) is being used to generate 7 MW of electricity, saving 17,828.7 tCO<sub>2</sub>-e/y. An atmospheric fluidised bed boiler was later installed to avoid pollution problems associated with the disposal of coal rejects (coal fines and char from the kiln). This generates 11 MW of electricity (UNFCCC, 2006b).

## 5.4 Rotary hearths

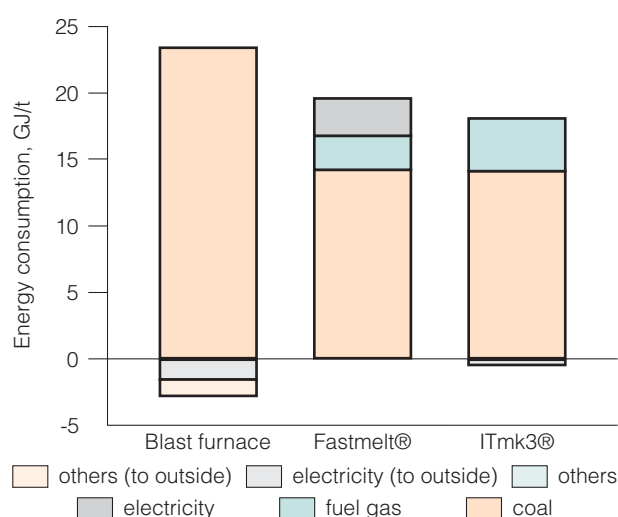
There are currently three Fastmet®/Fastmelt® plants operating in Japan processing steel making wastes. The first commercial ITmk3® plant at Hoyt Lakes, MN, USA, treating taconite (a low grade magnetite ore) began production in January 2010. It has a capacity of 500,000 t/y. The Iron Dynamics (IDI) process is operating commercially at Butler, IN, USA, processing a mixture of iron oxides fines and steel making wastes. The Inmetco™ plant at Elmwood City, PA, USA, treats stainless steel wastes. China is building a plant using the Shenwu process. This section will discuss Fastmet®/Fastmelt® and ITmk3® as examples of commercial RHF processes.

The RHF consists of a flat, refractory-lined hearth rotating inside a high temperature circular tunnel kiln. Pellets (made from iron ore fines and/or steel making wastes, coal and a binder) are evenly placed on the hearth, and heated by burners in the RHF roof and/or sidewalls. The pellets are reduced by the countercurrent flowing reduction gas as they pass round the hearth. The Circofer® process takes 6–12 mins when using iron ore fines, longer when processing iron oxide wastes. The low productivity of RHF's and excessive gangue in the DRI is overcome in the Circofer® process by charging the hot Circofer® DRI into a melting furnace (basically a submerged arc furnace) to produce hot metal (termed Fastiron®) or pig iron and slag. ITmk3® adds a partial melting step within the RHF (by passing the DRI through a high temperature zone) to remove gangue and produce pig iron nuggets. A comparison of the processes with other DRI processes is given in Table 10 on pages 50 and 51.

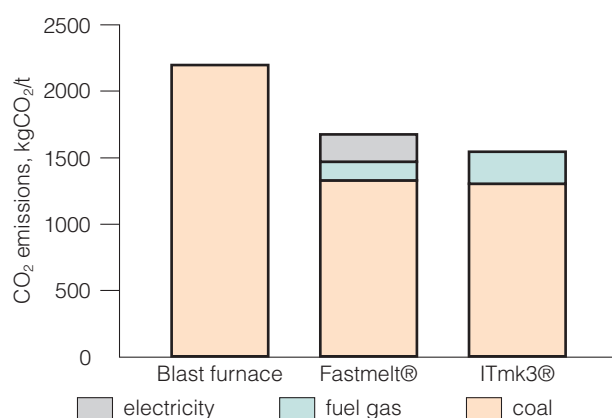
Circofer® consumes 80 kWh (0.29 GJ)/t briquettes (cold briquetting) plus 2705 kWh (9.7 GJ)/t DRI (RHF), giving a total energy consumption of 2785 kWh (10 GJ)/t DRI. A DRI melter consumes 1321 kWh (4.8 GJ)/thm. Thus the energy consumption of Circofer® is 4106 kWh (14.8 GJ)/thm. ITmk3® consumes 511 kWh (1.8 GJ)/t pellet (produced by cold briquetting) plus 4744 kWh (17.1 GJ)/t nuggets, giving a total energy consumption of 5255 kWh (18.9 GJ)/t nuggets (Hornby Anderson and others, 2002). Natural gas was the fuel for the RHF in all cases. The energy consumption of these processes depends on a number of factors. Energy consumption figures quoted elsewhere for Circofer® range from 14.5 to 20 GJ/thm (APPCDC, 2007; Croezen and Korteland, 2010).

The energy efficiency of these processes is relatively high as the sensible heat in the RHF is recovered in heat exchangers and used to preheat the RHF burner combustion air and, if used, the dryer air. Utilising higher volatile coals will generate more offgas than lower volatile ones. The offgas is also fully combusted. Offgas from the melting furnace (Circofer®), primarily CO, can be utilised as a fuel for the RHF. Either electricity or coal can be used as the energy source in the melting furnace. The use of coal increases the amount of discharged gas and reduces the need for external fuel gas such as natural gas (Tanaka and others, 2008).

The energy consumption and CO<sub>2</sub> emissions in the Circofer® and ITmk3® processes are lower than



**Figure 16 Energy consumption of iron making processes** (Tanaka and others, 2008)



**Figure 17 CO<sub>2</sub> emissions from iron making processes** (Tanaka and others, 2008)

those in a BF (*see* Figures 16 and 17). In these cases the sensible heat from the RHF is recovered as steam and used for power generation. In a 500,000 t/y Circofer® process, 313 kWh of electricity is produced and used to power the DRI melter. A 500,000 t/y ITmk3® plant generates 234 kWh, of which 104 kWh can be exported (Tanaka and others, 2008). It should be noted that additional energy is required to melt the ITmk3® pellets to produce hot metal, and this should be taken into account when comparing ITmk3® with a BF.

Seki and Tanaka (2008) calculated that, without any heat recovery, Circofer® and ITmk3® could reduce CO<sub>2</sub> emissions by about 500 and 400 kg/thm respectively, compared to a mini-BF (500 m<sup>3</sup> volume); this is about a 23% and 18% reduction respectively.

Therefore, CO<sub>2</sub> emissions could be lowered if RHF's are built instead of mini-BFs. Circofer® could lower CO<sub>2</sub> emissions by about 5% compared to a European Union average BF. If CCS is applied to a RHF-EAF, then CO<sub>2</sub> may reduce by 55% (Croezen and Korteland, 2010; Link, 2008). CO<sub>2</sub> emissions from the ITmk3®-EAF route are estimated to be about 20–25% less than those from the BF-BOF route, with CO<sub>2</sub> emissions from ITmk3®-EAF of 1734 kg/t steel (Lehtinen, 2003). Utilising charcoal as the reducing agent, instead of coal, would further lower CO<sub>2</sub> emissions.

## 5.5 Fluidised bed reactors

Some 0.34 Mt of DRI were produced by fluidised bed (FB) processes in 2010, down from 0.5 Mt in 2009 (Midrex Technologies, 2011). The main advantage of FB technology is that fine iron ore can be directly charged to the process without the need for pelletising or briquetting and their associated CO<sub>2</sub> emissions. Preheated iron ore fines are reduced in a series of one or more FB reactors by a reducing gas generated from coal or reformed natural gas. This section will discuss Circofer® and Finmet® as examples of a coal- and natural gas-based FB process, respectively. It has been proposed to couple a modified Circofer® plant with the HIs melt® reactor (*see* Section 6.4).

### 5.5.1 Circofer®

Circofer® is a two-stage process where preheated iron ore fines are first reduced in a circulating fluidised bed (CFB) reactor followed by further reduction in a bubbling fluidised bed (BFB). A heat generator is integrated into the circulating FB circuit to provide the energy necessary for the endothermic reduction reactions by partially combusting coal with oxygen. The process operates in a closed gas circuit without the production of export gas. The sensible heat of the reactor offgas, after being used for ore preheating, is recovered as steam in a waste heat boiler. The steam is then used in



the CO<sub>2</sub> scrubber, which removes CO<sub>2</sub> from the offgas before it is compressed, heated and returned to the reactors, as fluidisation gas, and to the heat generator. Char separated from the DRI can be recycled.

Coal consumption is ~323 kg/t HBI (with a coal CV of 31 GJ/t dry) and electricity consumption ~90 kWh/t HBI, with a net energy consumption of ~11.7 GJ/t HBI (Cairns and others, 1998). CO<sub>2</sub> emissions from Circofer® plus EAF for coal-based power generation are estimated to be 1738 kg/tcs, made up of 1276 and 432 kg/tcs from Circofer® and the EAF (steel making), respectively. With natural gas-based power generation, CO<sub>2</sub> emissions for Circofer® plus EAF are 1460 kg/tcs, 1197 and 233 kg/tcs from Circofer® and the EAF respectively (Orth and others, 2007). Circofer® operates in a closed gas circuit and already captures the CO<sub>2</sub>. Therefore emissions could be easily lowered by utilising the CO<sub>2</sub> for enhanced oil recovery or by underground storage. There is no need for further concentration as the captured CO<sub>2</sub> is of high purity (99% CO<sub>2</sub>).

### 5.5.2 Finmet®

Finmet® is a four-stage BFB reactor system which uses reformed natural gas as the reducing agent. Only one plant is still operating, a 2 Mt/y HBI plant at Puerto Ordaz, Venezuela. A similar four-stage FB system forms part of the Finex® process, where the reducing gas is generated by coal gasification (*see* Section 6.3).

In Finmet® iron ore fines are first dried in a FB dryer before passing through a series of four interconnected FB reactors where the fines are progressively reduced by counterflowing reducing gas. A mixture of recycled offgas (which has been cleaned of dust and moisture) and fresh gas generated by steam reforming natural gas provides the reducing gas. Each reactor is equipped with internal cyclones to separate and recycle the dust entrained in FB offgas. The reduced fines are hot compacted (HBI).

The cleaned and cooled offgas is mainly used as a fuel (with natural gas) for heating the reducing gas mixture (in the reducing gas furnace). The remaining recycle gas is returned via a recycle gas compressor to the process. The reformed gas stream and the recycle gas stream (or a portion thereof) are sent through a CO<sub>2</sub> removal system. The gas is then preheated in the reducing gas furnace to ~850°C before being sent to the FB reactors (Plaul and others, 2009).

Finmet® consumes ~360 m<sup>3</sup>/t HBI of natural gas (with a CV of 35 MJ/m<sup>3</sup>) and 150 kWh/t HBI of electricity, giving a net energy consumption of 14 MJ/t HBI (Cairns and others, 1998). Process-related CO<sub>2</sub> emissions have been estimated to be 771 kg/t DRI/HBI, that is, 212 kg in the reformer flue gas, 234 kg in the flue gas from the reducing gas furnace, 40 kg in the ore dryer flue gas, and 285 kg from the CO<sub>2</sub> removal unit. Gross CO<sub>2</sub> emissions are 993 kg/t DRI/HBI when CO<sub>2</sub> emissions due to electric power consumption at 0.933 kgCO<sub>2</sub>/kWh (149 kg) and from the production and transport of fine ore are taken into account. A Finmet® plant coupled with an EAF processing 20% scrap and 80% HBI would emit 1305 kgCO<sub>2</sub>/tcs. This would decrease by 2 kg/tcs if the CO<sub>2</sub> credit from selling the slag is taken into account (VATech, 2003). Storing the captured CO<sub>2</sub> (from the CO<sub>2</sub> removal unit) would lower emissions.

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## 6 Smelting reduction processes

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Smelting reduction processes have been developed that directly reduce iron ore (lump, fines or pellets) using non-coking coal, thus eliminating the need for coke ovens and sinter plants with their associated CO<sub>2</sub> emissions. Raw material costs are also lowered. Decreasing the number of processing steps could also improve efficiency since each processing step adds inefficiency to the overall steel making process, due to the energy and material losses in and between each step. Hot metal of a similar quality to that from BF's is produced; it can be fed directly into BOFs or EAFs or cast into pig iron.

Currently less than 1% of world steel is produced via smelting reduction processes. High capital costs in countries such as the USA, uncertainties due to the adoption of new technologies, the energy requirements and production costs, and limited scale are among the barriers hindering the uptake of these processes.

Smelting reduction processes can be classified into:

- those that include an iron ore pre-reduction stage, such as Corex®, Finex® and Redsmelt® NST. Offgas from the smelting reduction vessel is utilised to pre-reduce the iron ore before it is fed into the smelting vessel;
- direct smelting processes, that is, those without a pre-reduction step, such as HIs melt®, DIOS (although versions including a pre-reduction stage have been developed for both these processes), Ausiron®, and Romelt®. Smelting takes place in a single reactor where iron ore and coal are fed to a molten bath of metal and slag.

Some of the processes generate substantial amounts of offgas. Utilising the offgas could lead to significant CO<sub>2</sub> reduction, although combustion of the offgases would generate CO<sub>2</sub>. The offgas is richer in CO<sub>2</sub> than BFG and so facilitates CCS. The IEA has estimated that with the expansion of smelting reduction and nitrogen-free BF's, as much as 200–500 MtCO<sub>2</sub> could be avoided by 2050 (IEA, 2008a).

A disadvantage of most smelting reduction processes is that large volumes of O<sub>2</sub> (500–700 thm) are required by the process. Oxygen is expensive and consumes considerable quantities of energy (up to 3.5 GJ/thm, depending on the efficiency of the O<sub>2</sub> plant and process), which is sufficient to negate the energy advantages resulting from the closure of all coke ovens and sinter plants (Cairns and others, 1998). However, some variants of smelting reduction operate on air rather than O<sub>2</sub>; but in these cases the offgas contains more nitrogen which will affect CO<sub>2</sub> capture (*see* Chapter 9).

This chapter covers the Corex® and Finex® processes that are in commercial operation. HIs melt®, where a demonstration plant has been built in Australia, is discussed as an example of a direct smelting process. The influence of the quality of the coal and iron ore on energy consumption and hence CO<sub>2</sub> emissions will first be discussed.

### 6.1 Iron ore quality and reductant

Generally, smelting reduction processes can use lower quality ores than direct reduction processes since the gangue constituents are removed as liquid slag. A high gangue content, though, results in higher coal and O<sub>2</sub> consumption rates, and higher slag volumes. Higher coal rates can lead to higher CO<sub>2</sub> emissions. The metallurgical properties of the iron ore, particularly its inherent reducibility, also influence the amount of coal consumed. A higher reducible iron ore consumes less coal. Waste oxides from the integrated steelworks can be processed, either directly or after an agglomeration or briquetting stage. If agglomerates/briquettes are utilised then overall energy consumption and CO<sub>2</sub> emissions of the steelworks may increase due to emissions from the agglomeration plant.

The smelting reduction processes are more flexible than BFs with regard to coal requirements as coking properties are unimportant. Although they can operate with a wide range of coals, optimum performance is only achieved using coals with a limited range of properties. In general, less coal and O<sub>2</sub> is consumed when coals with lower moisture, volatile matter and ash contents, and higher fixed carbon and CVs are utilised. For Corex®, it has been estimated that a 1% increase in volatile matter or moisture raises the heat demand by about 1.68 GJ/h and 4.19 GJ/h, respectively (Gupta, 2002). On the other hand, Corex®/Finex® require a sufficient quantity and quality of gas for the pre-reduction unit to reduce the ore to DRI. A low VM coal may not produce enough gas, gas of sufficient quality for the pre-reduction unit, or enough offgas for power generation. Buying power generated from coal will increase indirect CO<sub>2</sub> emissions. Therefore lower energy consumption and CO<sub>2</sub> emissions are obtained with higher quality iron ore and coal. The influence of the quality of iron ores and coal on the performance and productivity of the smelting reduction processes, including coal consumption, is discussed in more detail in Carpenter (2004).

Substituting charcoal for coal can reduce CO<sub>2</sub> from smelting reduction processes, provided the charcoal is produced in a sustainable manner and is available at a reasonable price. The low strength and low abrasion resistance of charcoal may limit its use in Corex® plants. Waste plastics could probably partially substitute coal, but little work has been carried out on this subject.

## 6.2 Corex®

There are four Corex® plants currently in operation in China, India and South Africa, with a further three modules under construction. The largest C3000 module has an annual output of 1.5 Mthm. Posco's Corex® plant at the Pohang Works in South Korea was converted into the Finex® configuration in 2003 (*see* Section 6.3).

Smelting reduction is achieved in the Corex® process by employing two separate units, a reduction shaft and a melter-gasifier. Iron ore (lump, pellets and/or sinter) is first pre-reduced to DRI in the reduction shaft using offgas from the melter-gasifier. The resultant hot DRI, coal and limestone/dolomite are charged into the melter-gasifier. The coal is devolatilised by the heat in the reactor to produce a reduction gas of CO and H<sub>2</sub>, and a bed of char. Oxygen is injected lower down into the vessel where it reacts with the char to produce heat and further CO. The heat from the combustion of the char melts the DRI and the molten metal collects in the hearth. The metal and slag are tapped periodically. The main features of the process are summarised in Table 12.

The offgas from the melter-gasifier is cooled to about 850°C (by mixing with cooling gas) and cleaned in hot cyclones before it is fed into the reduction shaft. This is one place where sensible heat of the offgas could possibly be recovered. A heat balance analysis of a C3000 melter-gasifier found that the sensible heat of the offgas was 2.6 GJ/thm, that is, about 34% of the heat output. The offgas exits the reduction shaft at a temperature of 250–300°C. The sensible heat is around 0.7 GJ/thm, corresponding to 41% of the heat output of the reduction shaft, and can be used to heat low pressure water (Wang and others, 2008). After cleaning in a scrubber, the reduction shaft offgas is termed export gas. It has a net CV of around 7.3–8.5 MJ/m<sup>3</sup>. A typical composition of the export gas is given in Table 13. The amount and composition of the export gas will vary depending on the composition of the coal and operating conditions. The volatile matter yield is particularly important as it affects coal consumption, as well as the amount and CV of the export gas (*see* Section 6.1).

Although most smelting reduction processes do not use coke, a coke rate of 5–10% of total reductant rate is common practice in Corex® in order to obtain good permeability in both the reduction shaft and melter-gasifier (Lüngen and Steffer, 2007). Corex® has been operated without coke. Unlike BFs, only low quality coke (coke breeze) is required. Total CO<sub>2</sub> emissions and energy consumption from steelworks utilising coke, pellets and sinter could be higher than those that do not when the production of these materials are taken into account.

<b>Table 12 Comparison of smelting reduction processes</b> (Burke, 2009; Carpenter, 2004; Lee, 2008)			
	Corex®	Finex®	HIs melt®
Iron oxide feed	lump ore, sinter, pellets, partly fines	fines	fines (–6 mm), waste oxides
Pre-reduction furnace	reduction shaft	3 or 4 fluidised beds	optionally pre-reduced
Pre-reduction degree, %	80–95	85	10
Pre-reduction temperature, °C	800–850		700
Coal feed	lump	lump + pulverised	fines (–3 mm)
Smelting reduction reactor	melter-gasifier	melter-gasifier	vertical iron bath smelter
Smelting	melting of ore, gasification of coal	melting of ore, gasification of coal	in-bath (metal layer)
Pressure, kPa	300–450	300–450	80
Oxidising gas	oxygen	oxygen	hot air blast, oxygen
Post-combustion degree, %	~10	~10	50–75
Coal consumption, kg/thm	900–1050	700	700–810
Oxygen consumption, m <sup>3</sup> /thm	>500	>500	260 (if hot air blast enriched with oxygen)
Metal temperature, °C	1490–1520	1520	1420
Metal quality, %	C 4.5-4.7 Si 0.6-0.8 S 0.01-0.04 P <0.1	C 4.5 Si 0.65 S 0.03 P <0.1	C 4.4 Si <0.1 S 0.1 P 0.02 No silicon reduction
Offgas	medium CV (7.5–8.5 MJ/m <sup>3</sup> )	medium CV (7.5–8.5 MJ/m <sup>3</sup> ) 2.97 MJ/thm without PSA tailgas	medium CV (3.2 MJ/m <sup>3</sup> )
Process time	hours	hours	very fast
Net energy consumption, GJ/thm	18.9–21.7		18.9–20

The requirement for a highly reducing gas for the reduction shaft limits the opportunities for recycling heat to the melter-gasifier. HIs melt® (*see* Section 6.4) is designed to exploit the chemical energy of the melter gas by post-combustion with O<sub>2</sub> or air. CO is oxidised to CO<sub>2</sub>, and the chemical heat generated is used to heat the iron ore. The absence of post-combustion in Corex® means that much of the chemical energy is lost in the offgas. Consequently, coal consumption is higher than in any other iron making process.

The export gas typically contains around 30–35% of CO<sub>2</sub>. Holappa and Kekkonen (2006) calculated that if all the carbon from the raw materials and fuels are burnt to CO<sub>2</sub>, then 2500 kgCO<sub>2</sub>/thm would be emitted if the export gas was flared. This is higher than the 1318 kgCO<sub>2</sub> that would be emitted from BFG mainly due to the higher coal consumption of Corex®. Net energy consumption at the Posco Pohang Works was calculated to be 19.1 GJ/thm. This was based on the consumption of

**Table 13 Composition and CV of Corex® gas**  
(Hu and others, 2009)

CV, MJ/m <sup>3</sup>	7.3
Composition, %	
CO	35
CO <sub>2</sub>	33
H <sub>2</sub>	20
N <sub>2</sub>	2
CH <sub>4</sub>	2
Others	8

1471 kg of iron ore/thm, 29.5 GJ of coal/thm (995 kg/thm), 526 m<sup>3</sup> of oxygen/thm and 75 kWh of electricity/thm. Total energy input was 32.51 GJ/thm, and the total energy output was 13.4 GJ/thm from the export gas (Cairns and others, 1998). The energy efficiency and CO<sub>2</sub> emissions (and economics) of Corex® are therefore dependent on the efficient use of the export gas and the allocation of the related emissions.

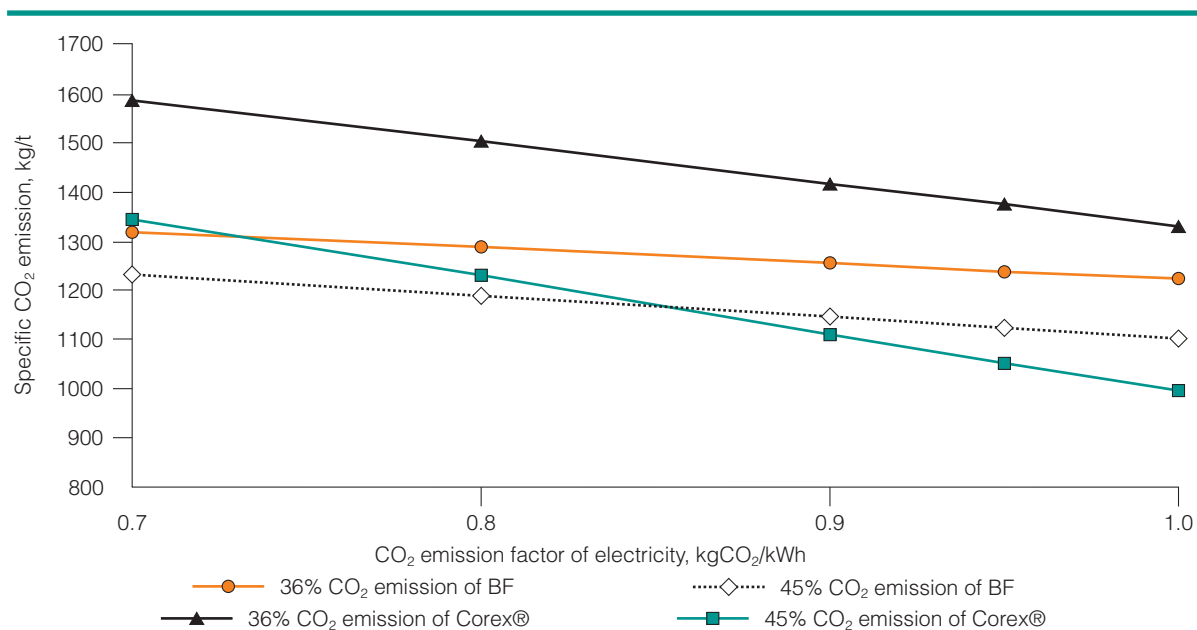
The export gas can be used, for example, for power generation, production of DRI in direct reduction plants, for heating purposes in the steelworks, injected into a BF, and as a chemical feedstock. Energy consumption at

the JSW Steel plant in India is ~21.7 GJ/thm and CO<sub>2</sub> emissions are 1420 kg/thm (Srinivasa Rao, 2007). The export gas is utilised for power generation, for the pellet plant and as a fuel in the integrated plant complex (Wieder and others, 2005). Power generation was introduced at this plant via two CDM projects. One project combusts BFG and Corex® export gas in a 100 MW power plant. Since the gases would have been flared in the absence of the project, the additional emissions from the generation of power by their combustion is zero. Emission reductions of 767,325 tCO<sub>2</sub>-e/y are projected over the 10 y crediting period (UNFCCC, 2006c). The second project was the construction of two 130 MW units to generate electricity using imported coal, and Corex® and other offgases that would otherwise have been flared. Maximising the use of offgas in the power plant fuel configuration reduces CO<sub>2</sub> emissions. The generated electricity is used in the steel plant and the state grid. It is estimated that 811,566 tCO<sub>2</sub>-e would be saved during the ten-year crediting period (UNFCCC, 2006d).

Assuming an efficiency of 38%, a Corex® C2000 plant can produce 170 MW power and 1 Mthm/y, while a C3000 plant could generate 215 MW power and 1.4–1.5 Mthm/y. It has been estimated that a Corex® C2000 module in a combined-cycle power plant, where the thermal efficiency is typically over 45%, would produce ~215 MWe and a Corex® C3000 module ~275 MWe (Böhm and Peer, 2002). Some of the export gas at the Baosteel C3000 plant is used in a 160 MW combined cycle to provide electricity to the steelworks and for export to the local grid (Liu and Gallagher, 2010).

Hu and others (2009) compared CO<sub>2</sub> emissions from BF and Corex® gases when these are used in combined-cycle power plants. The system boundaries included credits for export electricity and slag utilisation. The conventional BF route included coking, sintering, the BF and related support systems, whilst the Corex® route included coking, the Corex® unit and related support systems. Total CO<sub>2</sub> emissions for the two routes were similar, 1222.7 kgCO<sub>2</sub>/thm for the BF ironworks compared to 1212.3 kgCO<sub>2</sub>/thm for Corex®. CO<sub>2</sub> emissions from the Corex® route were lower than conventional BF iron making only when the thermal efficiency of the combined-cycle power plant is higher than 45% and the CO<sub>2</sub> emission factor of electricity is higher than 0.9 kgCO<sub>2</sub>/kWh. The electricity CO<sub>2</sub> emission factor differs from country to country. It is based on the different ratios of hydroelectric, nuclear, renewable energy and thermal power employed for the generation of electricity (Böhm and others, 2004). CO<sub>2</sub> emissions as a function of power generation efficiency and electricity CO<sub>2</sub> emission factor for BF and Corex® iron making are shown in Figure 18.

A LCA study (covering the mining of iron ore and coal up to the finished hot metal product) by Wegener and others (2009) found that the global warming potential of conventional BF and Corex® iron making routes were similar if the plants were built in Europe (EU25). CO<sub>2</sub> emissions from Corex® would be lower for plants in China because electricity generated from the Corex® export gas is replacing coal-based power generation. China has a high electricity CO<sub>2</sub> emission factor since a



**Figure 18 CO<sub>2</sub> emissions from BF and Corex® iron making systems as a function of power generation efficiency and electricity CO<sub>2</sub> emission factor (Hu and others, 2009)**

high proportion of its electricity is generated from coal. Thus total CO<sub>2</sub> emissions from Corex® (and other iron making processes) are dependent on where the plant is built.

Capturing and storing the CO<sub>2</sub> from the export gas would lower CO<sub>2</sub> emissions (*see* Chapter 9). CO<sub>2</sub> capture is already practised at the Saldanha C2000 plant in South Africa where CO<sub>2</sub> from the export gas is removed in a vacuum pressure swing adsorption process before it is used to produce DRI in a Midrex® shaft furnace (Wieder and others, 2005). The average energy consumption (Corex® + DRI) is 10.3 GJ/thm (Gielen and Moriguchi, 2002).

The export gas can be partially recycled to the reduction shaft after the removal of the CO<sub>2</sub>. This enables more efficient Corex® plant operation with a decreased energy demand on the melter-gasifier with resultant lower consumption of energy and O<sub>2</sub>. Slag production is also lowered as a result of the decreased coal consumption, resulting in a reduced energy loss from the sensible heat of the slag. The remaining diminished quantity of lower CV export gas can still be used for power generation (Böhm and Grill, 2009; Böhm and others, 2010). The captured CO<sub>2</sub> could then be stored underground. However, CO<sub>2</sub> capture can consume significant amounts of electricity.

If the Corex® module is incorporated into an existing integrated steelworks, then the export gas can be injected into the BF. Such an integration of processes would involve considerable changes in the gas energy of the steelworks. CO<sub>2</sub> is removed from the export gas before it is either heated to about 400°C and injected via the tuyeres into the BF or heated to around 850–1000°C and injected into the BF thermal reserve zone. Lower coke consumption (over 10%) and the substitution of coal, fuel oil or natural gas injectants would reduce CO<sub>2</sub> emissions from the BF. In addition, hot metal output increases (up to 10%) and the hot blast consumption decreases. More electricity could be generated as a consequence of the increase in the production of BFG with a higher net CV (Böhm and Peer, 2002; Lampert and others, 2010; Ziebig and others, 2008). If the generated electricity replaces electricity produced with a higher CO<sub>2</sub> emission factor, then CO<sub>2</sub> emissions from the steelworks would be lowered. Storing the captured CO<sub>2</sub> would further reduce CO<sub>2</sub> emissions.

Air separation units (ASUs), which are large consumers of energy, are commonly employed to produce the O<sub>2</sub> required for the melter-gasifier. Integrating the ASU with a combined-cycle power plant and with the smelting reduction process can help optimise energy recovery, increase power output and thus lower CO<sub>2</sub> emissions. There are various options to achieve this from nitrogen only

integration (nitrogen is produced in the ASU) to full air and nitrogen integration (*see* Carpenter, 2004). But integration adds a degree of operational complexity to the facility.

The use of higher quality iron ores and coal can also help lower energy consumption (*see* Section 6.1). PCI into the melter-gasifier is being tested as a way of saving fuel at a C3000 plant in China (Böhm and others, 2010). Waste plastics with a high CV value (around 41.9 MJ/kg) can be directly fed with the coal into the melter-gasifier to reduce fuel consumption, and consequently CO<sub>2</sub> emissions. About 100 kg of plastics/thm can be used (Gupta and Gupta, nd). The low strength and low abrasion resistance of charcoal limits its use in Corex® plants.

The majority of solid wastes produced by Corex® plants can be recycled, either within the steelworks or sold (Carpenter, 2004). Coal fines form the largest proportion of the generated solid wastes. This is a result of the Corex® process requiring lump coal (+5 mm). Depending on the coal used, a significant amount of fines is screened out and a use for these fines needs to be found to lower CO<sub>2</sub> emissions in an LCA of steel production. A certain percentage of coal fines can be charged directly into the melter-gasifier, or used in coke oven plants, in a power plant or cement plant, or injected into a BF. The coal fines can be briquetted and fed to the melter-gasifier. Up to 60% of coal fine briquettes have been charged into the melter-gasifier at the Posco plant without any problems. Fuel consumption decreased by about 7% because of the enhanced char bed permeability resulting in more efficient heat exchange at the char bed (Bae and others, 2000). The briquettes also allowed coke-free Corex® operation (Wieder and others, 2005). However, the briquetting plant may add to the overall energy consumption and CO<sub>2</sub> emissions of the steelworks.

The amount of slag produced in Corex® is higher than in BFs due to the higher coal and additives consumption. The composition of the slag is similar to BF slag and can be used in cement production or as an aggregate. Around 340 kgCO<sub>2</sub>/t slag could be saved when it is used as a substitute for cement clinker. This would reduce emissions from the cement industry, but not for iron and steel production since the CO<sub>2</sub> credits are allocated to the cement plant. The sensible heat of molten slag from a C3000 unit was calculated to be 0.7 GJ/thm, corresponding to 11% of the heat balance of the whole system. Ways of utilising this waste heat, which could lower CO<sub>2</sub> emissions, are similar to those used for BFs (*see* Section 4.5).

### 6.3 Finex®

Finex® is a variation of the Corex® process whereby iron ore fines are pre-reduced in a series of fluidised bed reactors instead of the reduction shaft, before they are charged to the melter-gasifier. By utilising iron ore fines, no agglomeration stage is required with its concomitant cost and CO<sub>2</sub> emissions. In 2003 Posco converted its Corex® C2000 plant (capacity 0.6 Mthm/y) in the Pohang Works, South Korea, to demonstrate the Finex® concept. A 1.5 Mthm Finex® plant, built at the same site, began operations in April 2007, and a third 2 Mthm plant is under construction, due for completion in 2013. According to the developers, a 1.5 Mthm/y Finex® plant can produce hot metal more cost effectively than a 3 Mthm/y BF. When O<sub>2</sub> and power plants are included in the comparison, the capital and operating costs of a Finex® plant are about 20% and 15% lower, respectively, than in the BF route (Lee, 2008).

In the Finex® process dried iron ore fines are charged, along with fluxes such as limestone or dolomite, into a series of 3 or 4 bubbling fluidised bed reactors. As the iron ore fines pass through the reactors, they are heated and progressively reduced in a countercurrent flow with reducing gas produced in the melter-gasifier. After exiting the final reactor, the DRI fines are hot compacted and fed into the melter-gasifier (*see* Section 6.2). Gasification of coal within the melter-gasifier generates the reducing gas for the fluidised bed train and the heat required to melt the hot-compacted iron to hot metal and to form the liquid slag. A portion (~30%) of the offgas exiting the top of the fluidised bed reactor train is recycled back into the melter-gasifier, after CO<sub>2</sub> removal, in order to achieve a higher gas utilisation rate.

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The elimination of sintering and coking plants should lower CO<sub>2</sub> emissions. However, some 70–100 kg coke is still needed for permeability reasons in the hearth of the melter-gasifier (Lüngen and Steffen, 2007).

The coal rate at Posco's 1.5 Mt/y Finex® plant has dropped from 850 kg/thm at the start-up of the plant to 700 kg/thm by April 2008, around the same rate as the best BFs (IEA, 2009a). This has been achieved by increasing the amount of pulverised coal (to 35% of the coal rate) injected through the tuyeres of the melter-gasifier. This has improved the heat exchange in the char bed. Recycling the pre-reduction offgas has also contributed to the lower coal consumption and overall enhanced energy efficiency (Lee, 2008). Developments to reduce the coal rate to 660 kg/thm are under way that will further lower CO<sub>2</sub> emissions (Park, 2008).

The energy consumption of Finex® is higher than conventional BFs. One reason is that fluidised beds are not as efficient at absorbing the sensible heat of the offgases as the countercurrent bed of the BF. Although heat exchangers are added to the system to recover the sensible heat, overall heat recovery is not as good as for the BF (Cairns and others, 1998).

Like Corex®, the energy efficiency and CO<sub>2</sub> emissions are mainly dependent on the efficient use of the export gas and the allocation of the related emissions. The amount and composition of the export gas are influenced by the composition of the coal (*see* Section 6.1) and operating conditions. The export gas can be used for a variety of purposes, as discussed in the previous section. Posco uses the export gas in a 145.9 MW combined-cycle power plant and for other purposes within the steelworks. By displacing electricity from the grid, 531,697 tCO<sub>2</sub>/y are abated (UNFCCC, 2008c).

A LCA study by Wegener and others (2009), discussed in the previous section, showed that GHG emissions vary depending on where the iron making plant is built. The global warming potential of conventional BF, Finex® and Corex® iron making routes were comparable if the plants were built in Europe (EU25). Both Finex® and Corex® would have a lower global warming potential than BFs if the plants were built in China or Brazil. For China, this is because the electricity generated from the export gas is replacing coal-based power generation.

Most of the CO<sub>2</sub> mitigation options and ways of lowering the energy consumption, at least those applicable to the melter-gasifier, discussed in the previous section are applicable to Finex®. These include the incorporation of the air separation units into the combined-cycle power plant and with the smelting reduction process to optimise energy recovery and increase power output. Utilising higher quality iron ores and coal can help lower energy consumption (*see* Section 6.1), and injecting waste plastics into the melter-gasifier will reduce fuel consumption. Posco is also investigating the use of H<sub>2</sub>-enriched syngas for iron ore reduction to lower CO<sub>2</sub> (Park, 2008). Utilising the sensible heat in the various offgas streams could further mitigate CO<sub>2</sub> emissions. Supplying the slag to the cement industry decreases CO<sub>2</sub> emissions by 790 kg/t slag (Park, 2008), but this benefit is usually assigned to the cement industry. Finex® plants with a capacity of 1–1.8 Mt/y would produce 300–370 kg slag/thm.

Finex® is well suited for carbon capture and storage (CCS). Part of the CO<sub>2</sub> is already removed from the offgas (which contains 33% CO<sub>2</sub>) via a pressure swing adsorption unit, PSA (*see* Chapter 9). The tail gas from the PSA contains 66% CO<sub>2</sub>. If this tail gas was stored, and with a coal rate of 660 kg/thm, then CO<sub>2</sub> emissions from Finex® would be 55% of those from a typical BF (Park, 2008). With some process redesign, all the CO<sub>2</sub> could be captured with no efficiency penalty to the Finex® process itself (IEA/UNIDO, 2011). Capturing and storing CO<sub>2</sub> from the power generation plant would further lower CO<sub>2</sub> emissions. Alternatively, the offgas could be completely recycled. CO<sub>2</sub> removal and recycling the offgas increases energy efficiency by 1.3–2 GJ/thm (IEA, 2009a; Lee, 2008).



## 6.4 HIs melt®

The HIs melt® process is the only direct smelting technology where the iron ore is reduced in a molten metal bath. In other bath smelting processes, the reactions occur in the slag layer and the slag acts as the heat transfer medium. The advantage is that dissolved carbon in metal reduces iron ore significantly faster than char in slag (Goldsworthy and McCarthy, 2001). The process was demonstrated in a 100,000 thm/y plant in Kwinana, Western Australia. A 800,000 thm/y commercial plant was commissioned at the same site in 2005 processing high phosphorus iron ore fines. Operations at the plant were suspended at the end of 2008 due to depressed global pig iron prices and poor market outlook. The plant will be moved to India under a Memorandum of Understanding signed between Rio Tinto and Jindal Steel and Power Ltd.

The heart of the HIs melt® process is a vertical water-cooled Smelting Reduction Vessel (SRV) which contains a liquid iron bath with a slag layer above. Preheated iron ore fines (typically –6 mm) and/or waste iron oxide materials, ground coal (typically –3 mm) and fine fluxes are injected through side mounted water-cooled lances deep into the melt. Rapid dissolution of coal and smelting occurs (within seconds). The gases (mainly CO and H<sub>2</sub>) liberated from this process are combusted by blowing hot O<sub>2</sub>-enriched air (1200°C) through a water-cooled lance located in the top of the SRV. Part of the heat generated by this post-combustion process is captured by the highly turbulent metal and slag droplets above the slag layer and transferred back to the metal bath as the droplets return to the bath. The hot metal is continuously tapped through a forehearth to maintain a nearly constant metal level within the SRV, whilst the slag is periodically tapped via a conventional water cooled taphole. The hot metal is then desulphurised. Since a HIs melt® facility uses much of the same equipment as a BF, it could be retrofitted into an integrated site (Goodman, 2007).

All the offgases are recycled. The hot offgas exiting the SRV is cooled (a source of heat loss) and cleaned. Its sensible and chemical energy is utilised to fire the stoves which preheat the hot air blast. Part of the offgas can be used to preheat and/or pre-reduce the iron-bearing materials or, if economically advantageous, used to generate electricity. The offgas from the CFB iron ore preheater in the Kwinana plant is sent to the waste heat recovery unit for steam generation.

The heat transfer efficiency in the SRV has been improved by installing two co-injection Giga lances (instead of separate coal and iron ore lances). This has additionally helped to lower the coal rate and increase the production rate (1834 thm/d in Dec 2008) (Burke, 2009; HIs melt Corp, 2008). The lowest coal consumption rate achieved was ~810 kg/thm; the design level is around 700 kg/thm. If HIs melt® was combined with the Circofer® pre-reduction process (*see* Section 5.5.1), a further reduction to 555 kg/thm would be possible. Depending on the efficiency of the coke oven, this could represent a saving of 20% of the coal demand of the coking, sintering and furnace stages of the BF process (IEA, 2009a).

The net energy consumption of HIs melt® is ~18.9 GJ/thm, although this figure is expected to decrease with further scale-up, optimisation and engineering developments (Carpenter, 2004). Studies indicate that a HIs melt® facility, at its current level of development, is comparable to the most efficient BFs in terms of energy utilisation and GHG emissions. The Kwinana plant emitted 1700–1900 kgCO<sub>2</sub>/thm in 2008 (Burke, 2009), down from 6200 kg and 4500 kgCO<sub>2</sub>-e/thm in 2006 and 2007 respectively. The reduction over the years can largely be attributed to improvements in coal use efficiency and increased production (Rio Tinto, 2008). If the ore preheater is replaced with a Circofer® CFB reactor then 900–1100 kgCO<sub>2</sub>/thm would be emitted (~50% reduction). The iron ore is pre-reduced to a metallisation degree of 80%, compared to 10% in the ore preheater. About 30–35% of the CO<sub>2</sub> is scrubbed from the Circofer® offgas and stored underground, and CO<sub>2</sub>-depleted scrubber offgas is then returned to the CFB reactor as fluidisation gas (Burke, 2009). About 70% of the CO<sub>2</sub> released in the complete process comes from the Circofer® unit. Half of the steam for the scrubbers can be covered with waste heat from the process; the other half would need to be produced separately (IEA, 2009a). High volatile coal is utilised instead of low volatile coal. CO<sub>2</sub> emissions can be further

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reduced to 100–300 kg/thm by injecting 100% O<sub>2</sub> instead of an O<sub>2</sub>-enriched hot air blast, and capturing 90–95% of the CO<sub>2</sub> in the Circofer® offgas and CO<sub>2</sub> from the SRV offgas for underground storage. Near net zero emissions are claimed if the SRV size is also increased from 6 m to 8 m, doubling the production capacity to 4 Mt/y (Burke, 2009).

Orth and others (2007) provide a more detailed process flowsheet of the combined Circofer® and HIs melt® reactors with CO<sub>2</sub> capture. They estimated that CO<sub>2</sub> emissions would amount to 1817 kg/tcs (when combined with a BOF), as opposed to 2227 kgCO<sub>2</sub>/tcs for production via the traditional BF/BOF route, a decrease of 18%. These figures are for coal-based power generation. The decrease would be 21% for power generation from natural gas. Without the O<sub>2</sub> steel making unit, CO<sub>2</sub> emissions from Circofer® plus HIs melt® are 1567 and 1473 kg/tcs for coal and natural gas power generation, respectively. It is assumed that no additional coke is required for steel making as the carbon content of 4.7 wt% in the hot metal supplies sufficient energy, and the iron ore is reduced to a metallisation degree of 75% in the Circofer® reactor.

CO<sub>2</sub> emissions can be further lowered by replacing coal with charcoal. Small-scale tests have shown that wood charcoal performs as well as coal. HIs melt® could potentially be run on 100% charcoal, producing around 65% less CO<sub>2</sub> for every tonne of iron, taking into account the energy used in growing, processing and transport of the charcoal (Cribb, 2006). Charcoal can also replace coal in a RHF when combined with a HIs melt® reactor (*see* Section 5.1). Waste plastics could also replace coal, although this has not been tested yet.

About 250–300 kg of slag/thm is generated. Questions have been raised about the suitability of its direct use in cement manufacture, and hence the CO<sub>2</sub> credit for slag use. However, the granulated slag can be utilised as a feed to cement kilns and for a variety of applications in the construction and agricultural industries (Carpenter, 2004).

HIs melt® is being integrated with the Isarna process, which is an enhanced version of the Corus cyclone converter furnace. The combination is called HIsarna (iron ore is melted in the cyclone part and smelted in the HIs melt® section), and is part of the European ULCOS programme. Directly hot-coupling the two process steps avoids energy losses from intermediate treatment of materials and process gases. It is planned to operate with 100% O<sub>2</sub>, thus facilitating CCS. In theory, HIsarna could reduce CO<sub>2</sub> emissions by ~20% compared to the current BF route, and by ~80% if CCS is employed. Its direct CO<sub>2</sub> emissions would be ~1320 kg/thm without CCS and 300 kg/thm with CCS, compared to the current EU average BF emissions of 1650 kg/thm (Croezen and Korteland, 2010). CO<sub>2</sub> emissions could be further lowered by partially substituting coal with biomass (after partial charring), natural gas or H<sub>2</sub>. Energy consumption would be ~13.6 GJ/thm, 20% less than the BF route which consumes 17 GJ/thm (Croezen and Korteland, 2010). Coal preheating and partial pyrolysis in a separate reactor can be added for the further optimisation of energy efficiency. A 60,000 t/y pilot plant has been built at the IJmuiden steelworks of Tata Steel Europe (formerly Corus) in the Netherlands.

## 7 Basic oxygen furnaces

The hot metal product from BFs and smelting reduction processes, and DRI/HBI from the direct reduction processes contain unwanted elements which are removed in the basic oxygen furnace (BOF) or electric arc furnace (EAF). This chapter discusses the principal methods for lowering the energy consumption and CO<sub>2</sub> emissions of BOFs; EAFs are covered in the following chapter. As discussed in Section 2.3, the energy consumption and CO<sub>2</sub> emissions of EAF-based mini-mills are lower than those of integrated steel plants.

Hot metal is supplied to the steel making plant, typically by transfer cars, where it may be desulphurised prior to processing in the BOF. The main function of a BOF, also termed LD (Linz-Donawitz) converter, is to remove carbon, silicon and other impurities from the hot metal through oxidation. Scrap (typically 10–25%), hot metal and fluxes (limestone or dolomite) are charged, in turn, into the BOF. Hot or cold DRI can also be charged, but hot charging helps to offset the energy losses associated with the gangue in the DRI. Oxygen is blown in at supersonic velocities where it oxidises the carbon, silicon and other elements in the hot metal, liberating heat, which melts the scrap (and DRI/HBI, if present). The fluxes remove the oxidised elements, forming a molten slag. Sufficient scrap or other coolants are added to cool down the reaction and maintain the temperature at ~1600–1700°C. Tap-to-tap times are ~40 minutes of which 50% is ‘blowing time’. Since the reactions are exothermic, no external heat source is necessary to melt the scrap (and DRI/HBI) and to raise the temperature of the metal to the desired range for tapping. Energy consumption in the BOF is to power auxiliary processes only.

Since the main energy input to the BOF plant is the sensible heat in the hot metal, energy consumption is strongly influenced by the hot metal ratio. This ratio depends primarily on the carbon and silicon content of the hot metal, the hot metal temperature and the steel temperature at the end of the blow. In addition, the consistency of the hot metal charge can improve control of the BOF process and gas collection, thereby reducing the need for reblows and minimising the offgas losses (Cairns and others, 1998). One way of decreasing the hot metal ratio is to increase the metallic iron input, in the form of scrap or DRI/HBI. This both lowers CO<sub>2</sub> emissions and energy use. However, due to process reasons, the amount of scrap and DRI/HBI that can be added is limited, typically to below 25–30%. Higher amounts are possible if the scrap and DRI/HBI are preheated or by post-combustion of CO to CO<sub>2</sub> within the BOF (*see* Section 7.1).

Table 14 GHG savings potential from increased use of metallised iron (Zuliani and others, 2010a)			
Process	Action	GHG savings, %	
BOF	5% increase in scrap charge by enhanced post-combustion	7	7
BF	scrap addition at 0.29 t/thm, OR	20	
	DRI/HBI addition at 0.29 t iron equivalent/thm		15
Total GHG reduction potential		26	21

The availability and market value of scrap, as well as the required steel specification, also influence the quantity of scrap used. However, increasing scrap melting in the BOF may or may not decrease energy if the ‘invested’ energy in the scrap is considered (Fruehan and others, 2000). Scrap can also be charged into the blast furnace. Table 14 shows the total GHG reduction potential of an integrated plant with enhanced scrap melting in the BOF and scrap or DRI/HBI addition to the BF. Adding DRI/HBI to the BF, instead of scrap, results in a 5% lower GHG saving. Optimisation of scrap between the BF and BOF to minimise CO<sub>2</sub> emissions was discussed in Section 4.1.1.

More than 100 m<sup>3</sup> of offgas exits the BOF at a temperature above 1650°C. Its CV is

~6–8 MJ/m<sup>3</sup>, although it has a low fuel value during much of the steel making cycle (IEA, 2007). The offgas is generated intermittently, varies greatly in temperature, carbon monoxide and nitrogen concentrations, and is very dirty. For these reasons, the gas is still flared at many sites, and is the

Compound	Volume, %
CO	55–80
CO <sub>2</sub>	10–18
H <sub>2</sub>	2–10
N <sub>2</sub> + Ar	8–26

major source of CO<sub>2</sub> emissions from the BOF plant. The gas typically contains 10–18% of CO<sub>2</sub> and 55–80% of CO (*see* Table 15). The carbon in the hot metal is removed as CO and CO<sub>2</sub> during the O<sub>2</sub> blow. Carbon may also be introduced to a much smaller extent from fluxing materials and other process additives that are charged to the furnace. Using the default values in the IPCC Guidelines for iron (0.04) and steel (0.01) for the fraction of carbon gives an emission factor of 0.11 tCO<sub>2</sub>/tcs for carbon removed from the iron as CO<sub>2</sub> (EPA, 2010b).

Fuel, GJ/t	–0.7
Steam, GJ/t	–0.2
Electricity, GJ/t	0.1
Oxygen, GJ/t	0.4
Final energy, GJ/t	–0.4
Primary energy, GJ/t	–0.3

Recovering the offgas and its sensible heat recovery (*see* Section 7.2) are key factors in improving BOF energy efficiency and lowering CO<sub>2</sub> emissions. Electricity consumption of BOFs is estimated to be 0.08 GJ (or 23 kWh)/tcs. This figure includes the production of O<sub>2</sub> and the operation of the BOFs. When the energy from the BOF is recovered (waste heat recovery and/or BOF gas recovery), the BOF becomes a net producer of energy. In a modern plant, energy recovery can be as high as 0.7 GJ/tcs (European IPPC Bureau, 2011).

Table 16 gives the world best practice BOF energy intensity values calculated by Worrell and others (2007), showing a final energy production, that is, the energy used at the production facility, of –0.4 GJ/t steel, that is, a net energy exporter in the form of BOF gas and steam. The primary energy (which is the energy used at the production facility plus the energy used to produce the electricity consumed at the facility) intensity is –0.3 GJ/t steel. This value includes electricity generation, transmission and distribution losses of 67%. The values are based on the World Steel Association's AllTech plant (defined in Cairns and others, 1998), which incorporates all proven energy saving technologies.

Currently, some steel producers capture and use the BOF gas, principally producers in Western Europe, Japan, South Korea, India and China (Park, 2008). It is much less commonly practised in North America and Australia. This is probably because the economics may be unattractive for retrofitting to old BOF plants (EPA, 2010b). Challenges to waste heat recovery include high capital costs and the substantial maintenance problems resulting from hot dirty gases (BCS Inc, 2008). The IEA (IEA, 2007) has estimated that the global iron and steel industry could save ~0.25 EJ/y and 25 MtCO<sub>2</sub>/y if the BOF gas was recovered.

## 7.1 In-furnace post-combustion

Enhancing post-combustion of CO to CO<sub>2</sub> within the BOF by secondary O<sub>2</sub> injection can increase scrap melting rates by 3–6% as complete oxidation of CO to CO<sub>2</sub> releases three and a half times more heat than partial oxidation (Zuliani and others, 2010a,b). Melting more scrap reduces the total energy to produce steel since using scrap in place of hot metal requires less than 30% of the energy. Lances have been designed that independently inject both primary O<sub>2</sub> for decarburisation and secondary O<sub>2</sub> for post-combustion, and these can be retrofitted. The lance design affects post-combustion efficiency.

The effectiveness of post-combustion is dependent on the efficient transfer of the generated heat from the offgas to the liquid and solid phases. A 5% increase in scrap melting by enhanced post-combustion lowers BOF CO<sub>2</sub> emissions by 10 kg/tls. Increasing the scrap to hot metal ratio at the BOF also reduces the demand for hot metal, coke and pellets, all of which combine to reduce CO<sub>2</sub> emissions from an integrated plant by ~7% or 135 kgCO<sub>2</sub>/tls (Zuliani and others, 2010a). It can be difficult, though, to optimise and control post-combustion.

## 7.2 Energy recovery from BOF gas

Recovering energy from the BOF gas involves making efficient use of both its chemical and sensible heat. There are two main methods for recovering energy from the gas before it is cleaned:

- ‘open combustion’ systems;
- ‘suppressed combustion’ systems.

In open combustion systems, CO (and H<sub>2</sub>) in the gas is fully or partially combusted by air introduced into the BOF gas duct. Gas temperatures of 1900°C can be reached. The heat generated is recovered in a waste heat boiler to produce steam, which can be used to generate electricity or for other requirements within the steelworks. About 80% of the total outgoing heat can be recovered from a full combustion system. The amount of air mixed with the BOF gas determines the amount of steam generated. However, as the steam is produced intermittently (BOF steel making is a batch process), it cannot always be fully utilised (European IPPC Bureau, 2011). Steam accumulators can be installed to ensure continuous supply of steam to the steam network. The CO<sub>2</sub> content is highest in fully combustion BOF gas. The offgas has no fuel value, and so is flared after the heat has been recovered, releasing CO<sub>2</sub>.

Suppressed combustion systems offer the best opportunity for both heat and fuel recovery. A skirt is lowered over the BOF mouth during O<sub>2</sub> blowing to reduce air infiltration and inhibit combustion of the CO in the flue gas duct. The resultant CO-rich gas is collected, cleaned and stored for subsequent use for power generation, as a fuel gas within the steelworks or for other uses. The gas can be utilised directly or blended with BFG and/or COG. A waste heat boiler, generating high pressure steam, can recover the sensible heat of the gas before it is cleaned and stored; this recovers ~10–30% (0.1–0.3 GJ/tls) of the total energy output. Another 50–80% is recovered as chemical energy (CO) from the BOF gas. Total energy recovery when applying suppressed combustion, BOF gas recovery and a waste heat boiler can be as high as 90%. Energy savings can amount to 0.35–1.08 GJ/tls with a leak-free system (European IPPC Bureau, 2011). With energy savings of 0.92 GJ/t steel, CO<sub>2</sub> emissions would be reduced by 46 kg/t steel (Worrell and others, 2010). Energy recovery would lower CO<sub>2</sub> generation from the use of natural gas and electricity by ~0.05 tCO<sub>2</sub>/t steel (EPA, 2010b). The BOF gas is not usually collected during the start and end of blowing because of its low CV and CO content, and is instead flared. Thus CO<sub>2</sub> is inevitably emitted.

An advantage with suppressed combustion over open combustion systems is the smaller gas flow since no combustion occurs and no additional air is introduced. The cooling and gas cleaning systems are therefore smaller. It also results in higher productivity since the O<sub>2</sub> blowing speed can be increased, and lower energy consumption of the fans (European IPPC Bureau, 2011). Installing an expert system to optimise the collection of BOF gas could save ~30 MJ/tcs (Cairns and others, 1998).

Tata Steel Europe (formerly Corus) recently installed a BOF gas recovery system at its steelworks at Port Talbot, UK. The BOF gas is used as a low energy fuel within the steelworks, halving the Works’ external requirement for natural gas. CO<sub>2</sub> emissions are expected to reduce by ~240 Mt/y (Corus, 2010). A CDM project at the Rourkela Steel Plant, India, will recover an additional 98 m<sup>3</sup> of gas/tcs from two BOFs for feeding into an internal power plant. This will lower CO<sub>2</sub>-e emissions by 8536 t/y by replacing power (~15 GWh/y) generated from coal and fuel oil (UNFCCC, 2007b).

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## 7.3 Electricity saving measures

The cooled BOF gas is cleaned in a wet scrubbing system, generally based on venturi scrubbers, a dry electrostatic precipitator or a combination of the two. Dry cleaning systems consume less electricity than wet systems, lowering energy consumption by ~3–6 kWh/tcs (Cairns and others, 1998; Jamek, 2009). The collected dust from electrostatic precipitators can be briquetted and returned to the BOF, depending on the tramp element composition. Dust recovery and recycling is possible from wet systems after sludge separation and drying (Jamek, 2009).

Installing variable speed drives on the ventilation fans can lower the energy consumption of both open and suppressed combustion systems. At one facility in the Netherlands, variable speed drives reduced energy consumption by 20% or 0.84 kWh (0.003 GJ)/tcs. At the Burns Harbor steel making facility, USA, variable speed drives and equipment modifications reduced energy use at the BOF by ~50% and also reduced operation and maintenance costs. The payback time was under two years (EPA, 2010b). Cairns and others (1998) estimated savings of ~10 kWh/tls and ~0.2 kWh/tcs for variable speed drives fitted on secondary fume extraction hoods and steam exhausters fans, respectively.

Additional energy efficiency improvements for BOFs are discussed in Cairns and others (1998) and Worrell and others (2010). These include vessel bottom stirring which can save up to 38.9 kWh (140 MJ)/tcs (Cairns and others, 1998).

## 7.4 Sensible heat recovery from slag

Slag from the BOF is cooled from a temperature of ~1450–1650°C and either sold or landfilled. The sensible heat from cooling the slag could be recovered. The slag sensible heat content at 1550°C is 0.15 GJ/tls. Although this figure looks small, the amount of slag produced at a plant each year is considerable; around 100–200 kg slag/tls is generated (IEA, 2007). Thus ~1–2 Mt of BOF slag/y could be produced in a 10 Mt/y steelworks. Around 1.02% of the waste heat lost in a plant of this size is through slag cooling (Li and others, 2010).

Heat recovery from BOF slags is not yet practised. Several systems has been investigated, such as dry granulation and heat exchange processes (*see* Section 4.5). Dry granulation using an air blast, rotating drum or a stirrer could recover 65–75% of the enthalpy of the slag (Jones, 2009). Slag has a heat content (enthalpy) of ~2.2 MJ/kg (Kuehn, 2010). However, further improvement of the heat recovery efficiency and higher gas temperatures are required for economically attractive heat recovery processes (Moon and others, 2010).

Along with the sensible heat recovery from molten slags, chemical heat recovery from slags is also possible. BOF slag contains a high fraction of CaO that exothermically reacts with CO<sub>2</sub> to form carbonate. The energy released in this reaction is substantial, some of which could possibly be recovered. The sensible heat recovery from molten slags is effective at higher temperature, but its efficiency decreases with temperature. On the other hand, chemical heat recovery from slags is applicable at less than 430°C. Thus, the efficiency of heat recovery from molten slags could possibly be maximised by combining the sensible and chemical heat recovery processes (Moon and others, 2010). The carbonation reaction is also an attractive way for storing CO<sub>2</sub> (*see* Section 9.1.7).

Utilising the slag can also help lower CO<sub>2</sub> emissions from the steelworks. Recycling the slag to the BF would decrease the limestone demand (due to the slag's CaO content) and thereby less CO<sub>2</sub> would be emitted (Ribbenhed and others, 2008). This use is dependent on the slag composition as compounds such as vanadium and phosphorus oxides adversely affect the process. Slag can be used externally in the cement clinker manufacturing process. The main limitation for increased steel slag use for cement production is its high phosphor content. Some slag can be added directly as a clinker substitute, but grinding the slag is an energy intensive process; therefore this option is not widely applied. Most slag

is used for road construction and civil works. This application generates some CO<sub>2</sub> benefits. BOF slag use for cement production is still limited and could be expanded significantly. The credits are ~0.6 tCO<sub>2</sub>/t clinker substitute. The total savings potential is ~50 MtCO<sub>2</sub> (IEA, 2007).

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## 8 Electric arc furnaces

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Scrap is the traditional input to EAFs, but with current shortages of high-quality, low price scrap, substitutes are increasingly being used. Alternative iron sources include DRI, HBI, iron carbides and hot metal. Input materials are often dictated by local circumstances. In Europe and North America, for instance, scrap is the main charge material, whereas in China, scrap is supplemented by hot metal, and in India by hot metal and DRI. In the Middle East, 100% DRI operation is standard (Opfermann and others, 2009).

EAFs remove the carbon, silicon and other impurities from the iron-containing materials in a batch process. Scrap, alternative iron and flux are charged into the top of the EAF, typically via a basket. After the roof is closed, carbon electrodes are lowered into the furnace and an arc of electricity raises the temperature to ~1600°C, melting the feed. Additional chemical energy may be supplied via oxyfuel burners and O<sub>2</sub> lances. The molten steel is tapped from the furnace into a ladle, and transferred to the ladle furnace where alloys are added to obtain the desired steel properties. Tap-to-tap times range from 35 to over 200 min with generally higher tap-to-tap times for stainless and speciality steels. Newer EAFs are designed to achieve tap-to-tap times of less than 60 min. The typical capacity of a mini-mill is 0.5 to 1 Mt/y of steel. Recently, EAFs have been incorporated into integrated steel plants.

Process-related CO<sub>2</sub> emissions from EAFs are generated primarily during the melting and refining processes, which remove carbon as CO and CO<sub>2</sub> from the charge materials and carbon electrodes. Smaller quantities of CO<sub>2</sub> are produced, where present, from the use of oxyfuel burners, post-combustion and carbon fines injection. The offgas from the EAF is typically sent to a baghouse for removal of particulates before it is discharged to the atmosphere. This is the major source of CO<sub>2</sub> emissions in a mini-mill. Indirect CO<sub>2</sub> emissions also result from the consumed electricity unless the electricity is produced by hydro or nuclear power plants, or from renewable sources. CO<sub>2</sub> emissions from EAFs in the USA were estimated to be 4.6 Mt in 2007 based on the IPCC Guidelines emission factor of 0.08 tCO<sub>2</sub>/t of steel and production of 58 Mt of steel (EPA, 2010b).

Thomson and others (2000) used an LCA approach to evaluate GHG emissions from EAF steel making. Indirect emissions include GHGs that are generated during the production of the process inputs (for instance, electricity, lime and oxygen). They found that indirect GHG emission sources, in particular electricity generation, were more significant than direct emissions. Direct GHG emissions only formed 27% of the total emissions from a conventional Canadian EAF (with an electricity generation source of 32% fossil fuel).

The EAF is the biggest user of energy in a mini-mill, accounting for close to 90% of the total electricity used (Natural Resources Canada, 2007). Electricity consumption of alternating current (AC) EAFs were in the range 408–530 kWh/t in Taiwan, and 360–510 kWh/t for direct current (DC) EAFs (Chan and others, 2010). Fruehan and others (2000) determined the practical minimum energy of an EAF to be 444 kWh (1.6 GJ)/t; the absolute minimum is 361 kWh (1.3 GJ)/t. This is the energy required to melt the scrap and produce liquid steel at 1600°C. Converting these energy figures to CO<sub>2</sub> emissions gives practical minimum and absolute CO<sub>2</sub> emissions of 277 kg/t and 225 kg/t, respectively. Given an electricity use of about 425 kWh/t, and EAF steel production of 391 Mt in 2005, the global energy use of EAF for steel production is 0.6 EJ/y. Reducing the average electricity use to 350 kWh/t, the level of new furnaces, could provide electricity savings of 0.1 EJ/y (IEA, 2007).

The energy demand of an EAF is influenced by the input materials, energy efficiency, operational efficiency and any installed energy recovery systems. Table 17 gives an energy balance for a modern 7 m diameter EAF processing 100% scrap. Electrical energy provides over 55% of the energy input, with chemical energy providing another 41%. The main source of energy loss is from the offgas (over



**Table 17 Energy balance for a modern EAF**  
(Zuliani and others, 2010b)

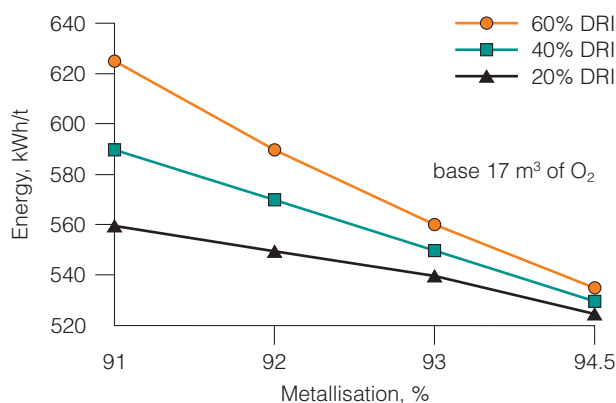
Energy input	kWh/tls	% of total energy
Electrical energy	400	55.4
Chemical energy – burners	80	11.1
Chemical energy – oxidation	220	30.5
Oil and hydrocarbons	22	3.1
Total energy inputs	722	100
Energy output		
Steel	388	53.7
Slag	46	6.4
Offgas – sensible heat	112	15.5
Offgas – chemical energy	122	16.9
Water cooling	54	7.5
Total energy outputs	722	100

32%), followed by water cooling and slag. Energy losses to the offgas typically represent between 220 and 440 kWh/t steel, depending on operating practices. In operations utilising high levels of chemical energy in the EAF, energy losses to the offgas can be as high as 50% of the total energy input (Jones, 2009). Before discussing EAF energy efficiency improvements and the recovery of chemical and sensible heat from the offgas, the influence of the raw materials will be discussed.

## 8.1 Raw material quality

The quality of the raw materials directly affects EAF energy consumption due to the reduced efficiency of the melting process (such as reduced arc efficiency and increased yield loss) and the need to increase slag volumes to remove residual constituents (Cairns and others, 1998). The quality of scrap

varies widely throughout the world and is a limiting factor for its increased use. Alternative iron materials are added to dilute the scrap's unwanted tramp elements in order to produce higher quality steels. However, energy consumption increases as increasing amounts of DRI are added. The ratio of scrap to alternative iron depends on the target product quality and the available scrap quality at each EAF.



**Figure 19 Energy consumption as a function of metallisation and relation with the scrap/DRI ratio** (Cairns and others, 1998)

94.5% for the different DRI charge proportions. For an EAF melting 60% DRI (94.5% metallisation) and 40% scrap, the increase in energy consumption compared to a 100% scrap feed is ~20–40 kWh/tls (Cairns and others, 1998).

Gangue is largely made up of silica ( $\text{SiO}_2$ ) which must be melted. For a charge containing 60% DRI, each 1% increase in silica content increases the energy consumption by ~10 kWh/t steel (Kekkonen and Holappa, 2000). Calculations by Cárdenas and others (2007) indicated that each 1% increase in DRI gangue content consumes an extra ~15 kWh/t steel and every 1% increase in metallisation (from 90%) lowers energy consumption by ~11 kWh/t steel.

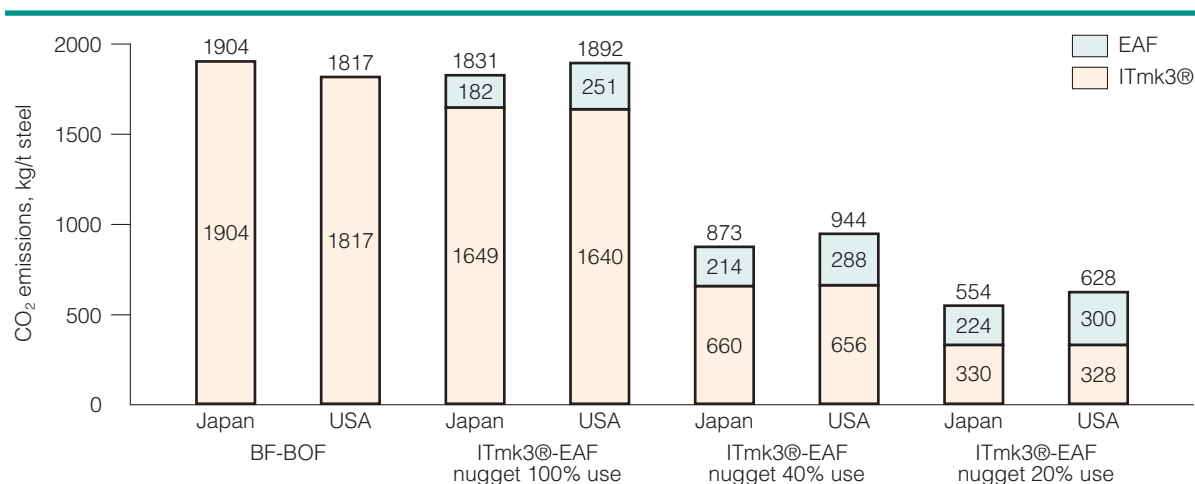
<b>Table 18 Energy input to EcoTech and AllTech EAFs (Cairns and others, 1998)</b>				
	EcoTech	AllTech	EcoTech	AllTech
Charge	100% scrap		60% DRI/40% scrap	
Electricity, kWh/tls	409	310	530	450
O <sub>2</sub> blowing for liquid steel oxidation, m <sup>3</sup> /tls	19.5	20	19.5	19.5
O <sub>2</sub> blowing for post-combustion, m <sup>3</sup> /tls	8.6	10	–	3
O <sub>2</sub> for oxyfuel burners, m <sup>3</sup> /tls	9	12	–	4
Natural gas, m <sup>3</sup> /tls	4.5	4	–	1.5
Carbon (coal injection and bucket charge), kg/tls	12.9	11	8	8
Ladle furnace, kWh/tls	35	35	35	35
Gas cleaning system, kWh/tls	30	30	30	30
Scrap preheater saving, kWh/tls	–	(70)	–	(40)
Total	5079 MJ/tls 1411 kWh/tls	4113 MJ/tls 1143 kWh/tls	5805 MJ/tls 1613 kWh/tls	5152 MJ/tls 1431 kWh/tls

Carbon in the DRI can provide chemical energy (from exothermic reactions) which improves thermal efficiency in the EAF, thus decreasing electric power requirements. In a typical EAF, about 30% of the energy input is provided by the chemical energy derived from the oxidation of carbon, other chemical reactions and oxyfuel combustion; the remaining 70% is electrical energy (Zaharia and others, 2009). The required carbon reductant is provided as charge carbon and/or by carbon injection, as well as in the DRI. Carbon (graphite) injection is ~12 kg/tls for DRI with 2.2% carbon, but just 0.5 kg/t when 4% carbon DRI is charged. The change from 2.2% to 4% carbon in cold DRI represents a decrease of ~11 kg of graphite and a power saving of 58 kWh/tls under the applied operating conditions (Duarte and others, 2010a).

The best practice primary energy intensity (which includes electricity generation, transmission and distribution losses of 67%) for EAFs processing 100% scrap is 5.5 GJ (1528 kWh)/t steel compared to 5.9 (1639 kWh)/t steel for 100% DRI, a difference of 111 kWh/t (Worrell and others, 2007). The energy intensity of the World Steel Association's EcoTech and AllTech processes (which include the gas cleaning system and refining of the liquid steel in a ladle furnace) for 100% scrap and 60% DRI/40% scrap charges are given in Table 18. The DRI has a 94.5% metallisation degree, and contains 2% carbon and 1.8% SiO<sub>2</sub>. Substituting 60% DRI for scrap increases the energy input to the AllTech process by 288 kWh/tls.

Processes such as Circofer® and Redsmelt® melt the DRI with flux in an electric furnace to remove the gangue and a major proportion of the sulphur originating from the coal before feeding the resultant hot metal to the EAF. This decreases the energy consumption of the EAF, but may increase or decrease the overall energy consumption of the plant when the energy consumption associated with melting the DRI is taken into account.

Not all alternative iron units increase the energy consumption when substituting for scrap. Energy consumption of an EAF with a 100% ITmk3® nugget charge is 409 kWh/t steel, compared to 456 kWh/t steel for a 100% scrap charge, an energy saving of 47 kWh/t (Fujita and others, 2010). The



**Figure 20** CO<sub>2</sub> emissions from ITmk3®-EAF and BF-BOF (Fujita and others, 2010)

iron nuggets (*see* Section 5.4) are basically gangue-free. Increasing the percentage of iron nuggets in the scrap charge lowers the resultant EAF CO<sub>2</sub> emissions (*see* Figure 20). The figure also shows how CO<sub>2</sub> emissions are dependent on the country in which the plant is built. The ITmk3®-EAF route has higher CO<sub>2</sub> emissions when built in the USA than in Japan since the CO<sub>2</sub> emissions per kWh in the USA are 40% higher. The carbon emission factor for electric power is 0.39 and 0.56 kgCO<sub>2</sub>/kWh in Japan and the USA, respectively. In the USA, although not in Japan, the conventional BF-BOF route has lower CO<sub>2</sub> emissions than ITmk3®-EAF because the CO<sub>2</sub> credit for electric power generated from the surplus gas is bigger in the USA than in Japan.

The use of hot metal decreases power consumption by 3.5 kWh per percentage point, whereas the use of DRI or HBI increases electricity needs by 0.8 kWh per percentage point (IEA, 2007). According to Sampaio and others (2009), charging 1 t of hot metal at 1430°C supplies ~250 kWh in the form of sensible heat, based only on the Fe content. Typically hot metal use is between 10% and 80% of the charge in modern EAFs. When 70–75% of hot metal was charged in Chinese EAFs, no electrical power was required. All the required heat was supplied by the O<sub>2</sub> blowers as chemical energy. The theoretical minimum energy required for a 50% hot metal/50% scrap charge, where the hot metal is charged at 1450°C, is 5875 MJ (1632 kWh)/tIs (Fruehan and others, 2000). For 50% solid pig iron, the minimum energy is 6533 MJ (1815 kWh)/tIs. Again, energy consumption is affected by the hot metal composition. Off-specification hot metal (and pig iron) containing high levels of silicon which, whilst providing an additional heat source to the EAF due to silicon oxidation, will also lead to increased slag production, adversely impacting energy consumption (Cairns and others, 1998). Charging hot DRI/HBI is discussed in Section 8.5.

### Biomass and waste polymers

Biomass and waste polymers can replace the charge carbon (added through the top of the furnace) and/or the injectant carbon (for slag foaming, discussed in Section 8.6) to reduce CO<sub>2</sub> emissions.

A feasibility study for replacing coke in Indonesian EAFs by charcoal produced from kernel shell residues from the palm oil industry has been carried out (JP Steel Plantech, 2007). Large size charcoal is mixed with the scrap charge and smaller sized charcoal is injected. Industrial trials indicated that the performance was about the same as coke, under similar operational conditions. Coke consumption at the steel plant was 25 kg/t steel, giving an annual coke consumption of 9000 t/y and CO<sub>2</sub> emissions of 28,050 t/y. Replacing 40% of the coke with charcoal would reduce CO<sub>2</sub> emissions by 11,220 t/y. Work carried out in Canada under the Canadian Steel Breakthrough Program indicated that substituting fossil fuel injection by charcoal injection could reduce GHG emissions of the slag foaming process by 25% (Natural Resources Canada, 2009). The strength of charcoal is not an issue in this application.

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A LCA assessment found that the gross energy requirement was reduced by 1.5 kWh/kg steel with 100% charcoal substitution for both a 100% scrap and a 90% scrap/10% pig iron charge, and the GHG reduction amounted to 0.15 and 0.14 kgCO<sub>2</sub>/kg steel, respectively. The assessment included replacing the carbon source in the ladle (re carburiser carbon), as well as the EAF (charge and injectant carbon source), casting and charcoal production with credits for electricity and eucalyptus oil coproducts. Without these credits the CO<sub>2</sub> reduction is 0.05 kg/steel for the 100% scrap charge (Norgate and Langberg, 2009). The authors also discuss the economics of charcoal use.

Waste tyres and waste plastics can be substituted for the carbonaceous materials; they serve as a supplementary chemical energy source, as well as a carbon source for slag foaming. Waste tyres have been top charged or, when shredded, injected into EAFs in regions such as Europe, Australia, Japan and the USA. Tyres have a high CV, high VM, high carbon and low moisture contents, and also contain iron (Zaharia and others, 2009). About 1.7 kg of tyres can replace 1 kg of anthracite (Clauzade, 2006). In addition, the rubber in tyres account for ~30% of natural rubber which is assumed to have no net GHG impact due to CO<sub>2</sub> storage by rubber trees (Atech Group, 2001) and hence could contribute to lower CO<sub>2</sub> emissions.

Tyre injection trials at OneSteel's Sydney steel mill, Australia, reduced electrical energy consumption from 424 kWh to 412 kWh/t billet, reduced the amount of carbon injectant required from 464 kg/heat to 406 kg/heat, and improved the number of liquid tonnes per power-on time minute from 2.12 to 2.2 t/min (OneSteel, 2010). In addition, injection of waste plastics with coke at OneSteel's Sydney and Laverton plants decreased the electrical energy consumption and CO<sub>2</sub> emissions, as well as the consumption of carbon, compared to coke alone (Sahajwalla and others, 2009). The performance of waste plastic injection is dependent on its composition. A polyurethane/coke blend showed better slag foaming compared to coke alone, followed by the polyethylene terephthalate/coke blend and then the polyurethane/coke blend (Sahajwalla and others, 2010). Polyethylene waste plastics can replace 30% of the coke and coal used in EAF steel making. Energy savings from this process are estimated to be ~12 kWh/t of plastic charge (Worrell and others, 2010).

## 8.2 Process optimisation and control

Some of the more important measures and techniques for improving the energy efficiency of EAFs are given in Table 19. This table includes the estimated amount of electricity saved and consequent CO<sub>2</sub> emission reduction, as well as the capital costs for retrofitting the technology/measure and the payback time for EAFs in the USA. Most of the technologies/measures reduce the annual operating costs.

Process control can optimise operations and thereby significantly lower energy consumption. These control systems use a variety of sensors, and can incorporate real-time monitoring of process variables. Installing neural network control systems, for example, can lower CO<sub>2</sub> emissions by 17.6 kg/tcs and save 30.6 kWh (0.11 GJ)/tcs (Worrell and others, 2010).

Flue gas monitoring and control systems can decrease CO<sub>2</sub> emissions by 8.8 kg/tcs and electricity consumption by 13.9 kWh/tcs (see Table 19). At one plant in the UK, retrofitting real time offgas monitoring and using the results to continuously adjust the natural gas burners resulted in a GHG emission reduction of 15 kgCO<sub>2</sub>-e/tcs, higher than those given in Table 19 for USA plants, despite the fact that the UK and USA have similar proportions of fossil fuel electricity generation of 68% and 69%, respectively. Electricity consumption decreased by 25 kWh/tcs (Thompson and others, 2000). The authors report even higher reductions of 20 kgCO<sub>2</sub>-e/tcs and 40 kWh/tcs achieved when a Canadian EAF introduced offgas analysis with improved combustion control. A 32% fossil fuel electricity generation factor was used in this case. Using real time monitoring of flue gas to control post-combustion is discussed in Section 8.8.

**Table 19 Energy efficiency technologies and measures applied to EAFs in the USA (EPA, 2010b; Worrell and others, 1999, 2010)**

	Emissions reduction, kgCO <sub>2</sub> /tcs	Fuel savings, GJ/tcs	Electricity savings, GJ/tcs (kWh/tcs)	Annual operating costs, US\$/tcs	Retrofit capital costs, US\$/tcs	Payback time, y
Improved process control (neural network)	17.6	0	0.11 (30.6)	-1.6	1.5	0.5
Flue gas monitoring and control	8.8	0	0.05 (13.9)	0	3.1	4.3
Adjustable speed drives			0.05 (13.9)		2.0	2-3
Bottom stirring/stirring gas injection	11.7	0	0.07 (19.4)	-3.1	0.94	0.2
Eccentric bottom tapping on existing furnace	8.8	0	0.05 (13.9)	0	5.0	6.8
Airtight operation			0.36 (100)			
Engineered refractories			0.036 (10)			
Transformer efficiency (ultra-high power transformers)	10.0	0	0.06 (16.7)	0	4.3	5.2
DC arc furnace	52.9	0	0.32 (88.8)	-3.9	6.1	0.7
Scrap preheating – tunnel furnace (Consteel®)	35.2	0	0.22 (61.1)	-3.0	7.8	1.3
Scrap preheating, post-combustion – shaft furnace (Fuchs)	35.3	-0.7	0.43 (119.4)	-6.2	9.4	1.0
Twin-shell DC with scrap preheating	11.1	0	0.07 (19.4)	-1.7	9.4	3.5
Foamy slag practice	10.6	0	0.07 (19.4)	-2.8	15.6	4.2
Oxyfuel burners	23.5	0	0.14 (38.9)	-6.2	7.5	0.9
Contiarc® furnace			0.72 (200)			
\$ year 2008						

As flue gas flow varies over time, adjustable speed drives offer opportunities to operate dust collection fans in a more energy efficient manner. Electricity savings are estimated to be 13.9 kWh (0.05 GJ)/tcs. Although dust collection rates were reduced by 2–3%, total energy usage decreased by 67% (EPA, 2010b; Worrell and others, 2010).

Injecting an inert gas, such as argon, into the bottom of the EAF (bottom stirring) increases heat transfer and can save 12–24 kWh/tcs of electricity (Worrell and others, 2010). Eccentric bottom tapping leads to slag-free tapping, shorter tap-to-tap times, and reduced refractory and electrode consumption. Energy savings of ~15 kWh (0.054 GJ)/tcs can be achieved (EPA, 2010b).

A large amount of air enters the furnace at ambient temperature. Its nitrogen and non-reactive O<sub>2</sub> contents are heated up and exit with the fume at a temperature of ~980°C, resulting in a significant thermal loss. Based on the results of pilot-scale trials on a 6 t EAF, an EAF consuming 500 kWh (1.8 GJ)/t of electricity could potentially save 110 kWh (0.4 GJ)/t with an airtight process, post-combustion and an efficient fume exhaust control. About 80% of the savings can be attributed to

a reduction of energy losses in the fumes and the remaining 20% from reduced thermal losses due to a reduced tap-to-tap time. The exhaust gas can be used as a fuel in the post-combustion chamber and reduces the amount of natural gas needed for the burner (EPA, 2010b; Worrell and others, 2010).

### 8.3 Transformer efficiency and DC arc furnaces

Installing more powerful furnace transformers can help reduce energy losses and tap-to-tap times, and increase productivity. Ultra-high power furnaces are those with a transformer capacity of more than 700 kV amp/t heat size. However, ultra-high power operation may lead to heat fluxes and increased refractory wear, making cooling of the furnace panels necessary. This results in heat losses that partially offset the power savings. Total energy savings are ~16.7 kWh (0.06 GJ)/tcs (EPA, 2010b).

New transformers were installed by Ugine Ardoise in France on two furnaces, increasing the operating voltage from 600 to 660 V in one furnace and from 400 to 538 V in the second. The higher power delivered decreased the power-on time by 7 and 14 minutes, respectively, leading to a productivity increase of 7 t/h of crude steel. The electrode consumption decreased by 0.1 and 0.5 kg/t, while power consumption dropped by 11 and 22 kWh/t respectively (Worrell and others, 2010).

DC EAFs use a single electrode and the bottom of the vessel serves as the anode. These furnaces consume ~10 kWh/tls less electrical energy than an equivalent AC EAF, although this figure is difficult to measure against a total energy value which is subject to variations (Cairns and others, 1998). The EPA (EPA, 2010b) puts the energy savings at ~10–20 kWh/tcs compared to new AC furnaces. Electrode consumption is also around half that of AC EAFs. Installing a DC furnace can save 88 kWh (0.32 GJ)/tcs of electrical energy and reduce CO<sub>2</sub> emissions by 52.9 kg/tcs (*see* Table 19).

### 8.4 Scrap preheating

Scrap preheating can reduce the power consumption of EAFs by using the waste heat in the furnace offgas to preheat the scrap charge. It is the most common method used for heat recovery from offgas, which is the main source of energy loss from EAFs. In addition, it is among the most effective methods of reducing CO<sub>2</sub> emissions (*see* Table 19). There are four basic types of preheating systems in operation, all of which can be retrofitted, provided there is room for the system:

- basket, where the scrap is preheated in the loading basket;
- Consteel® which preheats the scrap in a tunnel and continuously charges it through the side of the EAF during the melting process;
- single shaft furnaces, such as the finger shaft (Simetal<sup>CIS</sup>, previously called Fuchs) and Ecoarc™ furnace, where the preheated scrap is fed through the top of the EAF;
- twin shell where two shaft furnaces are positioned next to each other.

These systems differ in the percentage of the charge that can be preheated and the efficiency of the contact between the offgas and the charge (IEA, 2007). Systems such as Consteel® introduce air into the preheater to burn the CO and CO<sub>2</sub>. Consequently both the chemical and sensible heat in the offgas is used. Afterburners can be installed on shaft furnaces to completely combust all the CO. The systems can also increase productivity and decrease electrode consumption.

The amount of electricity saved by preheating depends on the system used and factors such as the percentage of preheated scrap charged, the preheat temperature and whether post-combustion is included (*see* Table 19). Electric power savings of 60 and 120 kWh/tcs have been quoted for Consteel® and shaft furnaces respectively, along with reduced electrode consumption and increased productivity (APPCDC, 2010). Retrofitting a Consteel® system at Celsa Nordic's Mo I Rana plant, Norway, decreased electricity consumption by 91 kWh/tls and increased productivity by 20%. There

is never any solid scrap present in the furnace. The scrap is not heated by the arc but by the pool of liquid steel in the vessel. Thus the process is quite different from the previous batch type, top charged EAF (Giavani and others, 2010).

Thomson and others (2000) calculated that total GHG emissions would be reduced by 99 kgCO<sub>2</sub>-e/tcs in an EAF with shaft preheating compared to one without preheating. It should be noted that there were differences between the two EAFs (furnace geometry, number of burners and other operational factors). Direct CO<sub>2</sub> emissions were essentially the same for both EAFs. But electricity consumption in the shaft preheating EAF was almost 100 kWh/tcs lower, decreasing indirect CO<sub>2</sub>-e emissions by 84 kg/tcs. The rest of the CO<sub>2</sub> reduction results from the reduced lime use (less lime processing is required). Retrofitting an Ecoarc™ furnace at Dongkuk Steel Mill's Incheon Works in South Korea is expected to reduce CO<sub>2</sub> emissions by 88,284 t/y and lower electric power consumption by ~36% (UNFCCC, 2009a).

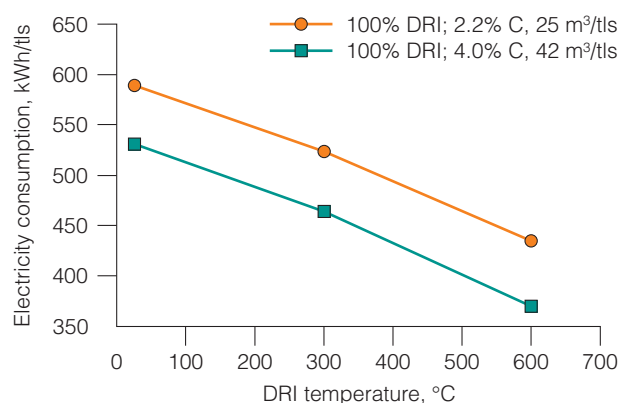
## 8.5 Hot DRI charge

Charging hot DRI/HBI rather than cold DRI/HBI provides additional sensible heat to the EAF, thereby reducing electric power consumption, shortening melting cycle times, increasing productivity and lowering CO<sub>2</sub> emissions. Hot DRI must be transported in a non-oxidising atmosphere. It can be transported via enclosed belt conveyors, a pneumatic transport pipe, an insulated hot transport vessel, or via gravity when the direct reduction furnace is above the EAF. The first three options could be retrofitted. Most new direct reduction-EAF installations feature hot charging options.

EAF electricity consumption decreases by ~20 kWh/tls for each 100°C increase in DRI charging temperature (Lüngen and Steffen, 2007). Thus, the savings when charging at over 600°C could be 120 kWh/tls or more. A reduction of 141 kWh/tls was achieved when 90% of hot DRI at 600°C was charged instead of 100% cold DRI (2.1% C) in an ultra-high power 150 t EAF at Emirates Steel Industries' plant in Abu Dhabi. The energy benefit comes mainly from:

- the enthalpy of the raw material corresponding to 105 kWh/tls;
- additional 1.5 m<sup>3</sup>/tls O<sub>2</sub> used with hot DRI, corresponding to 4 kWh/tls;
- improved metallisation of the hot DRI with respect to the cold DRI, corresponding to 23 kWh/tls;
- reduced thermal losses due to decreased power-on time, corresponding to 9 kWh/tls.

When 100% hot-charged DRI is introduced electricity consumption is expected to decrease by a further 12 kWh/tls to 380 kWh/tls (Razza and Patrizio, 2010). As noted in Section 8.1, energy



**Figure 21 Effect of DRI carbon content and charging temperature on electricity consumption** (Duarte and others, 2008)

consumption is influenced by the carbon content of the DRI. Figure 21 shows the effect of carbon content and the charging temperature of DRI on electricity consumption. Calculations by Duarte and others (2008) indicated that charging hot, rather than cold, DRI (3.7% C, 94% metallisation) could reduce CO<sub>2</sub> emissions from the EAF by 111 kg/tls.

A proposed CDM project at Essar Steel's plant at Hazira, India, is expected to decrease CO<sub>2</sub> emissions by 735,029 t/y by hot charging DRI instead of cold HBI (UNFCCC, 2009b). The calculated CO<sub>2</sub> reduction includes reduced energy consumption in the EAFs, briquetting machines and conveying system for HBI

transportation, as well as increased fossil fuel consumption in hot DRI transportation and increased nitrogen consumption (to prevent oxidation) in the hot DRI containers. The temperature of the DRI, which leaves the reduction furnace at 675°C, would drop by up to 40°C during transport to the EAF.

The maximum energy savings, productivity increase and CO<sub>2</sub> reduction potentials may not be achieved using conventional EAFs due to the different operation mode of the direction reduction furnace and EAF. While the former continuously produces hot DRI, the latter is a batch process. Continuous steel making processes are being developed. Charging hot metal was discussed in Section 8.1.

## 8.6 Slag foaming

Foamy slag covers the arc and provides an insulating surface to the melt, thereby reducing radiation heat losses. The furnace roof and walls are protected from excessive heating and radiation, and heat transfer to the charged materials is improved. Arc heat transfer efficiency can be as low as 36% without foamy slag, compared to 93–100% with a fully shielded arc (Opfermann and others, 2009). Slag foaming increases the electric power efficiency by at least 20% in spite of a higher arc voltage. The net energy savings (accounting for energy use for O<sub>2</sub> production) are estimated at 5.56–7.78 kWh (0.02–0.028 GJ)/t steel. Slag foaming could reduce CO<sub>2</sub> emissions by 10.6 kg/tcs (EPA, 2010b; Worrell and others, 2010). Foamy slag is generated by injecting carbon (such as granular coal) and O<sub>2</sub>, or by O<sub>2</sub> lancing alone (*see* Section 8.7). Replacing coal with biomass (wood charcoal) could further lower CO<sub>2</sub> emissions (*see* Section 8.1). Efficient carbon injection can additionally help reduce the iron content of the slag, even with simultaneous O<sub>2</sub> injection (Gervais and Brhel, 2010), and productivity may also increase through reduced tap-to-tap times. Retrofitting capital costs (in the USA) are about 15.6 \$/t capacity and the payback time is ~4.2 y (*see* Table 19 on page 77). But the use of slag foaming is not possible for some steel grades such as stainless steels and other high alloyed steels (European IPPC Bureau, 2011).

## 8.7 Oxyfuel burners and oxygen lances

Oxyfuel burners and O<sub>2</sub> lances have been used on EAFs for many years to reduce electricity consumption by substituting electricity with O<sub>2</sub> and hydrocarbon fuels. Most modern EAFs are equipped with them. Although CO<sub>2</sub> is generated through their use, total CO<sub>2</sub> emissions are lowered through the savings in electricity consumption (indirect CO<sub>2</sub> emissions). Oxyfuel burners and lances reduce total energy consumption by:

- decreasing the melting heat times, which saves 2–3 kWh/t/min of holding time (APPCDC, 2010);
- increasing heat transfer;
- reducing heat losses by facilitating slag foaming (*see* Section 8.6).

Moreover, electrode consumption decreases and productivity increases. As well as providing chemical heat, O<sub>2</sub> injection helps remove unwanted elements, such as silicon and phosphorus, from the molten steel. Oxyfuel burners, which commonly burn natural gas and O<sub>2</sub>, use convection and flame radiation to transfer heat to the scrap metal and DRI/HBI. Care must be taken to use oxyfuel burners/lances correctly otherwise there is the risk that the total energy consumption and CO<sub>2</sub> emissions will increase.

Burners are of varying forms, namely wall burners, combination lance burners or the more recent sonic velocity or coherent jet burners that inject not only a gas flame but also a coherent O<sub>2</sub> jet at sonic velocity that penetrates further into the molten bath. Combination lance burners operate in a burner mode during the initial part of the melting period. When a liquid bath is formed, the burners change over to a mode in which they act as O<sub>2</sub> lances. Some O<sub>2</sub> lances have the capability to inject carbon as well. Oxygen injected above the molten bath to combust CO (post-combustion) is discussed in the following Section.



The theoretical energy contribution for an EAF operating natural gas burners is  $\sim 6.8$  kWh/tls/m<sup>3</sup> of gas, assuming a thermal efficiency of 70%. Thus typical electrical energy saving is of the order of 30–70 kWh/tcs (Cairns and others, 1998). The APPCDC (2010) quote typical savings of 20–40 kWh/tcs for natural gas injection at 0.3 m<sup>3</sup>/kWh. Electricity savings are 0.14 GJ/tcs, with typical savings ranging from 2.5–4.4 kWh/m<sup>3</sup> of O<sub>2</sub> injection, with common injection rates of 18 m<sup>3</sup>/t. This saving probably takes into account the electricity consumed in O<sub>2</sub> production. Retrofit capital costs are 4.80 US\$/tcs for a 110 t EAF. Opfermann and others (2009) calculated that as  $\sim 3.5$ –5 kWh of chemical energy can be created per m<sup>3</sup>/O<sub>2</sub> and  $\sim 0.5$ –1 kWh of electrical energy is needed for the production of 1 m<sup>3</sup> of O<sub>2</sub>, a benefit of  $\sim 2.5$ –4 kWh/m<sup>3</sup> is achieved. Actual electricity savings will depend on the oxyfuel burner/lance system that is installed and the system that is replaced.

CO<sub>2</sub> emission reductions of 23.5 kg/tcs with electricity savings of 38.9 kWh/tcs can be achieved with oxyfuel burners (*see* Table 19 on page 77). Installation of the ALARC-Jet™ injection system (supersonic O<sub>2</sub> injection) on Jayaswal Neco Industries' EAF at Raipur, India, has reduced total power consumption by 44.09 GWh/y, thereby lowering CO<sub>2</sub>-e emissions by 37,075 t/y (UNFCCC, 2010). The EAF charge material consists of 80–85% BF hot metal, 15% DRI and the rest is scrap. Carbon is injected beneath the ALARC-Jet™ injector. The project has resulted in complete elimination of the electrical energy required for arcing in the EAF.

## 8.8 In-furnace post-combustion

Oxygen injected above the steel bath promotes combustion of the CO inside the furnace rather than in the offgas handling system. The reaction produces energy ( $\sim 25.3$  MJ/m<sup>3</sup> O<sub>2</sub>) that is utilised to preheat the charge (*see* Section 8.4) or the steel in the EAF ladle, reducing energy consumption and increasing productivity (Cairns and others, 1998; EPA, 2010b; IEA, 2007; Worrell and others, 2010). Although the combustion of CO produces CO<sub>2</sub>, total CO<sub>2</sub> emissions decrease due to the lower indirect CO<sub>2</sub> emissions from the electricity saved. Typical electricity savings are  $\sim 10$ –20 kWh/tcs, with productivity increases of up to 4% (IEA, 2007), although higher productivity increases have been quoted in the literature.

However, it can be difficult to optimise and control the post-combustion process. The generated CO<sub>2</sub> can react endothermically with the scrap or DRI/HBI producing FeO and CO, decreasing the yield. Tests conducted on a 90 t EAF using  $\sim 2$  kWh/m<sup>3</sup> of post-combustion O<sub>2</sub> resulted in a lower yield but increased productivity through a shorter power-on time (Opfermann and others, 2009).

Real-time monitoring of the offgas composition can be used to optimise post-combustion (*see* Section 8.2). It has been demonstrated that if O<sub>2</sub> injected for post-combustion is continuously controlled by real-time data acquisition of CO and CO<sub>2</sub> concentrations in offgases, a 50% increase in the recovery rate of chemical energy in fumes can be achieved compared to operation based on predefined set-points (EPA, 2010b; Worrell and others, 2010). The average direct CO<sub>2</sub> emissions achieved for all EFSOP® offgas monitoring and control system installations with offgas chemical energy optimisation (including in-furnace post-combustion) is  $\sim 18\%$  or 10–20 kgCO<sub>2</sub>/tls. Furthermore, improved chemical energy utilisation also reduced electricity consumption by on average 14 kWh/tls. As such indirect CO<sub>2</sub> emissions would be lowered by an additional 3.1 kg/tls for regions such as Canada where the power generation mix is 25% fossil fuels, and by 8.4 kg/tls for the UK and USA where the fossil fuel mix is about 68%. This gives a total CO<sub>2</sub> emission reduction of  $\sim 23$ –30 kg/tls (Zuliani and others, 2010a,b).

## 8.9 Offgas sensible heat recovery

As indicated in Table 17 on page 73,  $\sim 15.5\%$  of the EAF energy input is lost as sensible heat in the offgas. When taken together with uncombusted CO which is subsequently burnt in the post-

combustion chamber in the offgas treatment system, the total thermal energy that could be used for heat recovery is well in excess of 25% of EAF energy input (Zuliani and others, 2010a,b). Although offgas heat recovery could lower CO<sub>2</sub> emissions, it is not practised to any great extent due, in part, to the harsh environment that exists in the fume system and to the batch nature of the EAF process. Economic heat capture from EAF offgas could save 83 kWh (0.3 GJ)/t steel (EPA, 2010b).

After the coarse dust is removed from the offgas exiting the EAF, it is post-combusted, if required, to neutralise volatile gases. It is then cooled from ~1300°C to ~600°C in a water cooling system. A second cooling step rapidly quenches the offgas to 200–250°C to minimise the reformation of harmful dioxins and furans (Jamak, 2009). The heated cooling water in the first cooling step is often not at a high enough temperature (typically 20–40°C) and pressure to be of any practical use. By replacing the conventional low pressure water-cooled ducting with high-pressure boiler tubes designed to withstand the harsh EAF fume system conditions at pressures of 1.5–4 MPa, high pressure steam can be produced for in-plant use, for power generation or sold.

One system, the Evaporative Cooling System (ECS), uses the heat of evaporation to produce high-pressure steam at 216°C with the offgas temperature reduced to ~600°C (Zuliani and others, 2010a,b). Continuous steam production with an average rate of 20 t/h from a 140 t/h EAF can be achieved with the installation of steam accumulator tanks, as achieved at Georgsmarienhütte's EAF in Germany (Schliephake and others, 2009). The associated boiler required to produce an equivalent amount of steam would consume almost 13,000 kW/h. Hence, by employing the EAF offgas heat recovery technology, boiler equivalent CO<sub>2</sub> emissions of almost 112,500 t/y with coal firing or 57,000 t/y with natural gas firing would be eliminated.

It is also possible to combine a second stage where the offgas temperature is reduced from ~600°C to ~200°C with a waste heat boiler instead of the standard offgas quenching system. The combined heat recovery with the ECS and the waste heat boiler is 75–80% of the total energy content in the waste gas, about 20% of primary energy input (Zuliani and others, 2010a,b).

In cases where there is insufficient demand for steam from the EAF heat recovery, an Organic Rankine Cycle (ORC) turbine, which does not require superheated steam, can be used for power generation. ORC generators are already used in related industrial heat recovery applications. They typically operate at ~20% efficiency and could be expected to generate ~4 MW of electrical power from an average-sized EAF. This translates to 24,000 MWh/y of electrical energy, a saving of 7.5% in net electrical energy usage in the EAF or 2.73 t of GHG a year per % fossil fuel in the power generation mix (Zuliani and others, 2010a,b).

## 8.10 Sensible heat recovery from slag

One of the areas remaining where CO<sub>2</sub> emissions and energy consumption could be decreased is by recovering the sensible heat of the molten slag, a technology that is not currently practised due to technical and economic reasons. Around 6% of the energy input to an EAF is lost in the slag (*see* Table 17 on page 73), a not insignificant amount. With some 46–191 kg slag/t steel generated (Cairns and others, 1998) and given an enthalpy of 2.303 MJ/kg (Kuehn, 2010), the amount of energy lost in the slag is some 0.11–0.44 GJ (30–122 kWh)/t steel. A survey of the energy balance of 65 EAFs by Kirschen and others (2009) found that the amount of energy carried out by the slags ranged from 32 to 105 kWh/t tapped weight. These figures look small but when the amount of slag produced every day is considered, then recovery of the sensible heat from the slag, which leaves the furnace at a temperature over 1400°C, is worth considering. Techniques for achieving this that could probably be applied are discussed in Section 4.5. Utilising the slag in road construction and civil works generates some additional CO<sub>2</sub> benefits.

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## 9 CO<sub>2</sub> capture

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Steel companies are under increasing pressure to cut their CO<sub>2</sub> emissions. The previous chapters discussed how this could be achieved by improving energy efficiency, reducing coke and coal consumption, utilisation of by-product fuels, increasing the use of biomass and renewable energy, and other techniques. But the scope for further reduction by these means is limited in state-of-the-art facilities. A state-of-the-art mill is a much optimised system in terms of consumption of fuels and reducing agents with a potential of energy savings of only ~10% (Birat, 2010b). Further significant CO<sub>2</sub> reduction will require the implementation of carbon capture and storage (CCS) or new technologies.

Although CO<sub>2</sub> capture is carried out at a commercial scale (at the Saldanha plant in South Africa, for instance, and some DRI facilities), the CO<sub>2</sub> is currently flared. Storing this CO<sub>2</sub> would lower emissions. There appears to be no major technical issues for underground storage of CO<sub>2</sub>. The CO<sub>2</sub> captured at the Great Plains Synfuels plant in North Dakota, USA, has for some years been transported by pipelines for enhanced oil recovery at the Weyburn oil field in Saskatchewan, Canada. But there are a number of issues still to be resolved before CCS is commercially deployed. These include monitoring and validation, economic, regulatory and legal issues, and public acceptance. Monitoring and measurement systems must be implemented to ensure that any escaping CO<sub>2</sub> is detected and the leaks plugged. The IEA projects a significant role for CCS in their Blue Map scenario, with around 30.24 MtCO<sub>2</sub>/y captured in 2020, rising to 822.6 MtCO<sub>2</sub>/y in 2050 (IEA, 2009b). The IEA Blue Map scenario, in which global energy-related CO<sub>2</sub> emissions are halved from current levels by 2050, assumes that policies are in place to provide strong incentives for CCS and other low-carbon technologies.

CO<sub>2</sub> emissions at steel plants arise from power production, as well as from iron and steel making. Capturing and storing the CO<sub>2</sub> from the power plant (one of the largest CO<sub>2</sub> sources, if present) would need to be implemented to lower overall CO<sub>2</sub> emissions from the site. The capture of CO<sub>2</sub> from power plants is outside the scope of the report having been reviewed in the IEA CCC reports by Davidson (2007, 2009) and Davidson and Santos (2010). Nevertheless, some CCS technologies applicable to power plants can potentially be applied to the iron and steel industry. This chapter will discuss capture technologies applied at iron and steel making facilities, before looking at the economics of CCS.

### 9.1 Carbon capture technologies

Carbon capture technologies produce CO<sub>2</sub> in a concentrated form for potential compression, transport and storage. The opportunities for CO<sub>2</sub> capture in steel production vary depending on the process and feedstock. The direct emission sources in integrated steel plants from which CO<sub>2</sub> could be removed are the stack gases (flue gas) from the lime kilns, sinter plants, coke ovens, hot stoves, BFs (if flared), and BOFs. The offgas from EAFs is the main source of CO<sub>2</sub> emissions in mini-mills. Table 20 provides typical characteristics and composition of these gaseous streams. The technologies that could potentially be employed to capture the CO<sub>2</sub> are those categorised under post-combustion capture for power plants.

Some 85% of the carbon (CO<sub>2</sub> plus CO) introduced into the iron and steel making process is present at one time in three gas flows, ~70% in the BFG, 9% in COG, and 7% in BOF gas (Farla and others, 1995). These process gases are typically used as low grade fuel within the steelworks. It seems advantageous to recover the carbon before their combustion because nitrogen in the combustion air lowers the carbon concentration in the flue gases. Moreover, the process gases are produced at a few sources only. Burning the gases releases CO<sub>2</sub> at a number of smaller point sources across the site from which the CO<sub>2</sub> is less easily captured. However, removing CO<sub>2</sub> changes the composition,

**Table 20 Characteristics of CO<sub>2</sub> sources in integrated and mini-mill steel mills** (Wiley and others, 2011)

	Integrated steel mill							Mini-mill
	Power plant stack	Lime kiln stack	Sinter plant stack	Coke oven stack	Hot stove stack	BOF stack	BFG	EDF offgas
CO <sub>2</sub> emitted, Mt/y	3.69	0.05	1.67	1.73	1.94	0.28	2.61	0.11
Flow rate, m <sup>3</sup> /s	400	16	337	132	14	194	240	6
Pressure, kPa	101.3	101.3	101.3	101.3	101.3	101.3	101.3	101.3
Temperature, °C	300	300	100	100	300	300	373	300
Composition, vol%								
N <sub>2</sub>	68	70	70	67	68	13	50	56
H <sub>2</sub> O	8	21	21	5	10	2	5	1
CO <sub>2</sub>	23	7	8	27	21	15	22	40
CO	–	–	1	–	–	70	20	–
O <sub>2</sub>	1	2	–	1	1	–	–	3
H <sub>2</sub>	–	–	–	–	–	–	5	–

characteristics and amount of the BFG, COG and BOF gas and this could affect their use and may require changes to the iron and steel making process. Removing CO<sub>2</sub> from BFG could be advantageous as this would upgrade its quality. This could allow it to be used directly in a gas turbine avoiding the necessity of mixing it with other gases with a higher energy content such as natural gas and COG. Capturing CO<sub>2</sub> from the stack gases would not require fundamental changes in the iron and steel making process.

Since BFG is the largest source of carbon, most of the effort to develop CCS for integrated steelworks is concentrating on the application of CCS to the BF. One technology being investigated is top gas recycling (TGR) after CO<sub>2</sub> removal (*see* Section 4.3.1). Birat (2010a,b) has called this ‘in-process’ capture. Operating the BF with a pure O<sub>2</sub> blast, instead of air, avoids the accumulation of nitrogen due to TGR, making CO<sub>2</sub> capture easier to accomplish. Injecting pure O<sub>2</sub>, a technology not yet proven, has been termed oxyfuel BF.

CO<sub>2</sub> capture is already widely applied in the production of DRI in order to enhance the fuel gas quality. Costs for CO<sub>2</sub> removal for this process are only the CO<sub>2</sub> compression and storage costs. The main sources of CO<sub>2</sub> emissions from the Midrex® shaft furnace process is from the natural gas reformer flue gas and the shaft furnace offgas. Midrex Technologies has introduced a version that captures the CO<sub>2</sub> from the shaft furnace offgas before it is mixed with the natural gas and sent to the reformer. The natural gas based Energiron process already captures the CO<sub>2</sub> from the shaft furnace offgas before it is recycled to the shaft furnace for internal reforming and reduction (*see* Section 5.2).

In both the Circofer® and Finmet® processes, CO<sub>2</sub> is removed as part of the process from the offgas exiting the fluidised bed reactors before it is recycled back to the reactors (*see* Section 5.5). CO<sub>2</sub> could also be captured from the offgas from rotary kilns and rotary hearths, at a cost.

In the smelting reduction processes, CO<sub>2</sub> could be removed from the smelting vessel offgas. The Saldanha Corex® plant in South Africa already captures the CO<sub>2</sub> from the Corex® offgas

(see Section 6.2) before it is sent to a separate Midrex® DRI shaft furnace. The Finex® plant in South Korea captures CO<sub>2</sub> from the fluidised bed reactors as part of the process before the gas is recycled to the fluidised bed reactors and melter-gasifier (see Section 6.3). The HIsarna process (see Section 6.4) plans to operate with 100% O<sub>2</sub> (oxyfuel), thus facilitating carbon capture from the smelter offgas.

The technologies for capturing CO<sub>2</sub> from the various gaseous streams can be divided into:

- chemical or physical absorption, or combined chemical and physical absorption (hybrid system);
- adsorption using solid adsorbents;
- physical separation via membranes or molecular sieves;
- phase separation by cryogenics and gas hydrates;
- chemical bonding via mineral carbonation.

Before examining these technologies, the shift process is discussed as including a shift reactor enables more of the carbon to be removed. It should be noted that the energy used for the recovery of CO<sub>2</sub> leads to new CO<sub>2</sub> emissions, both direct and indirect. These emissions need to be taken into account when calculating the amount of avoided or net captured CO<sub>2</sub>.

### 9.1.1 Shift process

Some gases, such as BFG, BOF gas and Corex® export gas, contain a significant amount of carbon monoxide. Including a shift reactor before the CO<sub>2</sub> capture unit would enable the removal of this carbon. In the shift reactor, CO is reacted with steam under pressure to produce CO<sub>2</sub> and H<sub>2</sub>. The process is accomplished in two reactors, a high temperature (~400°C) shift reactor followed by a low temperature (over 250°C) shift reactor. Steam is recovered from the offgas of the second reactor, and some of the residual heat is used to preheat the feedstock and steam for the first reactor (Farla and others, 1995; Gielen, 2003). Excess steam is produced that could be used elsewhere in the steelworks.

Including a shift reactor could increase carbon capture from less than 50% to 85–99.5% of the total carbon in BFG (Gielen, 2003; Kuramochi and others, 2011). The resultant H<sub>2</sub>-rich gas could enable a higher electrical efficiency when it is used for power generation, although this does require important modifications to the gas turbines (Lampert and others, 2010). Vlek (2007) investigated the use of BFG after CO<sub>2</sub> removal and with different degrees of shift, in a power plant in VelsenNoord/IJmuiden, Netherlands. Natural gas would be fired as well. Shifting all the BFG, and removing the CO<sub>2</sub>, was not investigated as it would affect the composition of the fuel gas in such a way that it could not be used in the existing installation anymore. The BF Plus technology, developed by Danieli Corus and Air Products, includes an optional shift reactor and CO<sub>2</sub> removal unit to capture the CO<sub>2</sub> from the BFG before it is used for combined cycle power generation (Air Products, 2011).

Whether the increase in CO<sub>2</sub> captured is worth the additional investment (and operational costs) would need to be assessed. Ho and others (2011) found that converting the CO to CO<sub>2</sub> does not reduce the overall capture cost for conventional (air-blown) BFG when the gas is used for power generation. Although there is a reduction in energy consumption (from over 1500 to 1080 kJ/kgCO<sub>2</sub> captured), the economic benefit of shifting CO is offset by the additional capital costs for the shift reactor, feed gas compressor and H<sub>2</sub> turbine. For Corex® export gas, however, converting the CO to CO<sub>2</sub> is economically advantageous because of its higher CO content. Although the capital costs increase, the energy penalty falls by almost a third (from over 1400 to 550 kJ/kgCO<sub>2</sub> captured), which significantly reduces the operating costs per tonne of CO<sub>2</sub> captured. Water gas shift processes are under development with lower energy consumption, such as the water gas shift membrane reactor, which converts CO to CO<sub>2</sub> and separates the H<sub>2</sub> from CO<sub>2</sub> in a single reactor. This increases the heating value of the fuel gas (H<sub>2</sub>), which could be used for power generation with the same efficiency as natural gas (Gielen, 2003).

Table 21 Commercial CO <sub>2</sub> solvents used in industry (IEA, 2008b)			
	Solvent name	Solvent type	Process conditions
Physical solvents	Rectisol®	methanol	-10/-70°C, >2 MPa
	Purisol®	n-2-methyl-2-pyrrolidone	-20/+40°C, >2 MPa
	Selexol™	dimethyl ethers of polyethyleneglycol	-40°C, 2–3 MPa
	Fluor solvent™	propylene carbonate	below ambient temperatures, 3.1–6.9 MPa
Chemical solvents	MEA	2,5n monoethanolamine and inhibitors	40°C, ambient to intermediate pressures
	amine guard	5n monoethanolamine and inhibitors	40°C, ambient to intermediate pressures
	Econamine <sup>SM</sup>	6n diglycolamine	80–120°C, 6.3 MPa
	ADIP®	2-4n diisopropanolamine (DIPA) 2n methyldiethanolamine (MDEA)	35–40°C, >0.1 MPa
	MDEA	2n methyldiethanolamine	
	Flexsorb®, KS-1, KS-2, KS-3	hindered amine	
	Benfield™ and versions	potassium carbonate and catalysts. Lurgi & Catacarb processes with arsenic trioxide	70–120°C, 2.2–7 MPa
Physical/chemical solvents	Sulfinol®-D, Sulfinol®-M	mixture of DIPA or MDEA, water and tetrahydrothiophene (DIPAM) or diethylamine	>0.5 MPa
	Amisol®	mixture of methanol and MEA, DEA, diisopropylamine (DIPAM) or diethylamine	5/40°C, >1 MPa

## 9.1.2 Absorption processes

Separation of CO<sub>2</sub> from gas streams can be achieved by chemical or physical absorption or by a combination of the two (hybrid method). CO<sub>2</sub> is removed by the chemical or physical solvent in one reactor (absorption column), and the solvent is regenerated in a second reactor (stripping column).

The CO<sub>2</sub> is stripped from the chemical solvents by applying heat (steam) and from physical solvents by heating, pressure reduction, or a combination of both. The CO<sub>2</sub> is then cleaned and dried, if necessary, before it is compressed for transport and storage.

Absorption processes are widely used in the chemical, refinery and gas processing industry and could potentially be applied in the iron and steel industry. Table 21 lists the principal solvents used by industry.

### Chemical absorption

Chemical solvents are most suitable for deep removal of CO<sub>2</sub> from gas streams with low CO<sub>2</sub> concentrations and a low partial pressure of 0.5 MPa or lower (Gielen, 2003). Thus chemical absorption is being investigated for BFG, BOF gas, natural gas DRI process gases, fluidised bed DRI production gases, smelting offgases and others.

The most common chemical solvents used for CO<sub>2</sub> capture are amines and the most widely used is monoethanolamine (MEA). One of the earliest trials carried out at BF2 at RPA Toulachermet, Russia, utilised MEA to remove CO<sub>2</sub> from the BFG before it was recycled to the O<sub>2</sub>-blown BF (TGR-BF) (Tseitlin and others, 1994). Amine solvents have a high capture efficiency and selectivity. However, disadvantages include equipment corrosion, solvent degradation, low CO<sub>2</sub> loading capacity, high thermal energy consumption during solvent regeneration, large footprint, and removal and disposal of solvent degradation products (Davidson, 2007). Corrosion and solvent degradation is due to O<sub>2</sub> and SO<sub>x</sub> in the offgas and has occurred in the context of power plant flue gas. Offgases in the iron making processes generally have lower O<sub>2</sub> and SO<sub>x</sub> contents than power plant flue gas, and so corrosion may be less of a problem. If the SO<sub>x</sub> level is a problem, it can be easily removed before the gas enters the CO<sub>2</sub> capture unit.

New amine solvents and blends are being developed to mitigate some of the disadvantages, and to reduce the cost of absorbent regeneration that presently forms around half of the CO<sub>2</sub> capture costs. Blending existing solvents can exploit the desirable characteristics of the different solvents.

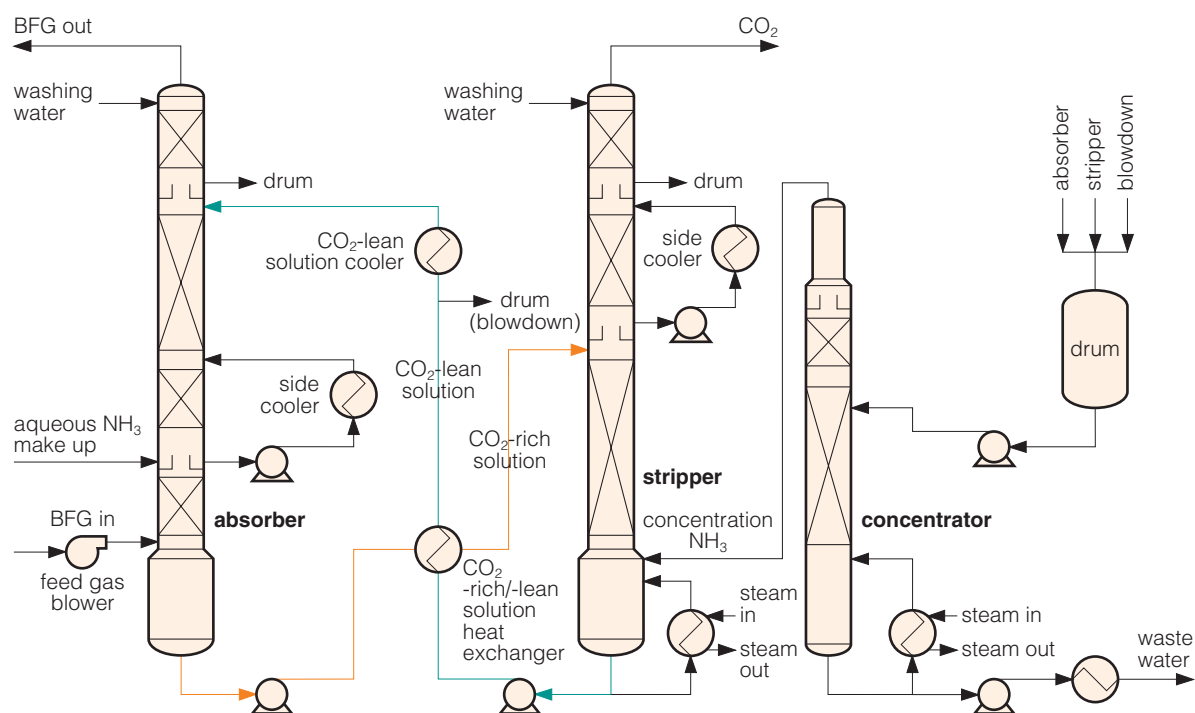
The performance of various amines for capturing CO<sub>2</sub> from BFG before it is recycled to the BF was modelled by Tobiesen and others (2007). They found that 2-amino-2-methyl-1-propanol (AMP, a sterically hindered primary amine) was more energy efficient (based on steam consumption) than the methyldiethanolamine (MDEA, a tertiary amine)/piperazine mixture, which in turn was more energy efficient than MEA. Including an intercooler between two absorber columns decreased the heat requirement to 2.2, 2.4 and 2.5 MJ/tCO<sub>2</sub> captured for AMP, MDEA/piperazine and MEA, respectively.

Cheng and others (2010) investigated the use of aqueous solutions of MEA, 2-(2-aminoethylamino)ethanol (AEEA) and piperazine solvents, and their mixtures, for removing CO<sub>2</sub> from the hot stove flue gas containing 30 vol% CO<sub>2</sub>. A rotating packed bed absorber was used since it would take up less space when retrofitting in a steelworks. The mixtures containing piperazine were more effective than MEA and AEEA alone. However, a piperazine concentration higher than 15 wt% is not possible due to its limited solubility in water at room temperature.

Chemical absorption processes are expensive. The cost of thermal energy accounts for a large percentage of the cost due to the large amount of energy required to break the strong bonds created between the solvent and CO<sub>2</sub>. Japan is developing amine-based solvents that can regenerate under lower temperatures and use less energy than present absorbents, as well as effectively utilising waste heat to regenerate the absorbent. Under the COCS (Cost Saving CO<sub>2</sub> Capture System) project sterically hindered amines and hydroxyl amines were developed for capturing CO<sub>2</sub> from BFG. The best performance achieved an energy consumption of 2.5 GJ/tCO<sub>2</sub> compared to 4 GJ/tCO<sub>2</sub> for MEA. Applying the new absorbents could reduce CO<sub>2</sub> capture costs by 40% (Goto and others, 2009; RITE Today, 2011). Further research to develop absorbents that will reduce the energy consumption to a target 1.8 GJ/tCO<sub>2</sub> is being carried out under the CO<sub>2</sub> Ultimate Reduction in Steel making Process by Innovative Technology for Cool Earth 50 (COURSE50) project. A membrane flash process for regenerating the solvent using waste heat is also being developed to save energy (*see* Section 9.1.4).

Inorganic alternatives to amines are commercially available, such as sodium and potassium carbonates. These solutions do not degrade, have a low corrosion rate, and a lower heat of reaction with CO<sub>2</sub> and cost less than MEA (Davidson, 2007). Sodium and potassium carbonate solutions, though, have a number of disadvantages including low reaction rates with CO<sub>2</sub>, higher energy consumption for regeneration compared to alkanolamines, and limited solution concentrations due to the precipitation of bicarbonate salts (Zhu, 2011). Yoon and others (2011) have developed a potassium carbonate/hindered cyclic diamine solvent that could be used in the steel industry for gases containing 15–20% CO<sub>2</sub>.

The use of aqueous ammonia for capturing CO<sub>2</sub> from BFG is being investigated in Korea. The major advantages of ammonia over MEA are the higher removal efficiency, higher CO<sub>2</sub> loading capacity



**Figure 22 Process schematic of CO<sub>2</sub> capture using aqueous ammonia** (Rhee and others, 2011)

(three times that of MEA), lower cost, and lower regeneration energy (Rhee and others, 2011). By-products of the process include ammonium bicarbonate, nitrate and sulphate which could be used as fertilisers. The main drawbacks are the loss of ammonia due to its volatility and the formation of precipitates. Ammonia has been used to remove H<sub>2</sub>S and other sulphur compounds from COG for a long time (Kim and others, 2009), and so steelworks have experience in using ammonia.

Posco has built a pilot plant at its Pohang steelworks processing 50 m<sup>3</sup>/h of BFG. The regeneration energy is supplied by recovering low temperature waste heat from the power plant stacks (Kim and others, 2009). To reduce ammonia loss, washing water is supplied to the upper part of the absorber and stripper columns to remove ammonia in the outlet gases. Ammonia is then recovered in a concentrator column and recycled to the lower part of the stripper (*see* Figure 22). A CO<sub>2</sub> removal efficiency of over 90% was achieved with a 9 wt% ammonia solution and a regeneration temperature of ~78°C. The loading capacity was ~0.043 kgCO<sub>2</sub>/kg ammonia, and the steam consumption rate was 35–40 and 35–38 kg/h for the stripper and concentrator, respectively (Rhee and others, 2011).

The IEA does not consider chemical absorption suitable for CO<sub>2</sub> capture in the iron and steel industry as insufficient waste heat is available. Only about half of the necessary heat could be recovered from coke ovens, sinter plants, BF slag, and BOF slag and slabs. A separate combined heat and power (CHP) unit would be required to provide additional heat. Integrated oxyfueling is therefore preferred (IEA, 2008b). As part of COURSE50, Japan is investigating ways of capturing unused low to medium temperature waste heat, such as the use of heat pumps and phase change materials (Wooders and Beaton, 2011).

### Physical absorption

Absorption in most current physical solvent systems occurs at high CO<sub>2</sub> partial pressures and low temperatures. The solvents combine less strongly with CO<sub>2</sub> than chemical solvents and therefore require less energy for separation and regeneration. Capacity can be higher since the physical solvents are not limited by the stoichiometry of the chemical system. Physical absorption is usually the preferred method at CO<sub>2</sub> concentrations higher than 15% (IEA, 2008b). The commercially available physical solvents used by industry are given in Table 21 on page 86.



Since physical absorption can operate at high CO<sub>2</sub> partial pressure, it can be used to separate CO<sub>2</sub> from the process gas after a water gas shift reactor (*see* Section 9.1.1). Gielen (2003) suggests that 85–99.5% of the carbon in BFG could be captured by combining Selexol™ with a shift reactor operating at ~2 MPa. Another benefit of including a shift reactor is that SO<sub>2</sub> is converted to H<sub>2</sub>S, which is removed as part of the Selexol™ or Rectisol® (with an intermediate shift reactor) processes. Van Horssen and others (2009) expect the sulphur content of BFG to be more than 90% lower than without CO<sub>2</sub> capture (with Selexol™) at the steelworks in IJmuiden, Netherlands.

The high partial pressure of CO<sub>2</sub> in BFG and Corex® export gas makes the capture of CO<sub>2</sub> with physical solvents more cost effective when the purified gas is utilised in gas turbines which require high pressure fuels (Lampert and Ziebig, 2007; Lampert and others, 2010; Vlek, 2007). This is instead of using the purified gas as a fuel for hot stoves, coke ovens and elsewhere. In their analysis Lampert and others (2010) set the pressure in the Selexol™ absorption chamber at 1.8 MPa, allowing the direct utilisation of the purified gas in the combustion chamber of a modern gas turbine. The overall power consumption for raw compression and the absorption installation amounts to 26.3 MW and 46 MW for the Corex® and BF gases, respectively, when ~90% of the CO<sub>2</sub> is removed. The lower power consumption for Corex® gas is due to its higher CO<sub>2</sub> content (35 mol% compared to 16 mol% for BFG) and hence higher CO<sub>2</sub> partial pressure. If the power consumption connected to the raw gas compression is omitted, since no further compression is required for its use in a CHP plant, the power consumption of the absorption process itself is 8.1 MW and 10.7 MW for Corex® and BF gases, respectively. The specific power consumption for Corex® and BF gases was estimated to be 335 and 505 kJ/kgCO<sub>2</sub> removed, respectively. Instead of utilising the purified Corex® gas for power generation, the gas can be injected into a BF (*see* Section 6.2).

The energy penalty for CO<sub>2</sub> removal from shifted BF and Corex® gases via Selexol™ is 1080 and 550 kg/kg of captured CO<sub>2</sub> (Ho and others, 2011). These values include compression of the captured CO<sub>2</sub> to 10 MPa, ready for transport to a storage site. The energy penalty is not offset by utilising the purified gases for power generation.

A Rectisol® unit is included in the Mycol™ plant being built in India (*see* Section 5.2). Cheng and others (2010) investigated the use of methanol (Rectisol® process) to capture CO<sub>2</sub> from hot stove flue gas in a rotating packed bed absorber. The capture efficiency at 10°C and 0.31 MPa (the maximum pressure allowed due to pressure limitations in the rotating absorber) was ~15%. This is lower than chemical absorption using piperazine mixtures, possibly due to the lower absorption rate of CO<sub>2</sub> in methanol.

### 9.1.3 Adsorption processes

Adsorption involves passing the CO<sub>2</sub> containing gas through a bed of solid sorbent (such as zeolites or activated carbon) which adsorb the CO<sub>2</sub>. Once the bed is fully loaded, the gas is sent to a second adsorbent bed. The fully loaded bed is regenerated by reducing the pressure (pressure swing adsorption, PSA or vacuum pressure swing adsorption, VPSA), increasing the temperature (temperature swing adsorption, TSA) or applying a low voltage electric current (electric swing adsorption, ESA). Only PSA and VPSA will be discussed since they are used commercially in the iron and steel industry, and other industrial facilities.

PSA and VPSA processes typically operate at near ambient temperature. The higher the pressure during adsorption, more CO<sub>2</sub> is adsorbed. The bed is desorbed by reducing the pressure to above one atmosphere (0.1 MPa) (PSA) or below atmospheric pressure (VPSA). Using two adsorbent vessels allows near continuous operation and also enables the gas leaving the vessel that is being depressurised to be used to partially pressurise the second vessel. This results in significant energy savings. The electrical energy needs for a PSA unit (Finex® plant) is 0.71 GJ (197 kWh)/thm, excluding the electricity needed to pressurise the CO<sub>2</sub> to 10 MPa ready for transport (IEA, 2009a).

Since PSA and VPSA require process gas compression, their performance seems to depend on how the net electricity consumption for gas compression can be minimised (Kuramochi, 2011). Large amounts of adsorbent are required because the capacity and CO<sub>2</sub> selectivity of the adsorbents are low, and contaminants, such as SO<sub>2</sub> and H<sub>2</sub>O, can adversely affect the process. Therefore PSA and VPSA are typically used to treat higher CO<sub>2</sub> containing gas streams. New adsorbents with higher gas adsorption capacities and lower costs are being developed. Since PSA and VPSA operate under pressure, they could be used to separate CO<sub>2</sub> from the process gas after a water gas shift reactor (*see* Section 9.1.1).

The PSA unit at Posco's Finex® plant in South Korea removes CO<sub>2</sub> from the fluidised bed reactors offgas to produce a 3% CO<sub>2</sub> containing gas for recycling back to the reactors. The tail gas from the PSA unit contains 66% CO<sub>2</sub> and 17% CO (Lee, 2008). VPSA is in commercial use at the Saldanha steel plant in South Africa (*see* Section 6.2).

The large-scale tests of TGR-BF carried out in the experimental BF in Luleå, Sweden, removed CO<sub>2</sub> via a VPSA unit (*see* Section 4.3.1). This technology was chosen because it was the simplest and cheapest solution to produce a recycling stream of gas where the concentration of the reducing components, mainly CO, would be maximised (Birat, 2010b). The VPSA processed up to 97% of the BF top gas, and lowered the CO<sub>2</sub> content to below 3%; CO recovery was 88%. CO<sub>2</sub> emissions were reduced by 76% compared to the reference period, resulting from a 24% reduction at the BF by gas recycling plus a 52% reduction at the VPSA, provided the captured CO<sub>2</sub> is stored (Danloy and others, 2009). In the planned larger-scale trials, the CO<sub>2</sub> will be stored in a deep saline aquifer and thus a higher level of CO<sub>2</sub> purity is required. The PSA unit will therefore be combined with a cryogenics unit (*see* Section 9.1.5). The cryogenics unit will generate an extra stream of reducing gas which will be recycled to the BF (Birat, 2010b).

Utilising VPSA and cryogenics to separate CO<sub>2</sub> from the gas stream exiting the shift reactor in the coal-based ULCORED direct reduction process (*see* Section 5.2) will consume more power than a high performance amine scrubber (260 compared to 160 kWh/tCO<sub>2</sub> captured). In both cases the CO<sub>2</sub> is compressed to 11 MPa. The choice of technology will depend on local requirements as each technology has its pros and cons (Bergman and Larsson, 2008).

#### 9.1.4 Membranes

Gas separation membranes (such as polymers, ceramics, metals and zeolites) rely on differences in physical and chemical interactions between gases and a membrane material, allowing one component to pass through the membrane faster than another. Membrane processes can achieve over 80% CO<sub>2</sub> separation efficiency. The main advantages of membrane processes are that no regeneration energy is required, no waste streams are generated, and the separation units are small and simple to operate. But membranes are sensitive to sulphur compounds and other trace elements, and particulates must be removed from the gas feed. Membranes usually cannot achieve a high degree of separation and consequently, multiple stages and/or recycle of one of the streams is necessary. This leads to increased complexity, energy consumption and costs (CSLF, 2010). New membrane materials are being developed to mitigate these handicaps. Gas absorption membranes are hybrid systems that combine a membrane with the selective absorption of a solvent, such as amines, improving on both.

Development of a membrane capable of separating oxygen and nitrogen in air could play an important indirect role in CO<sub>2</sub> capture (CSLF, 2010). Lower cost oxygen is important for O<sub>2</sub>-blown BFs and coal gasification processes producing syngas for DRI processes.

Membranes are used commercially for CO<sub>2</sub> removal from natural gas at high pressure and high CO<sub>2</sub> concentrations, and therefore could be applied to BFG and other high concentration CO<sub>2</sub> streams in steelworks. Lie and others (2007) compared the performance of three types of membranes for

**Table 22 Summary of the performance of the four simulation cases** (Lie and others, 2007)

	Case 1*	Case 1†	Case 2*	Case 2†
CO <sub>2</sub> in feed, t/h	420	420	299	299
CO <sub>2</sub> recovery, %	97	97	79	83
Feed temperature, pressure stage 1, °C; MPa	30; 0.48	30; 0.48	30; 0.45	30; 0.48
Feed temperature, pressure stage 2, °C; MPa	–	22; 0.26	–	22; 0.26
Membrane area, m <sup>2</sup>	1.3 x 10 <sup>6</sup>	3 x 10 <sup>6</sup>	4.9 x 10 <sup>5</sup>	1.2 x 10 <sup>6</sup>
Plant compression duty*, MWe	93	103	62	73
Membrane section compression duty†, MWe	48	59	37	48
Expander energy‡, MWe	3.6	3.4	14.3	14.3
Total compression duty§, GJe/tCO <sub>2</sub> recovered	0.8	0.9	0.5	0.6
Membrane section duty, GJe/tCO <sub>2</sub> recovered	0.4	0.5	0.24	0.33
* includes compression to 11 MPa for pipeline transport				
† taken as the compressor duties from where feed enters battery limits up to and including compression of CO <sub>2</sub> product to 0.15 MPa				
‡ adiabatic efficiency of 75% used				
§ energy recovered in expander taken into account				

capturing CO<sub>2</sub> from BFG. Bench-scale tests with single gases found that the fixed site carrier membrane (a polymeric membrane with amine groups) showed superior selectivity for CO<sub>2</sub> over CO, N<sub>2</sub> and H<sub>2</sub> and had a higher CO<sub>2</sub> permeance (productivity) than the adsorption selective carbon and carbon molecular sieving membranes. In addition, H<sub>2</sub> is retained on the high pressure side (as opposed to the carbon membranes), requiring no extra H<sub>2</sub> separation unit. Water in the feed gas is an advantage instead of a problem since the polymer membrane must be humidified during operation. Table 22 gives the results of a simulation study for recovering CO<sub>2</sub> from BFG produced in a nitrogen-free (O<sub>2</sub>-blown) BF (case 1) or conventional BF (case 2) with the fixed site carrier membrane. Cases 1a and 2a are based on ideal selectivities from the single gas permeation experiments and use one membrane unit. Cases 1b and 2b use half of the single gas selectivities obtained by doubling the single gas permeances for all components except CO<sub>2</sub>, and utilise two membrane units. 97% CO<sub>2</sub> recovery was achieved for the O<sub>2</sub>-blown BFs. Electricity consumption ranged from 0.24 GJ/tCO<sub>2</sub> captured for just the membrane section, increasing to 0.5 to 0.9 GJ/tCO<sub>2</sub> captured when the CO<sub>2</sub> was compressed to 11 MPa for pipeline transport. Estimated costs range from 15 €/tCO<sub>2</sub> for case 2a to 17.5 €/tCO<sub>2</sub> for case 1b (€ year 2005).

A membrane flash process utilising waste heat is being developed in Japan. After passing the BFG through a DEA absorber column (*see* Section 9.1.2), the CO<sub>2</sub>-rich solution is heated to 70°C utilising waste heat before passing through the middle of an aluminium oxide tube membrane to recover the CO<sub>2</sub>. The sensible heat of the BF slag is thought to be a possible waste heat source. The electric energy consumption for the process is ~0.39 kWh/kgCO<sub>2</sub> recovered for a 2 mol/L DEA solution, decreasing to ~0.2 kWh/kgCO<sub>2</sub> for a 5 mol/L DEA solution for a 22 vol% CO<sub>2</sub> containing BFG with a CO<sub>2</sub> recovery rate of 80% (Okabe and others, 2009).

### 9.1.5 Cryogenics

CO<sub>2</sub> can be separated from other gases by cooling and condensation. While cryogenic separation is

used commercially for gas streams with a high CO<sub>2</sub> concentration (typically >90%), it is not used for more dilute CO<sub>2</sub> streams because of the high energy requirements (CSLF, 2010). A cryogenic CO<sub>2</sub> separation plant for treating Corex® export gas (35% CO<sub>2</sub>) was calculated to consume ~32 MW, a much higher power requirement than a Selexol™ unit (~8.1 MW). However, the purified gas, with a low temperature, can be easily compressed to the pressure required for the combustion chamber of a gas turbine (Lampert and others, 2010). Some components, such as water, have to be removed before the gas stream is cooled to avoid blockages in the cryogenic flow lines (CSLF, 2010). Cryogenic separation, though, does have the advantage that it produces liquid CO<sub>2</sub> ready for ship or pipeline transport to the storage site. It also has a low temperature and could be used as a cooling agent (Lampert and others, 2010).

The most promising applications for cryogenic separation are expected to be for the separation of CO<sub>2</sub> from high pressure gases or from offgas from O<sub>2</sub>-blown BF's. In the planned demonstration of the TGR-BF (O<sub>2</sub>-blown) under the ULCOS programme, the CO<sub>2</sub> captured by the PSA unit will be further purified by cryogenics to produce liquid CO<sub>2</sub> ready for underground storage. The cryogenic unit also generates an extra reducing gas stream for recycling to the BF. A cryogenics unit could be used on its own in the HIsarna process (*see* Section 6.4), since it generates a high CO<sub>2</sub> gas stream (Birat, 2010b). The oxygen for the BF or HIsarna reactor could be supplied by cryogenic separation of air, a technology already applied commercially in other industries.

### 9.1.6 Gas hydrates

Hydrate-based CO<sub>2</sub> separation is in the research and development phase. In this technology CO<sub>2</sub> molecules are trapped in the cages, or clathrate hydrates, formed by water molecules under high pressure and low temperatures. The CO<sub>2</sub> is recovered from the hydrates either by heating or depressurisation in a second reactor, and the separated water is recycled back to the hydrate crystallisation reactor. Processes being developed for the power generation industry (for flue gas and syngas) use one or more hydrate crystallisation reactors. Compressing the gaseous stream to the required hydrate formation pressure is expensive. Therefore compounds, such as tetrahydrofuran, are added to lower the hydrate equilibrium pressure. Impurities in the gaseous stream may adversely affect the process, and agglomeration of hydrate crystals can create barriers to efficient gas/water contacts.

Duc and others (2007) investigated a continuous hydrate process for capturing CO<sub>2</sub> from BF gases utilising tetra-n-butyl ammonium bromide (C<sub>16</sub>H<sub>36</sub>NBr, TBAB) as the hydrate promoter. Six stages of crystallisation are required to meet the CO<sub>2</sub> specification (<4 vol% CO<sub>2</sub>, 0°C, 11 MPa) for pipeline transport and storage. Pressures in the six stages varied from 0.75 to 5 MPa, and the temperature in each crystalliser is kept at 10°C. The electric power consumption for the four kinds of BF investigated varied from 362 to 1302 kWh/tCO<sub>2</sub> captured, at a cost of 14.5 to 29.6 €/tCO<sub>2</sub> captured (*see* Table 23). The total cost of CO<sub>2</sub> capture increases to 21.2 to 40.8 €/tCO<sub>2</sub> captured when investment and production costs are included. The compressors formed 50–80% of the costs, and so costs could be

**Table 23 Power consumption and cost of hydrate CO<sub>2</sub> capture** (Duc and others, 2007)

	N <sub>2</sub> -free BF with shaft injection (TGR-BF)	Conventional BF top gas	N <sub>2</sub> -free BF plasma	Conventional BF flue gas
CO <sub>2</sub> concentration of inlet gas, %	36	23	35	24
Electric power consumption, kWh (GJ)/tCO <sub>2</sub> captured	420 (1.51)	1302 (4.69)	362 (1.3)	730 (2.63)
Cost, €/tCO <sub>2</sub> captured	16.8	22.4	14.5	29.6

reduced by finding another additive that allows hydrates to be formed at a lower pressure. The cost also decreases when the gaseous stream contains a higher CO<sub>2</sub> concentration. The exception was the gas from the conventional BF because the inlet gas had a lower pressure (0.1 MPa) and a higher temperature (200°C) than the others.

### 9.1.7 Mineral carbonation

Slags generated during the iron and steel making processes have a high alkaline earth metal oxide content (in the form of silicates, free lime and other minerals) and could potentially be utilised to capture and permanently store CO<sub>2</sub> via mineral carbonation. Calcium oxide and magnesium oxide in the slags react with CO<sub>2</sub> to form stable calcium carbonate (calcite).

Carbonation processes under development can be classified (Bacocchi and others, 2010) as:

- direct, where the reactions with CO<sub>2</sub> occur either in the aqueous phase (such as the two-stage slurry reactor developed at the Missouri University of Science and Technology in the USA (Richards and others, 2008) or at the gas-solid interface;
- indirect, in which the alkaline metal is first extracted from the slag matrix and is then precipitated as carbonate. Extraction agents investigated include acetic acid (Eloneva and others, 2008; Teir and others, 2007), nitric acid (Doucet, 2010), hydrochloric acid (Kunzler and others, 2011), hydroxides and ammonium salts (Fogelholm and others, 2009).

In both routes, the slag is first ground. This activates the surface of the mineral to increase its effective carbonation rate and yield, and also improves the recovery of iron currently lost to the slag. CO<sub>2</sub> uptake is influenced by the slag composition, which is highly variable, and operational parameters, such as pressure, temperature and particle size distribution (Uibu and others, 2011). A carbonation reactor could be retrofitted in a steel mill and will most likely be installed after a gas cleaning system to prevent contamination with dust (Rawlins and others, 2006).

The energy requirements of the processes and/or solvent regeneration costs can be high (Doucet, 2010). In addition, carbonation processes generate their own CO<sub>2</sub> emissions. Producing marketable carbonate products that are suitable for polymer fillers, agricultural and construction applications could lower the costs. Precipitation of high quality calcium carbonate would enable its sale to the paper industry (Fogelholm and others, 2009). Leaching of potentially harmful constituents from steel slag is reduced after its carbonation (Comans and others, 2010), allowing its use in civil engineering applications. Utilising carbonated slag blocks in the ocean promotes the growth of algae which will further absorb CO<sub>2</sub> through photosynthesis (Baoshan Iron and Steel, 2008).

Theoretically CO<sub>2</sub> storage capacity is ~0.25 kgCO<sub>2</sub>/kg of slag on the basis of the total calcium content (Huijgen and others, 2005). Although CO<sub>2</sub> storage in steel making slags is unlikely to have a substantial impact on global CO<sub>2</sub> emissions, estimates suggest that 6–11% of the CO<sub>2</sub> emissions from integrated steelworks and 35–45% from scrap-based steelmakers could potentially be stored in the slags generated from the BOF, EAF and ladle metallurgy furnace (Rawlins and others, 2006; Richards and others, 2008). By carbonating Finnish steel making slags, 0.6 Mt/y of CO<sub>2</sub> could be stored (Fogelholm and others, 2009). If 1 t BOF slag absorbs 200 kgCO<sub>2</sub>, then Baosteel in China could lower its CO<sub>2</sub> emissions by 0.22 Mt/y (Zuo, 2008). Mineral carbonation therefore has the potential to reduce CO<sub>2</sub> emissions at individual steel plants, assuming that economically-viable industrial carbonation processes can be developed.

Instead of utilising slag, it has been proposed that the mineral tailings that are left after processing serpentine ore could be used. The serpentine contains iron oxide that is easily separated by grinding and magnetic separation. The iron ore pellets produced are sent to the steel mill. Nearly 20% of the iron oxide required in a 4536 t/d (5000 ton/d) steel plant could be supplied by the serpentine ore, the tailings of which could store 100% of the steel plant CO<sub>2</sub> emissions. The carbonated mineral waste

could be disposed of in the serpentine mine. Carbon costs could be offset by selling carbon credits. However, more research is required to accelerate the reaction time of the silicate minerals with CO<sub>2</sub> in aqueous solutions (Lackner and others, 2008).

## 9.2 CCS costs

One of the key challenges in capturing CO<sub>2</sub> from steelworks is the complexity of the plant infrastructure. CO<sub>2</sub> emissions are dispersed over a large area from many point sources. Two options are available for capturing the CO<sub>2</sub>. Firstly, the flue gases could be treated individually at each point source before being combined for transport. Alternatively, CO<sub>2</sub> could be processed in a centralised location, and thus potentially yield economies of scale. The challenges of point source treatment are the availability of adequate space for each capture facility and the ability to supply energy to each facility. The challenge for a centralised facility is that it may be difficult and costly to install long and large ducts that collect the flue gas at each point source and transport it to the centralised facility. Ho and others (2011) suggest an intermediate option for a chemical absorption system whereby solvent absorption units are installed at each point source with one centralised solvent regeneration unit. Chemical handling and safety pose one challenge for this option. This could also be applied to other technologies which include separate ‘capture’ and ‘regeneration’ units. It seems likely that CCS will first be installed at a large point source, such as the BF and hot stoves, and the technology proved, before the smaller point sources are tackled. Applying CCS to all stacks in an integrated steel plant is possible in theory and would lead to near zero CO<sub>2</sub> emissions. For mini-mills, CCS would first be applied to the EAF.

The CO<sub>2</sub> capture technologies discussed in the previous sections each have their optimal field of application, and their own advantages and disadvantages. Chemical absorption, for example, suits low concentration CO<sub>2</sub> streams, whereas physical absorption, PSA, VPSA, membranes and cryogenics are more suited to higher CO<sub>2</sub> containing streams. Table 24 compares the mature CO<sub>2</sub> capture technologies for the steel industry. The composition of the input gas (in this case a TGR-BF) is 45 vol% CO, 37 vol% CO<sub>2</sub>, 10 vol% N<sub>2</sub>, and 8 vol% H<sub>2</sub>, all on a dry basis. Although PSA and VPSA have the lowest energy consumption, the captured CO<sub>2</sub>-rich gas is not of a high enough purity for storage. Adding a cryogenics unit is required. The total energy consumption of this setup is still lower than an amine system. For a TGR-BF, the PSA and VPSA, with cryogenics, schemes are best in terms of technical performance and cost, both operating and capital (Birat, 2010b). However, a chemical absorption (amine) solution has been selected for BFG under the COURSE50 programme in Japan. Research and development is expected to lower the energy requirements of the process and to develop ways of utilising the wasted heat.

A drawback for some CO<sub>2</sub> capture technologies is the high energy consumption, and, where used, steam consumption. If the CO<sub>2</sub> capture technology that is retrofitted requires steam and there is no extra steam generation capacity available, then a new steam generator would need to be built, at a cost. The steam and energy consumption of various CO<sub>2</sub> capture technologies compiled by Kuramochi (2011) from the literature are summarised in Table 25.

The cost of CCS is a complex issue, mainly because there is little experience in its actual operation. Assumptions on system boundaries, fuel price, capital cost estimation, interest rate, and economic lifetime, among other factors, have a large impact on the economics. Moreover, the economics of CCS are influenced by the location of the steel plant as parameters such as energy and material prices, grid electricity CO<sub>2</sub> emission factor and interest rates differ significantly from country to country. Despite this, many papers have published estimates of CCS (Duc and others, 2007; Farla and others, 1995; Gielen, 2003; Ho and others, 2011; Kuramochi, 2011; Kuramochi and others, 2011; Lampert and Ziebik, 2007; Lampert and others, 2010; Lie and others, 2007; Tobiesen and others, 2007; Torp, 2005; Vlek, 2007; Wiley and others, 2011). The CO<sub>2</sub> costs of 63 iron and steel making routes under different scenarios have been assessed under the ULCOS programme (Birat and Lorrain, 2008). The economics

**Table 24 Comparison of mature CO<sub>2</sub> capture technologies for the steel industry (Birat, 2010b)**

	PSA	VPSA	VPSA + compression and cryogenic flash	Amines + compression	PSA + cryogenic distillation + compression
Recycled gas (process gas)					
CO yield, %	88	90.4	97.3	99.9	100
CO, vol%	71.4	68.2	68.9	67.8	69.5
CO <sub>2</sub> , vol%	2.7	3	3	2.9	2.7
N <sub>2</sub> , vol%	13.5	15.7	15.6	15.1	15.4
H <sub>2</sub> , vol%	12.4	13	12.6	12.1	12.4
H <sub>2</sub> O, vol%	0	0	0	2.1	0
CO <sub>2</sub> -rich gas captured					
CO, vol% (dry)	12.1	10.7	3.3	0	0
CO <sub>2</sub> , vol% (dry)	79.7	87.2	96.3	100	100
N <sub>2</sub> , vol% (dry)	5.6	1.6	0.3	0	0
H <sub>2</sub> , vol% (dry)	2.5	0.6	0.1	0	0
Suitable for transport and storage?	no	no	yes?	yes	yes
CCS process					
Electricity consumption, kWh/tCO <sub>2</sub>	100	105	292	170	310
Capture process, kWh/tCO <sub>2</sub>	100	105	160	55	195
Compression for storage (11 MPa), kWh/tCO <sub>2</sub>	–	–	132	115	115
Low pressure steam consumption, GJ/tCO <sub>2</sub>	0	0	0	3.2	0
Total energy consumption, GJ/tCO <sub>2</sub>	0.36	0.38	1.05	3.81	1.12

of a state-of-the-art integrated steel making plant, with and without CCS and located along the coastal region of Western Europe, is currently being investigated by the IEA Greenhouse Gas R&D Programme. It is difficult to compare the published costs due to differences in the assumptions and the lack of cost information for some factors. A standardised procedure is required. The capital cost values given in Table 25 have been standardised by Kuramochi, and include CO<sub>2</sub> compression to 11 MPa; a capital cost scaling factor of 0.85 was used. The Euro cost year is 2007. CO<sub>2</sub> capture from Corex® process gas has the lowest capital cost.

CO<sub>2</sub> capture costs for BFs have been estimated at 20–25 €/tCO<sub>2</sub> (or 40–50 US\$/tCO<sub>2</sub>), although changes in furnace productivity can have a significant impact on the process economics (IEA, 2008b). The marginal investment costs will be higher for retrofits than for new builds. Avoided emissions take into account the emissions that are not captured. In the short to medium term (5–15 y), a CO<sub>2</sub> avoidance cost (€2007) of 40–65 €/tCO<sub>2</sub> at a CO<sub>2</sub> avoidance rate of ~0.7–0.8 tCO<sub>2</sub>/t HRC, or 40–45% of the total carbon input to the plant, is possible for a TGR-BF. Costs will be higher if this technology is retrofitted to existing BFs. The uncertainty of the cost estimation is particularly high for this technique (25 €/tCO<sub>2</sub> avoided for CO<sub>2</sub> capture with VPSA), because the large additional power

<b>Table 25 Key parameters of various CO<sub>2</sub> capture options for BF and Corex® reported in the literature (Kuramochi, 2011)</b>			
CO <sub>2</sub> capture technique	Specific energy consumption, GJ/tCO <sub>2</sub> captured		Specific capital cost, €/tCO <sub>2</sub> captured/y
	Steam	Electricity	
<b>Air-blown BF</b>			
Chemical absorption			
MEA	3.2–4.4	0.51–0.55	70–90
KS-1	3	0.5–0.51	60–70
Other amines	2.5–4.7	0.35–0.51	70–80
Advanced solvents	2.2–2.5	0.50	70
Physical absorption (Selexol™)	–	0.77	180
Shift + Selexol™*	0.5†–0.62	0.63–0.91‡	20–190
Selective carbon membrane	–	0.69–0.89	80
Hydrate crystallisation	–	4.7	220
<b>TGR-BF</b>			
Chemical absorption (MEA)	3.3	0.62	60
VPSA	–	0.94	50
Physical absorption (Selexol™)	0.21	0.93	60
Selective carbon membrane	–	0.79–0.88	60–90
Hydrate crystallisation	–	1.5	70
<b>Corex®</b>			
Chemical absorption (MEA)	4.4	0.45	40
Physical absorption (Selexol™)	–	0.97	40
Shift + Selexol™*	0.63	0.60§`	20–110
<p>* CO<sub>2</sub> capture using water gas shift improves the quality of exported fuel gas (higher H<sub>2</sub> content). Gielen (2003) assumes a benefit of 0.28 GJe/tCO<sub>2</sub> captured. However, this benefit is excluded here. The power consumption and cost figures differ significantly between Gielen (2003) and Vlek (2007). The difference in specific power consumption is partly because the study by Vlek (2007) takes into account not only gas compression and steam consumption but also power consumption for solvent circulation and loss of calorific value due to shift reaction. The cost scaling factor was calculated to be 0.68</p> <p>† Steam required for water gas shift is recovered from waste heat streams</p> <p>‡ Ho and others (2011) report 1.36 GJ/tCO<sub>2</sub> captured, including the steam consumption converted to electrical terms</p> <p>§ Ho and others (2011) report 0.83 GJ/tCO<sub>2</sub> captured, including the steam consumption converted to electrical terms</p>			

consumption for CO<sub>2</sub> removal and oxygen generation, and reduction of BFG export makes the technology sensitive to energy prices. Add-on CO<sub>2</sub> capture for conventional BF are expected to be similar, although at a lower CO<sub>2</sub> avoidance rate of ~0.3–0.4 tCO<sub>2</sub>/t HRC (Kuramochi, 2011).

Capture costs (A\$2008) at CO<sub>2</sub> emission point sources for an integrated steel mill in Australia are estimated to range from 77 to over 600 A\$/tCO<sub>2</sub> avoided with MEA solvent absorption. The direct emission point sources with costs below 100 A\$/tCO<sub>2</sub> avoided are the power plant, coke ovens, hot stoves and sinter plant stacks. These four point sources are where CO<sub>2</sub> capture is likely to be first implemented as a 5 Mt steel plant could then reduce its CO<sub>2</sub> emissions by over 7.5 Mt/y. Treating BFG is estimated to cost 71 A\$/tCO<sub>2</sub> avoided, about the same as for the power plant. It may therefore be preferable to capture the CO<sub>2</sub> from the power plant flue gas at the existing plants rather than from



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the BFG. CO<sub>2</sub> capture at the BF would alter the characteristics of the resultant BFG which is currently used on site as a significant source of low grade fuel. At a mini-mill (EAF), CO<sub>2</sub> emissions could be reduced by 0.1 t/y at a cost of over 250 A\$/tCO<sub>2</sub> avoided (Wiley and others, 2011). Based on current technology, it was estimated that carbon capture would require a carbon price of at least 65 A\$/tCO<sub>2</sub> emitted to be economically attractive.

CO<sub>2</sub> capture from smelting reduction process gas is considered to be more cost-effective than that from air-blown BF gas because of the higher CO<sub>2</sub> concentration. In the short to medium term, a CO<sub>2</sub> avoidance cost of 25–55 €/tCO<sub>2</sub> avoided for the Corex® process, at an avoidance rate of 0.7–2 tCO<sub>2</sub>/t HRC could be achieved (Kuramochi, 2011). The higher end of the cost range includes a shift reactor in order to remove more carbon. Kuramochi and others (2011) suggest that when a new steel making plant is considered, smelting reduction technologies, such as Corex®, may become a strong competitor to the conventional BF-based process in a carbon-constrained society when equipped with CO<sub>2</sub> capture. Smelting reduction can achieve considerable reduction in CO<sub>2</sub> emissions compared to the BF process, with similar steel production costs. Although conventional steel making using BFs is expected to dominate the market in the long term, the need for drastic CO<sub>2</sub> emissions reduction may drive the sector towards large scale implementation of advanced smelting reduction technologies.

Gas based DRI production would allow CCS at a relatively low cost, below 25 US\$/tCO<sub>2</sub>. But DRI facilities are concentrated in relatively few countries and are comparatively small scale. As a result, this approach has so far received only limited attention. With the expected rapid growth in DRI production in the Middle East and elsewhere, the potential for CO<sub>2</sub> capture could amount to 400 Mt/y by 2050 (IEA, 2008b).

The published economic assessments mainly use cost data for industrialised countries and may not be applicable in the emerging economies with their lower equipment costs and cheaper labour. The potentially cheaper CO<sub>2</sub> capture could accelerate the relocation of steel plants from industrialised countries to emerging economies (Kuramochi and others, 2011).

Currently the CO<sub>2</sub> capture from coal-based iron and steel making processes is expensive and the high cost could inhibit widespread commercial deployment of CCS. Commercial viability partly depends on the price of carbon emissions which is set by government policy. The European Union's establishment of the European Trading System, and likely implementation of reduction targets in other jurisdictions, may provide economic incentive for implementation of CCS and CO<sub>2</sub> abatement technologies. More large scale demonstration projects, such as the Florange project (*see* Section 4.3.1), could lead to lower costs in the future. If all technical, financial and cost barriers are overcome, then CCS could be deployed in the steel industry.

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## 10 New technologies

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Technological developments in the steel industry over the last 30 years or so have made substantial reduction in CO<sub>2</sub> emissions possible, as described in the previous chapters. Extensive research is being carried out into further ways of lowering CO<sub>2</sub> emissions and in the development of innovative iron and steel making processes that avoid the use of carbon-based reducing agents. Most of the CO<sub>2</sub> generated in the iron making process comes from the chemical interactions between carbon and iron ore. Thus replacing carbon-based reductants with a carbon-free one may enable near zero CO<sub>2</sub> iron production, without the need for CCS. The long-lived nature of the current capital stock limits the rate at which new technologies can be adopted. This chapter looks at hydrogen reduction and electrolysis of iron oxides.

### 10.1 Hydrogen reduction

Reducing iron ores with H<sub>2</sub> yields water vapour instead of CO<sub>2</sub> with a carbon-based reductant. The water in the offgas can be easily separated by condensation. The overall decrease in CO<sub>2</sub> emissions is mainly dependent on the CO<sub>2</sub> emissions associated with the H<sub>2</sub> generation process. H<sub>2</sub> is currently produced from fossil media (natural gas, coal, oil), by biomass gasification, and from non-carbon sources, such as water electrolysis. The use of fossil media, such as the reforming of natural gas or methane, generates CO<sub>2</sub> that would need to be captured and stored, at a cost. Water electrolysis is expensive and its CO<sub>2</sub> emissions are related to the availability of green electricity. It requires ~5 kWh/m<sup>3</sup> of H<sub>2</sub> (Birat and Borlée, 2008), although future developments will reduce this value.

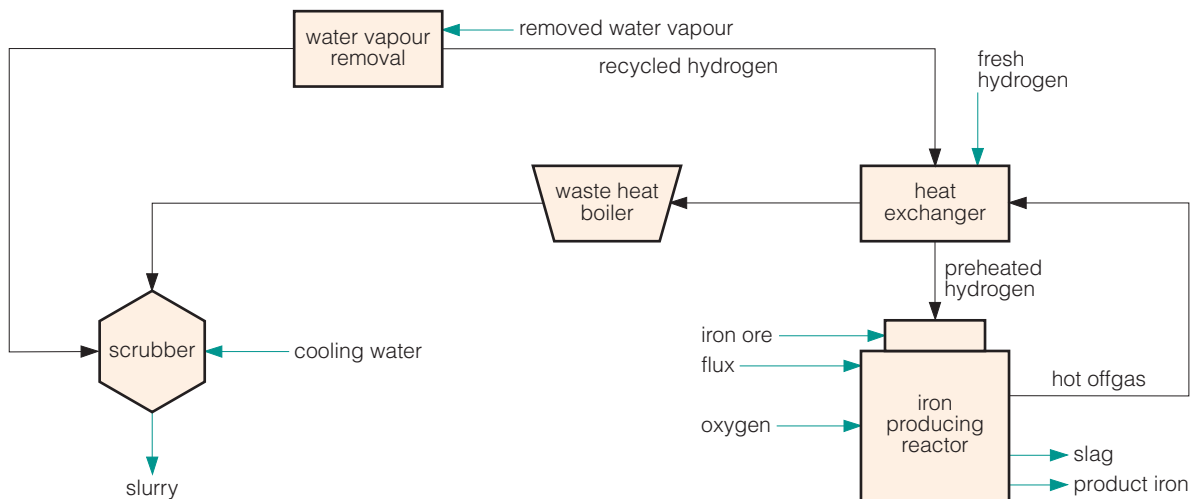
The utilisation of waste heat from coke ovens for COG reforming to produce H<sub>2</sub> is being investigated in Japan (Kojima, 2009). As the amount of waste heat from coke ovens is limited, this is a niche option that will generate less than 0.5 GJ additional H<sub>2</sub>/t of steel (IEA, 2009a). Injecting the H<sub>2</sub> into a BF (*see* Section 4.2) would lower, but not eliminate, CO<sub>2</sub> emissions since coke is still present in the BF. H<sub>2</sub> can also be used as the reductant in conventional direct reduction reactors. One issue, though, will be to prevent sticking of the DRI (Birat and Borlée, 2008). If H<sub>2</sub> is produced by water electrolysis using hydro or nuclear electricity, then CO<sub>2</sub> emissions could be lowered to less than 300 kg/t HRC (Ranzani da Costa and others, 2008).

Molecular H<sub>2</sub> cannot reduce liquid iron oxide: atomic or ionised H<sub>2</sub> is necessary. But these states can only be achieved at very high temperatures such as in the vicinity of an electric or plasma arc (Hiebler and Plaul, 2004; IEA, 2009a). By using high temperatures and avoiding contact between the iron ore particles, sticking and fusing of the particles can be eliminated. In addition, the iron product from H<sub>2</sub> reduction does not contain carbon, and thus the iron can go directly to the refining unit.

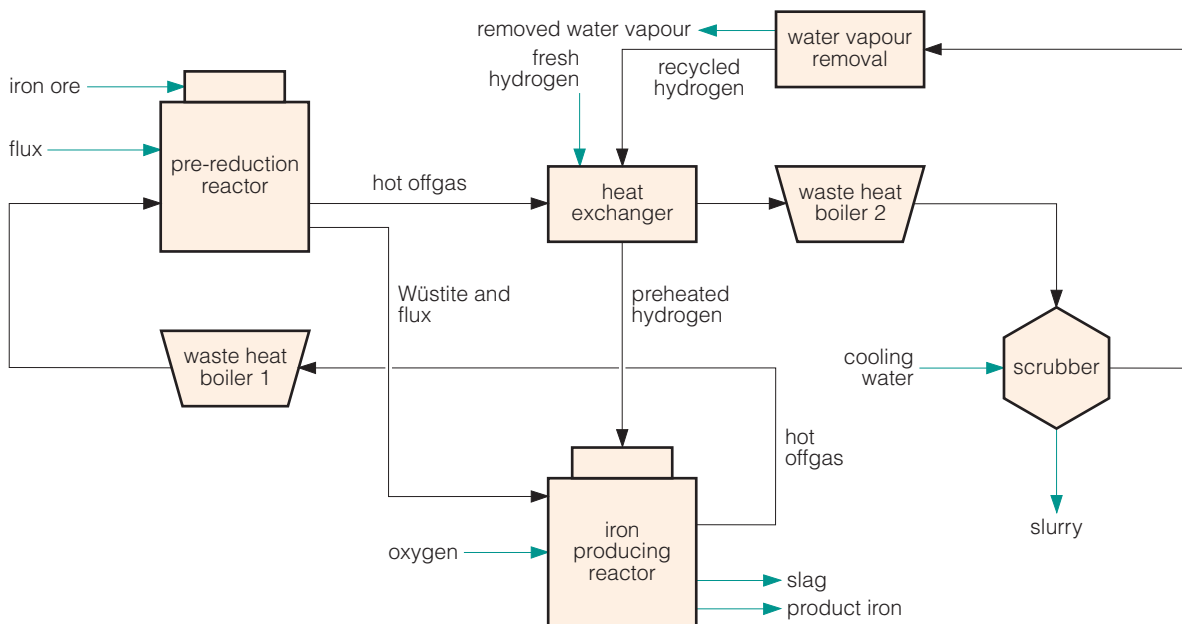
One group investigating the reduction of iron ore fines in a H<sub>2</sub> plasma is based at Montanuniversität Leoben in Austria. In the proposed process, iron ore fines and lime additives (to achieve the required slag viscosity) are charged into the smelter. The plasma-forming H<sub>2</sub>/argon gas mixture enters via hollow graphite electrodes, where the H<sub>2</sub> acts as both a heat carrier and reducing agent. The generated hot metal (with a reduction degree of over 97%) is tapped, degassed to remove dissolved H<sub>2</sub> and O<sub>2</sub>, and alloyed to the required grade. To lower energy consumption, the sensible heat of the smelter offgas is utilised to preheat and pre-reduce the iron ore fines (up to a reduction degree of ~33%) in a fluidised bed system. The sensible heat of the preheater offgas is recovered in a boiler and the generated steam is sent to the steam reformer where H<sub>2</sub> is produced. After passing through the boiler the offgas is cleaned and recycled to the process (Badr, 2007; Hiebler and Plaul, 2004).

An analysis, carried out as part of the ULCOS project, indicated that a 1 Mt/y steel plant would consume 1.03 MWh (3702 MJ)/t steel and 690 m<sup>3</sup> of H<sub>2</sub> (Badr, 2007). Direct CO<sub>2</sub> emissions are

## a) one-step



## b) two-step



**Figure 23** Flowsheets of the one-step and two-step pilot-scale suspension process (Kimura, 2010)

~29 kg/t steel. The hot metal product contains over 99% of iron and the slag ~30% of iron oxide. Plasmas formed from natural gas and its mixture with H<sub>2</sub> have been investigated. CO<sub>2</sub> emissions and energy consumption were higher than those from a H<sub>2</sub> plasma, but would still be lower than the BF-BOF route (Badr and others, 2007). However, the process has not yet been proven at pilot scale. Its thermal efficiency with respect to heat losses can be high and the large iron oxide (FeO) content of the slag is a drawback. Concern has also been expressed over plasma stability when using 100% reducing gases. The economics of the process is dependent on the availability of cheap electricity and H<sub>2</sub>.

The direct gaseous reduction of iron ore fines in a suspension process that utilises a flash type furnace, similar to those used for smelting copper ores, is being investigated at the University of Utah in the USA as part of the American Iron and Steel Institute's CO<sub>2</sub> Breakthrough Program. Iron ore fines are sprayed directly into the reactor where they are reduced in a hot reducing gas generated by the partial combustion of H<sub>2</sub>. Instead of H<sub>2</sub>, cheaper natural gas, coal, syngas or other reducing agents could be used, but CO<sub>2</sub>

emissions will be higher. Bench-scale kinetic measurements have shown that 90–99% reduction can be achieved within 1–7 s at 1200–1500°C, depending on the amount of excess H<sub>2</sub> supplied with the iron oxide (Choi and others, 2009). Figure 23 provides flowsheets for a one- and two-step (which includes pre-reduction of the iron ore fines) version of the process. The sensible heat from the various offgases is recovered and H<sub>2</sub> is also reclaimed for recycling to the iron producing reactor. Steam generated in the waste heat boiler can be used for power generation. The energy required in the iron producing reactor is generated by H<sub>2</sub> combustion for both processes (Kimura, 2010).

A material and energy balance analysis has indicated that the suspension process with H<sub>2</sub>, natural gas or bituminous coal as the reductant/fuel may require ~38% less energy than the BF process. H<sub>2</sub>, for instance, consumes 12.06 GJ/thm compared to 19.49 GJ/thm for the BF process. The calculation does not take into account the energy needed to produce the H<sub>2</sub>. Most of the energy savings result from the elimination of the iron ore pelletising and sintering steps and the cokemaking plant. Using H<sub>2</sub> would generate only 4% of the CO<sub>2</sub> produced in the BF process (71 kgCO<sub>2</sub>/thm for H<sub>2</sub> compared to 1671 kgCO<sub>2</sub>/thm for the BF process), whereas natural gas and coal generate 39% and 69% of those from the BF process, respectively (Sohn, 2008; Sohn and others, 2009). The hot metal product has a lower phosphorus and similar sulphur contents to BF-produced hot metal. The process has still to be proved at pilot-scale.

In conclusion, although H<sub>2</sub> reduction shows a potential advantage over carbon-based reductants from an environmental viewpoint, the economics are dependent on the availability of low cost H<sub>2</sub>. Despite extensive research on developing H<sub>2</sub> energy to replace fossil fuels, a cheap method of producing H<sub>2</sub> (that does not generate CO<sub>2</sub>) still needs to be developed.

## 10.2 Electrolysis

Electrolysis is widely used on an industrial scale to produce aluminium, magnesium and other metals, but is still at the laboratory stage for iron making. In this technology electrons, provided by electricity, are used as the reducing agent. Iron ore is placed in a solution (termed the electrolyte) and an electric current is passed through it. Negatively charged oxygen ions migrate to the positively charged anode, where the O<sub>2</sub> bubbles out and is captured. Positively charged iron ions are transported to the negatively charged cathode where they are reduced to elemental iron.

Two electrolysis routes are currently being investigated:

- an electrowinning process, ULCOWIN (an ULCOS project), in which iron ore grains are suspended in an alkaline sodium hydroxide solution at a temperature of 110°C. The result is a solid iron product. A pilot plant with a capacity of 5 kg iron/d has been proposed (see [www.ulcos.org](http://www.ulcos.org));
- molten oxide electrolysis, where the iron ore is dissolved in a mixed oxide solvent, such as silicon oxide and calcium oxide, at ~1600°C. The resultant molten iron collects at the bottom of the cell and is siphoned off. This process is under development in Europe (the ULCOS project, ULCOLYSIS) (Birat and Borlée, 2008) and by the Massachusetts Institute of Technology (MIT) in the USA (Sadoway and Ceder, 2009). A molten lithium carbonate electrolyte at a lower temperature (~800°C) is being investigated at the George Washington University, USA (Licht and Wang, 2010; Shiells, 2010).

The oxygen generated in the process is a marketable by-product, thereby decreasing the overall cost of the process. Since electrolysis produces no CO<sub>2</sub>, it could theoretically be zero-carbon but only if the electricity needed to power the process is produced without generating CO<sub>2</sub> emissions. The energy consumption is dependent on the cell configuration, the chemistry of the electrolyte and the process temperature. The molten oxide electrolysis process consumes ~2000 kWh/t iron at 1600°C (Kleiner, 2006). This is lower than the energy needed in the BF (4980 kWh (17.9 MJ)/t iron) (Allanore and others, 2011). Less power is required for electrolysis at lower temperatures.

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The team at George Washington University have developed a solar technique, called solar thermal electrochemical photo (Step), which uses the sun's thermal energy to melt the lithium carbonate solution and the visible light energy to power the electrolysis (Shiells, 2010). No CO<sub>2</sub> is produced but the Step technology has not yet been proven at industrial scale. Several engineering problems still need to be solved before electrolysis becomes economically viable. This includes the development of a cheap, carbon-free inert anode that is resistant to the corrosive conditions in molten oxide electrolysis.

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## 11 Conclusions

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With the growing concern over climate change, steel makers are faced with the challenge of finding ways of lowering CO<sub>2</sub> emissions without seriously undermining process efficiency or considerably adding to costs. The iron and steel industry is the largest industrial source of CO<sub>2</sub> emissions due to the energy intensity of steel production, its reliance on carbon-based fuels and reductants, and the large volume of steel produced – over 1414 Mt in 2010. World steel production has increased steadily over the last forty years and this growth is expected to continue, especially in the emerging economies. Since China is the largest producer of steel and also the world's largest emitter of CO<sub>2</sub>, this is where CO<sub>2</sub> measures will potentially have the biggest effect, followed by India.

The carbon intensity of iron and steel production varies considerably between the production routes, ranging from around 0.4 tCO<sub>2</sub>/t crude steel for scrap/EAFs, 1.7–1.8 tCO<sub>2</sub>/t crude steel for the integrated BF-BOF to 2.5 tCO<sub>2</sub>/t crude steel for coal-based DRI processes. All steel plants would lower their indirect CO<sub>2</sub> emissions if they could switch to electricity generated from hydroelectric or nuclear power plants, or from renewable energy. If this were possible, it could result in near zero CO<sub>2</sub> emissions for a scrap/EAF mini-mill. In the future, indirect CO<sub>2</sub> emissions from the iron and steel industry will gradually decrease as electricity decarbonises.

There are a number of technologies and measures available to abate direct and process CO<sub>2</sub> emissions from the different iron and steel making processes that involve:

- minimising energy consumption and improving the energy efficiency of the process;
- changing to a fuel and/or reducing agent with a lower CO<sub>2</sub> emission factor;
- capturing the CO<sub>2</sub> and storing it underground.

Minimising energy consumption and improving energy efficiency by employing best available technologies (BATs) and techniques have led to significant CO<sub>2</sub> reductions over the past thirty years or so. Further reductions have been achieved by closing small and energy inefficient plants and modernising others. Additional improvements are still possible through the further implementation of BATs at plants without them. Based on steel production levels in 2007, the IEA estimated that if the BATs were employed by the global iron and steel industry then around 5.57 EJ could be saved, avoiding 421 Mt of CO<sub>2</sub>. This is around 20% of the iron and steel industry's direct CO<sub>2</sub> emissions. The measures that can be implemented at a plant will largely depend on the specifications of the installed facilities, its energy management, as well as its integration with upstream and downstream processes. Not all of the BATs are necessarily suitable for all installations or can be easily retrofitted. Each plant will have its own unique solution. For integrated steel mills BATs include coke dry quenching (or advanced water quenching), top pressure recovery turbines and top gas recycling.

As well as offering some of the least-cost options to reduce CO<sub>2</sub> emissions, energy efficiency measures may also increase productivity and improve the quality of the product. Retrofitting technologies that require a major rebuild or refurbishment, though, will be expensive. The cost effectiveness of the technologies will vary from plant to plant. Retrofitting is more expensive and often less efficient than building a new one when the plant is coming to the end of its technical life. Optimising iron production by installing (or updating) process control and management systems is one of the simplest, and probably the cheapest, means of improving energy efficiency and consequently lowering CO<sub>2</sub> emissions.

The potential for energy efficiency improvements at a steelworks varies depending on the production route employed, product mix, and the energy and carbon intensities of the fuel and electricity. Energy recovery from the various gaseous streams is practised in all the iron making processes. This includes recovering the calorific value in the various gas streams (such as BFG, COG, BOF gas, offgas from direct reduction reactors, Corex® export gas) before they are emitted to the atmosphere. The gases

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can be utilised as a fuel, to produce steam for internal use or to generate electricity. Any excess power can be sold to the grid, generating income for the steel maker. One way to obtain the necessary capital and technology to introduce this measure in steelworks in the emerging economies is through the clean development mechanism (CDM) set out in the Kyoto Protocol. This allows the transfer of CO<sub>2</sub> emission certificates to the foreign investor. Significant CO<sub>2</sub> reductions can be achieved.

Unfortunately, combusting the offgases produces CO<sub>2</sub>. In the future, carbon capture and storage may need to be retrofitted to on-site power plants, as well as the stacks in the steelworks.

There is still scope to increase waste heat recovery at steel making plants by recovering the thermal and sensible heat from the various gaseous steams, and the solid and liquid products. In integrated steelworks this includes installing technologies such as coke dry quenching, which can recover around 80% of the coke's sensible heat which can be used to generate about 160 kWh/t coke. Recovering the sensible heat from the Corex® melter-gasifier and shaft reduction offgases could save around 2.6 and 0.7 GJ/thm respectively. Technologies are available for recovering the sensible heat from lower temperature gases, although the costs might outweigh the benefits. Commercial technologies for recovering the sensible heat in the liquid slags are still under development.

Other energy efficiency measures include replacing electric motors used to drive the fans and other equipment with more energy efficient ones, feeding hot DRI into EAFs and installing more powerful furnace transformers to EAFs. Many of these measures are off-the-shelf technology and can be easily implemented.

The feedstock quality (coal and ore quality) can also affect energy efficiency markedly. Processing higher quality feedstocks results in lower energy consumption. Unfortunately, the availability of good quality lump ore is decreasing, whilst the amount of low grade iron ore fines is increasing. Processes (such as Finex®) that can use iron ore fines directly, without the necessity of pelleting and sintering plants, could result in lower energy consumption and CO<sub>2</sub> emissions.

Recycling scrap steel reduces the energy needs and direct CO<sub>2</sub> emissions. However, the amount that can be recycled in a BF is limited to less than 30%. The scrap/EAF route is the lowest emitter of CO<sub>2</sub>, but further growth is dependent on the availability of high-quality, low price scrap. The lack of scrap resources in countries such as China and India limits their scope to replace alternative iron (such as DRI) in the EAF or to switch from BF-BOF to scrap/EAF production. Steel production is increasing in these countries so more scrap will become available in the future. The BF-BOF production route, though, is expected to remain the dominant method of steel production due to the products's higher quality and lower content of undesired residual material.

Energy efficiency measures alone will not be enough to offset the growth in CO<sub>2</sub> emissions resulting from increasing steel production. The iron and steel industry in the European Union, USA and elsewhere have already taken the most cost-effective steps to conserve energy, and so future gains will be harder and more costly to achieve. Moreover, the best steel mills are now operating close to the laws of thermodynamics and so have limited potential to improve their energy efficiency further. One option is to switch to a fuel and/or reducing agent with a lower carbon content, and hence lower CO<sub>2</sub> emissions factor. The extent to which coal can be replaced is dependent on the iron making process. For blast furnaces it would mean injecting natural gas instead of pulverised coal, but the volume is limited due to process constraints. Gas-based DRI could replace coal-based production. India is the largest producer of coal-based DRI and replacing this with gas-based DRI technologies could substantially lower its CO<sub>2</sub> emissions. But this would necessitate a major, and expensive, rebuild exercise. In addition, natural gas resources in India are limited and so this option is unlikely to be widely employed. Expansion of gas-based DRI production is only likely in regions with cheap and abundant natural gas supplies, such as the Middle East, or where there are stranded gas reserves.

Replacing coal and natural gas with biomass can reduce CO<sub>2</sub> emissions. In general, direct reduction processes can utilise up to 100% wood charcoal either within the reactor (rotary kilns, rotary hearths)

or by gasifying biomass instead of coal and injecting the resultant syngas into the shaft furnace. HIs melt® could also potentially be run on 100% wood charcoal instead of coal. The amount that can be achieved by this measure is limited in the Corex® process, due to the low strength and low abrasion resistance of charcoal, and in integrated steelworks. Wood charcoal does not have the physical strength to support the iron ore burden in large blast furnaces (no material has yet been found that can replace coke) and its inclusion in the coking coal blend adversely affects coke quality. This limits charcoal addition to 10% in both of these cases. Research on improving the mechanical stability of charcoal is required. Small blast furnaces can operate with 100% charcoal, as is the case in Brazil. Charcoal can also be fed into EAFs. But the sustainable production of charcoal from planted trees needs large amounts of land. Producing 500 Mt of hot metal requires over 40,000 hectares (400 km<sup>2</sup>). There is also the competition with land for food production and with other industrial users, such as the power generating industry, that will lead to increased biomass costs. These factors limit the role of biomass in CO<sub>2</sub> abatement.

Besides lowering CO<sub>2</sub> emissions, the use of wastes has a number of potential benefits including the recovery of their energy content, conservation of non-renewable fossil fuels, reducing production costs and eliminating their disposal in landfills. Replacing some of the coal with waste plastics and waste tyres (which also contain some iron) has been successfully carried out in integrated steelworks and in EAFs. But again, the amount is limited in blast furnaces and coke ovens due to operational factors, and the varying quality of the waste plastics. Little work has been carried out on their use in direct reduction and smelting processes – more needs to be done. Most iron making processes can recycle at least a small amount of steel wastes to recover their iron content.

Further substantial CO<sub>2</sub> reduction will only be achieved by equipping plants with carbon capture and storage (CCS). Applying CCS to all the stacks in a steelworks is possible, provided there is space. It would not upset the upstream and downstream processes, but would be expensive. CO<sub>2</sub> capture is a proven technology at the Saldanha plant in South Africa (Corex® process) and is widely applied in some natural gas-based DRI processes. Part of the CO<sub>2</sub> is also removed from the recirculation gas in the Finex® process. Thus storing the captured CO<sub>2</sub>, instead of flaring, would immediately lower CO<sub>2</sub> emissions. Costs would only be for CO<sub>2</sub> compression and storage.

Blast furnaces are the largest potential source of direct CO<sub>2</sub> emissions in integrated plants. BF Plus technology, developed by Danieli Corus and Air Products, is now commercially available. It includes an optional shift reactor and CO<sub>2</sub> removal unit to capture CO<sub>2</sub> from the BF top gas before it is used for combined cycle power generation. Including a shift reactor before the CO<sub>2</sub> capture unit enables more CO<sub>2</sub> to be captured, but increases capital and operating costs. Top gas recycling with CO<sub>2</sub> removal (by pressure swing adsorption), and operating with an oxygen blast (oxyfuel, a technology that still needs to be demonstrated at an industrial scale) could also substantially reduce CO<sub>2</sub>. Slags generated during the iron and steel making processes have a high alkaline earth metal oxide content and could potentially be utilised to capture and permanently store CO<sub>2</sub> via mineral carbonation.

A drawback for some CO<sub>2</sub> capture technologies is the high energy consumption and, where used, steam consumption. The capture process could be optimised by utilising waste heat from other on-site processes to regenerate the capture solvents for those technologies which use solvents. CCS is expensive, and the high cost could inhibit its widespread commercial deployment. CO<sub>2</sub> capture is generally cheaper for the direct reduction and smelting reduction processes than for air- or oxygen-blown blast furnaces. The commercial viability of CCS partly depends on the price of carbon emissions which is set by government policy. More large-scale demonstration projects, such as the Florange project in France could lead to lower costs in the future. If all technical, financial and cost barriers are overcome, then CCS could be more widely deployed in the steel industry. Developing new technologies, such as the HIsarna process, that are designed to generate a nitrogen-free and CO<sub>2</sub> rich offgas which will make CO<sub>2</sub> capture easier and cheaper, is another way forward.

Innovative iron and steel making processes that avoid the use of carbon-based reducing agents are a



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long-term prospect. Processes still at the research stage include the use of hydrogen or electrons (molten oxide electrolysis and electrowinning) as the reducing agents. These technologies will depend on a cheap CO<sub>2</sub>-free hydrogen production process being developed and the availability of cheap CO<sub>2</sub>-free electricity respectively.

To conclude, no single option can yield the necessary CO<sub>2</sub> emission reductions but a combination of technologies are available that can be retrofitted to achieve significant reductions. If CCS is fitted then steel plants could become near zero emitters of CO<sub>2</sub>.

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