Coal use in the new economies of China, India and South Africa

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Abstract

This report examines the use of coal for power generation and major industrial applications in the growing dynamic economies of China, India and South Africa, each of which relies heavily on coal for energy production. There are some similarities in the uses and technologies deployed in these three countries, but there are also differences. The use of some technologies is widespread, whereas others have developed to meet more specific local requirements, hence their geographical application is more limited. These similarities and differences are examined and compared with world best practice.

In all three countries, as in many others, there are coal-consuming plants where performance and efficiency is on a par with the best in the world. However, such application is not necessarily universal and there are often big differences between the best and worst performers. These differences are generally greater than in OECD nations. Through existing collaborations with OECD industry, modern technologies are already being introduced into these three countries. However, in order to improve effectiveness of a particular sector as a whole, in some cases, greater replacement of the existing infrastructure is required, and there are parts that would benefit from greater penetration of world best practice.

Acronyms and abbreviations

BAT	best available technology
BHEL	Bharat Heavy Electricals Ltd
BOF	basic oxygen furnace
BOO	build-own-operate
CCC	(IEA) Clean Coal Centre
CCS	carbon capture and storage
CDQ	coke direct quenching
CFB	circulating fluidised bed
CFBC	circulating fluidised bed combustion
CIAB	Coal Industry Advisory Board
COG	coke oven gas
CSLF	Carbon Sequestration Leadership Forum
CSQ	coke stabilisation quenching
CTL	coal-to-liquids
CV	calorific value
DC	dry cooling
DCL	direct coal liquefaction
DME	dimethyl ether
DRI	direct reduced iron
EAF	electric arc furnace
EOR	enhanced oil recovery
EPRI	Electric Power Research Institute, USA
ESP	electrostatic precipitator
EU	European Union
FBC	Fluidised Bed Combustion
FEED	Front End Engineering and Design
FGD	Flue gas desulphurisation
GE	General Electric
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
IPP	independent power producer
IPR	intellectual property rights
LCPD	Large Combustion Plant Directive
LHV	lower heating value
LPG	liquefied petroleum gas
MEA	methanolamine
MPa	megapascals
MTBE	methyl tertiary butyl ether
Mtce	million tonnes coal equivalent
Mtoe	million tonnes oil equivalent
NAFTA	North American Free Trade Agreement
NDRC	National Development and Reform Commission, China
NETL	National Energy Technology Laboratory, USA
NTPC	National Thermal Power Corporation, India
OECD	Organisation for Economic Co-operation and Development
OMB	opposed multi-burner
PCC	pulverised coal combustion
PCI	pulverised coal injection
PFB	pressurised fluidised bed
R&M	renovation and modernisation
SAIL	Steel Authority of India Ltd
SC	supercritical
SCR	selective catalytic reduction
SEB	State electricity board
SNCR	selective non catalytic reduction
SNG	Synthetic natural gas
TDF	tyre derived fuel
thm	tonne of hot metal
TGR	top gas recovery
toe	tonne oil equivalent
TRT	top recovery turbine
TVE	Town and Village Enterprise (China)
UCG	Underground coal gasification
UMPP	Ultra Mega Power Project
USC	ultra-supercritical
US EPA	United States Environmental Protection Agency
UN	United Nations
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
VSBK	vertical shaft brick kiln
WEO	World Energy Outlook

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1 Introduction

In the present report, the use of coal in the rapidly expanding economies of China, India and South Africa is examined. In each country, recent years have witnessed significant economic growth and growing industrial development. And, in all three, coal continues to play an important role in supplying energy to the power generation sector and a number of major industries. Over the past two decades, both coal production and consumption has increased dramatically in all three countries (Figures 1 and 2). In each, efforts aimed at diversifying sources of energy continue. However, for many years, coal will continue provide a significant proportion of each nation's energy requirements.

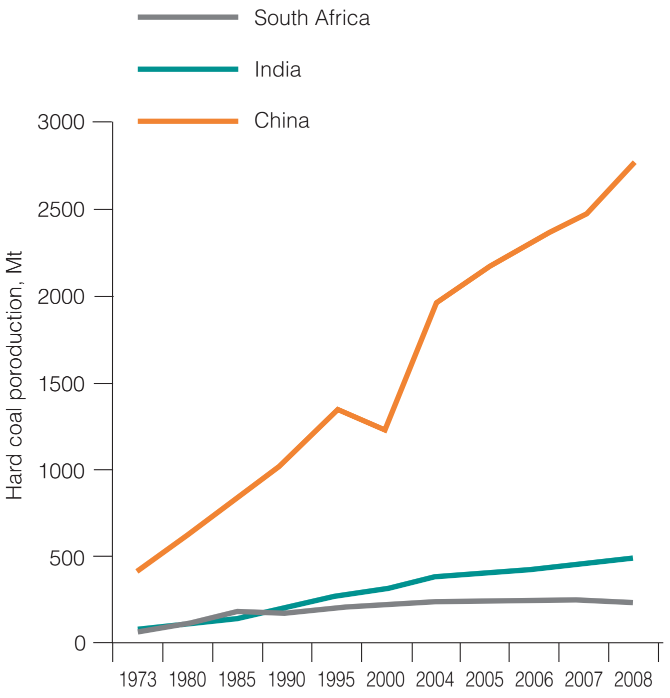

Figure 1 **Hard coal production for China, India and South Africa (1973-2008)**

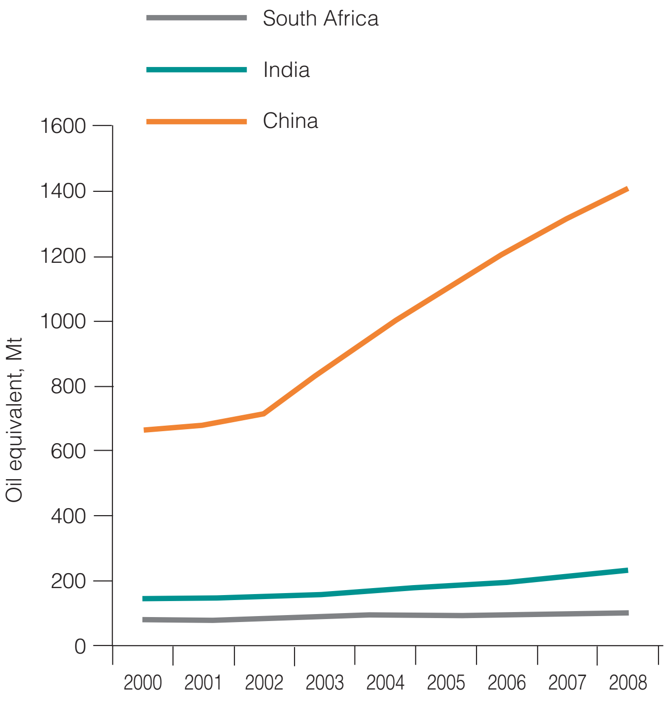

Figure 2 **Coal consumption for China, India and South Africa (2000-08)**

Over the past decade, China has undergone significant economic reform and has emerged as one of the world's fastest developing economies. In response to this economic growth and the rapid expansion in industrial production, coal production, consumption and electricity demand has increased accordingly. China currently accounts for more than 47% of world hard coal production and nearly 64% of total non-OECD production. In 2008, the country produced 2.76 Gt, an increase of 295 Mt over 2007. Of the total global increase in hard coal production recorded in 2008, 73% is attributable to China (OECD/IEA, 2009). The country has an estimated total of 192 Gt of proven recoverable coal reserves (167 Gt hard coal, 25 Gt brown coal) (OECD/IEA, 2009). Consumption of coal in China is driven to a large extent by electricity demand. The growing energy requirement has meant that coal consumption has climbed steadily and despite recent rises in production, increasingly, this is being met by imports. In 2008, these amounted to 45.6 Mt (35.3 Mt steam coal and 10.3 Mt of coking coal). For the foreseeable future, coal will remain the country's main source of energy even though alternative sources (such as wind power) are being increasingly exploited.

Similarly, in India, coal is the only abundant indigenous energy resource (73.5 Gt, mainly hard coal) and remains the dominant fuel for power generation and many industrial applications. Although much is of poor quality, the economic and strategic benefits over other forms of energy will ensure a continuing pivotal role in the Indian economy for many years. The country is currently the second largest non-OECD hard coal producer, and third in the world. Between 2008 and 2009, hard coal production increased by 35 Mt to 485.9 Mt. However, India relies heavily on imports and in 2008, imported nearly 60 Mt of hard coal (30.9 Mt steam coal and 28.8 Mt of coking coal).

Traditionally, coal has also dominated the South African energy supply sector (Figure 3) and the country's energy economy remains overwhelmingly dependent on it. It possesses the world's sixth largest recoverable coal reserves (53 Gt), ~5% of the world total. The country produces 97% of Africa's hard coal, around 4% of the world's total production. Coal provides around 75% of total primary energy, generates nearly 90% of the country's electricity, and provides feedstock for almost a third of its liquid fuels via Sasol's coal-to-liquids processes. It is also used directly as an energy source in a number of major industrial sectors. In 2008, coal production was 236 Mt, around a third of which was exported. Annual coal consumption is ~177 Mt. Of this total, ~125 Mt/y

Figure 3 South African coal mining operations (courtesy Anglo Coal)

Figure 4 Anglo coal train en route to South African power plant (courtesy Anglo Coal)

is used in Eskom's power plants (Figure 4) and the remainder by Sasol, other industrial applications, and smaller users.

The importance of coal as a source of energy in these three countries' major industrial sectors is examined in the following sections. Where appropriate, the efficiency and effectiveness of coal-fired processes are compared with world best practice, and those in use in other parts of the world.

2 Coal-fired power generation

In China, India and South Africa, coal is used to generate a significant proportion of each country's electricity. Much of this is bituminous coal (Figure 5). All three countries suffer electricity shortages and are in the process of adding additional coal-fired capacity. In China, at the beginning of 2008, total installed capacity reached 633.5 GW (488.4 GW of coal-fired plants), an increase of 91 GW over the previous year (Smouse, 2009). Annually, China plans to add an average of about 50 GW of new coal-fired capacity for some years (Minchener, 2009). India, in 2004, had ~70 GW of coal-fired plants (Bhattacharya, 2008) and total installed capacity is now approaching 150 GW. By 2012 it is expected to have reached ~212 GW. Despite additions made to the country's generating capacity, India continues to suffer from a shortage of power. Although the general availability of electricity has grown in recent years, increased demand has consistently outstripped supply. Demand continues to rise, with the projected rate of increase in consumption (up to 2020) the highest in the world. This will require further large capacity additions coupled with upgrading of the existing fleet, many of which perform poorly.

South Africa has a total installed generating capacity of 37.1 GW, 32.2 GW of which is coal-fired; these plants provide ~93% of South Africa's electricity. The public utility, Eskom, is increasing capacity through the modernisation and upgrading of existing plants, re-starting mothballed units, and developing two new major coal-fired projects (van der Riet and Begg, 2003).

Below, the different types of generating technologies used in each country are examined.

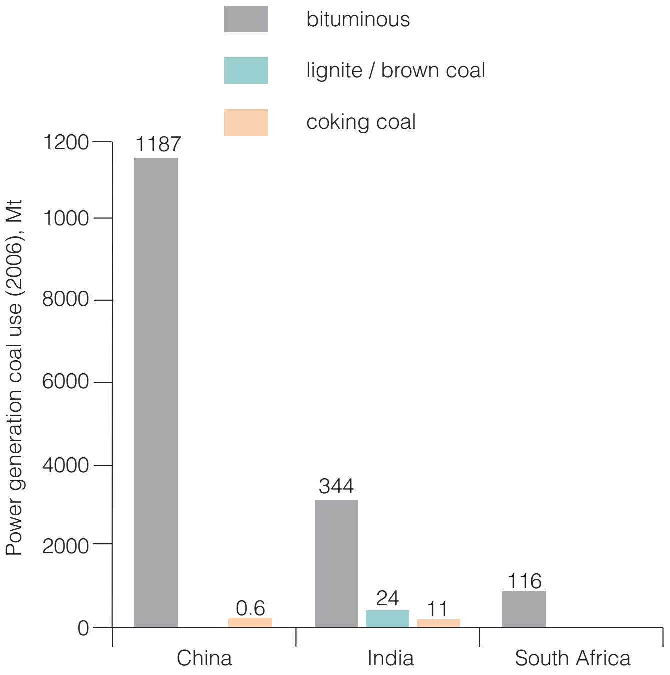

Figure 5 Coal use by power generation sectors (2006)

2.1 Pulverised coal combustion

Globally, this is the most widely used technology for generating electricity from coal. The dominant technology in all three countries is subcritical PCC, although the situation is changing. In China, more than 8000 subcritical PCC units are in operation, some characterised by low efficiencies. However, government policy now requires that as generating companies bring new higher efficiency capacity on line, they must close older low efficiency plants in appropriate measure. According to the 11th Five Year Plan, in order to meet national energy conservation targets, around half of existing small units (~50 GW) will be closed by 2010. During 2007, more than 550 such units were closed (total of 14.4 GW), followed by a further 13 GW in 2008. This ongoing replacement of small units with larger, more efficient plant is driving up the average efficiency of the fleet and has so far saved an estimated 18.8 Mtce and reduced associated CO_2 emissions by 29 Mt (Wang and Zeng, 2008).

PCC subcritical technology also dominates the Indian power sector, with individual stations varying in capacity from 60 to 2600 MW; these generally operate between 2 and 11 units. Most PCC units use ~18 MPa/540/543ºC main steam conditions. Total installed generating capacity is now approaching 150 GW, most of which is based on subcritical PCC technology. Despite efforts to address the situation, many older Indian power plants operate at efficiencies far from optimum, hence have considerable scope for improvement. Their low efficiency results from a range of factors that includes poor maintenance, high auxiliary power consumption, reducing coal quality, and the hot climate. Units of 200–215 MW form the backbone of the power sector (~46% of installed capacity) and, despite some remedial efforts, it is the performance of many of these that is the poorest. However, overall fleet efficiency is gradually improving, but not as quickly as China, owing to the slower build up and poorer performing State Electricity Board stations that represent about two thirds of India's electricity generating capacity.

South Africa has a total installed generating capacity of 37.1 GW, 32.2 GW of which comprises PCC plants using subcritical steam conditions. Eskom's coal-fired plants are the main providers of electricity, generating ~93% of the country's needs. Details of these are shown in Table 1.

Within the three respective power sectors, recent years have witnessed a gradual increase in individual unit capacity. This has been particularly true for China, although a similar trend has also occurred in India. The average Chinese unit size is increasing as smaller units are systematically closed down and replaced with larger, more efficient ones. During 2007-08, more than 27 GW of small capacity units was retired, and by 2010, around half of all such units (~50 GW) will have been closed (Wang and Zeng, 2008).

Table 1 Eskom PCC fired power plants (Eskom, 2009; IEA/OECD, 2007; CoalPower)

Plant	Units, MWe	Total capacity, MWe	Efficiency, LHV net, %	Availability over last three years	Steam conditions			Comments
					Pressure, MPa	Main steam, °C	Reheat, °C	
Arnot	6 x 350	2100	35.6	92.07	17	516	516	On-going refurb
Camden	8 x 200	1600	33.4	na	11	543		On-going refurb
Duvha	6 x 600	3600	37.6	89.85	17	540	540	
Grootvhei	6 x 200	1200	32.9	na	11	543		On-going refurb
Hendrina	10 x 200	2000	34.2	88.78	11	543		
Kendal	6 x 686	4116	35.3 DC	93.69	19	543	543	
Komati	5 x 100 4 x 125	1000	30.0	na	9	519		On-going refurb
Kriel	6 x 500	3000	36.9	93.37	17	516	516	
Lethabo	6 x 618	3708	37.8	93.05	18	540	540	
Majuba	3 x 665 DC 3 x 710 wet	4110	35.3 DC 37.7 wet	97.17 DC na	17	540	540	
Matimba	6 x 665	3990	35.6 DC	93.67	17	540	540	
Matla	6 x 600	3600	37.6	93.84	18	540	540	
Tutuka	6 x 609	3654	38.0	93.41	17	540	540	
Average			35.56	92.98				

DC dry cooled

In India, since the 1950s, average unit capacity has also gradually increased. There is currently a strong focus on adding 660 MW units, likely to increase further to 800–1000 MW in the near future (Sinha, 2006). In 2007, the fleet included 25 x 500 MW (eight under construction) and 6 x 660 MW units, also under construction. At present, the biggest segment of the Indian power fleet comprises 34 GW of 200–210 MW, 6 GW of 250–500 MW, and 19 GW of 500+ MW units (Srivastava, 2008). Worldwide, units of 200–300 MW make up 21.4% of the total generating fleet. In India, this proportion is somewhat higher at 46%. However, as in China, this ratio is changing as the number of larger capacity units continues to increase.

Figure 6 Changshu supercritical pulverised coal-fired power station in Jianshu Province. The plant uses three 600 MWe once-through SC wall-fired boilers supplied by Doosan (courtesy Doosan Babcock)

2.1.1 Uptake of supercritical or ultra-supercritical PCC technology

In parts of the OECD, supercritical PCC technology is well-established. For example, in Germany, 25% of coal plants are SC, in the USA ~20% are SC, and in Japan, the proportion is 70%. In China, the current focus is on the deployment of 600 MW or 1000 MW SC/USC PCC units, with plans to build up to 100 of them (OECD/IEA, 2006). Nearly all units that have recently become commercial, as well as those proposed or under development, have been based on these unit capacities. There are currently >150 SC and USC PCC Chinese units on order or under construction and, by the end of 2009, 24% of China's plants will be SC or USC. Figure 6 shows an example of a recently completed Chinese SC PCC power plant.

Within India, there is also a programme to introduce SC PCC technology. In 2008, there were at least 18 SC projects under construction or proposed, totalling nearly 55 GW. Several are close to commissioning, namely the Sipat plant in Chhattisgarh and the Bahr project in Bihar. Each is deploying three 660 MW units. Equipment is being supplied by Doosan Heavy Industries and Techno Prom Export of Russia respectively (Topper, 2008). India plans to have 24 GW of SC capacity operational by 2015 (Bhattacharya, 2008) increasing to 32 GW (47 units) by 2020 (Smouse, 2009). There will be a series of Ultra Mega Power Projects (UMPPs) each of ~4 GW. These will adopt SC conditions. Several are already under development, the most advanced being the Mundra 4 GW project in Gujarat. Overall, UMPPs are expected to eventually add some 32 GW of capacity to the Indian power sector.

In South Africa, Eskom is developing two new major SC PCC projects with a combined capacity of 9 GW. These comprise the Bravo project at Kusile (6 x 790 MW) and the Medupi station (6 x 750 MW). Hitachi is supplying SC boilers for both.

Figure 7 summarises current coal-fired capacities and planned or operational supercritical/ultra-supercritical capacity in each country.

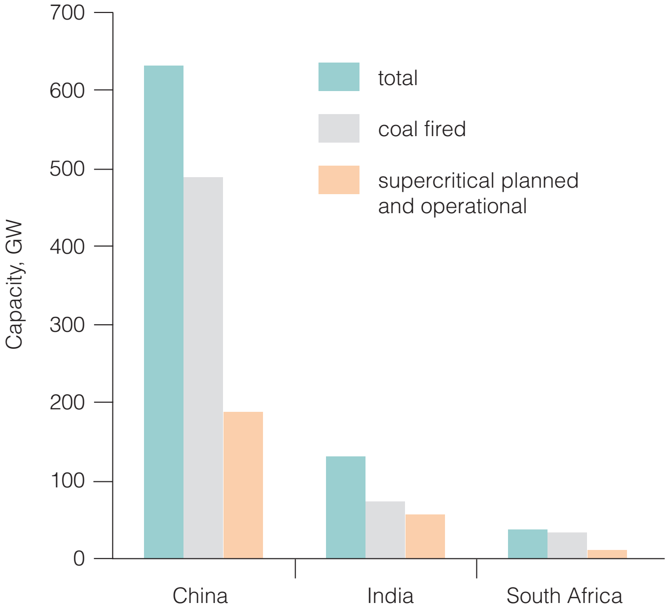

Figure 7 Current coal-fired capacities and planned or operational supercritical/ ultra-supercritical capacity (Smouse, 2009; Topper, 2008; Eskom, 2009)

The steam conditions for the latest flexible USC units currently being constructed or offered in Japan and Europe are 25–30 MPa/600°C/620°C (Blue Wave, 2007). Although earlier Chinese SC PCC plants adopted steam conditions similar to those used elsewhere (for instance, in the USA, The Netherlands, Denmark and Australia), current design steam parameters for 1000 MW USC units in China are close to this, at 25 or 27 MPa/600°C/600°C (Table 2) (Zongrang, 2007). These are on a par or higher than those being adopted for some plants in the USA, Germany, and Japan (Blue Wave, 2007; IEA/OECD, 2007). Steam conditions for proposed Indian SC projects are somewhat lower, typically ~25.0 MPa/540°C/565°C, although two 800 MW projects will use 24.7 MPa/565°C/593°C (broadly similar to those currently proposed for some US projects).

2.1.2 Generation efficiency

On-going changes within the Chinese power sector, including the adoption of large capacity SC units, are gradually increasing the average fleet operating efficiency. In 2004, this was ~30% (LHV). It is currently ~34% (LHV) (Table 3). The OECD average is around 36% (Figure 8).

Table 3 Efficiency of different Chinese coal-fired power plants (2006) (Tian, 2008; Wang and Zen, 2008 – citing NDRC data)

Technology	Unit size, MW	Net efficiency, % LHV
USC	1000	43.03
USC	600	42.09
SC	600	41.10
Subcritical	300	36.15
Subcritical	100	29.98
Subcritical	50	27.93
Subcritical	25	24.58
Subcritical	12	22.35
Subcritical	6	20.48
Average 2006		33.49
Average 2007		34.43

Table 2 Recent Chinese USC plants coming on line (Zongrang, 2007)

Project	Capacity, MW	Steam conditions MPa/°C	Boiler manufacturer	Technology support
Zheijiang Yuhuan	4 x 1000	25/600/600	Harbin Boiler	MHI
Shandong Zouxian	2 x 1000	25/600/600	Dongfang Boiler	Hitachi
Waigaoqiao Phase III	2 x 1000	27/600/600	Shanghai Boiler	Alstom
Jiangsu Taizhou	2 x 1000	25/600/600	Harbin Boiler	MHI

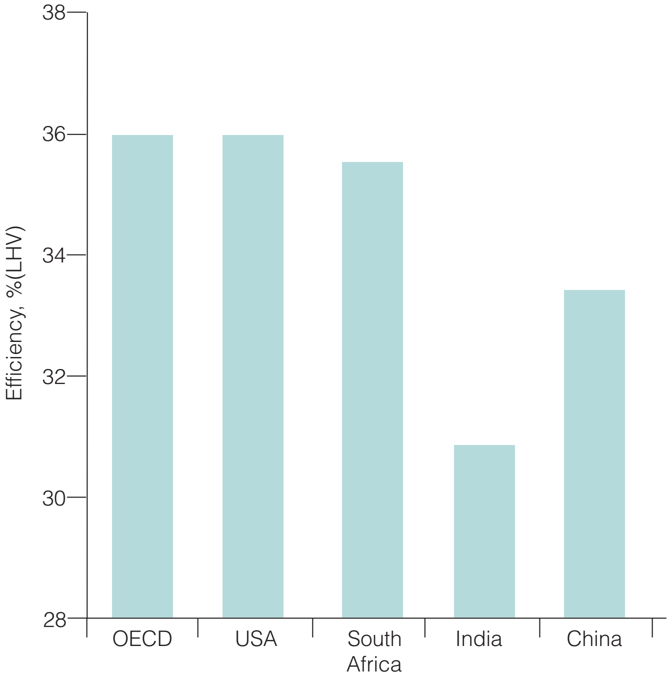

Figure 8 Average coal-fired power generation efficiencies (Tian, 2008; Wang and Zeng, 2008; Smouse, 2009; Eskom, 2009)

Table 4 Efficiency of different capacity Indian generating units (Mills, 2007)

Unit size (MW)	Total no units	Average actual gross efficiency, %	Average actual net efficiency, %
500	18	35.67	33.25
200, 210, 215 (KWU)	154	34.98	31.96
200, 215 (LMZ)		34.62	31.66
100–200	84	27.55	24.22
<100	87	25.79	22.8

In India, overall efficiency is improving more slowly than in China, owing to the slower rate of new build. Coal quality is also poor and ambient temperatures high. In 2006, the average efficiency was 27.6% (LHV basis), compared to the OECD average of 36.7% (Ricketts, 2006, using IEA gross generation data for 2003). The current estimate is ~30% (Smouse, 2009). The ongoing SC programme will raise this. The average efficiency of different capacity units is given in Table 4.

The average efficiency of the South African generating fleet is 35.56 % (LHV) although a number are somewhat lower than their counterparts in most OECD countries. This results mainly from poor coal quality and the high ambient temperatures that limit condenser vacuum, especially when dry cooling is used. Again, ongoing refurbishments and the new SC plants will increase this.

2.1.3 Unit age and Renovation and Modernisation (R&M) activities

In all three countries, there are significant differences in age between the newest and oldest PCC units operating. Equally, in all three, there are changes taking place as increasingly, new units replace older ones. The most rapid pace is taking place in China, where new coal-fired power plants continue to be built at a remarkable rate (Figure 9). In 2005, China had in operation 133 GW of coal-fired capacity built between 1996 and 2005, compared to the USA's 4.9 GW. It also had 82.6 GW built between 1986 and 1995, compared to the USA's 26.6 GW. In 2007, China built 959 units (849 subcritical and 110 SC) during the last ten years (17 in the USA); 500 are between eleven and twenty years old (85 in the USA); 194 are between twenty-one and thirty years (203 in the USA); 137 are between thirty-one and forty years (247 in the USA); and there are only 67 more than forty-one years old (580 in USA) (Smouse, 2009).

In India, because of the shortage of electricity, many coal-fired power plants continue to operate beyond their design lifetimes. For many years, the country has maintained a rolling R&M programme, focused mainly on 200–210 MW units that are 20 or more years old (Mills, 2007). Many coal-fired units have operated without modernisation for far longer periods than their counterparts in OECD countries. By 2008, 51 units operated by NTPC had reached >100,000 hours of operation; some exceeded this by a considerable margin – 17 had reached between 150,000 and 200,000 hours. Of the country's 200–210 MW units, 37 are 15–20 years old and 77 are more than 20 years old (Srivastava, 2008). In 2004, ~50% of the global coal-fired fleet (mainly 300+ MW units) was 25 or more years old (Bhattacharya, 2008). The age

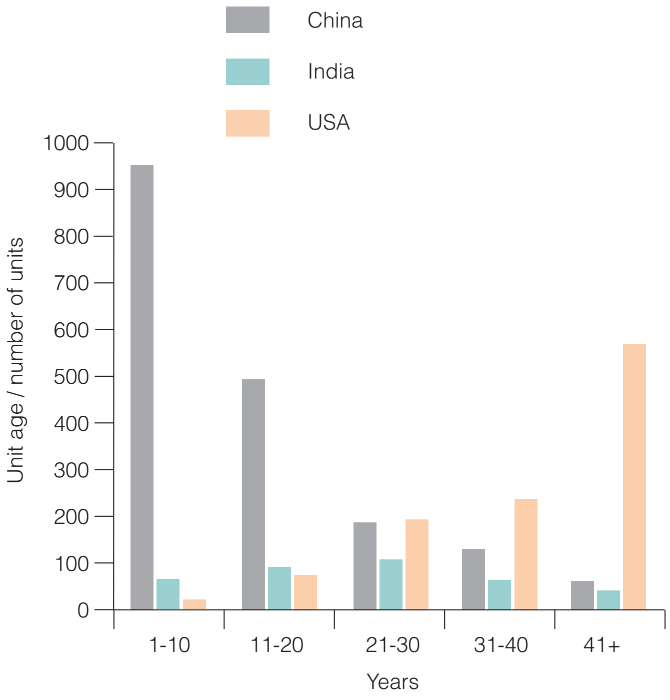

Figure 9 Power generation – unit age

Table 5 Age profile for Indian coal-fired PCC units (Smouse, 2009)

Age, years	Number of units	Combined capacity, GW
10 or less	74	18
11–20	102	106
21–30	119	21
31–40	70	6
41 or older	50	3

Figure 10 The Komati coal-fired power plant in South Africa. Mothballed in 1990, it is currently being upgraded, refurbished and recommissioned (courtesy Eskom)

profile of Indian coal-fired units is given in Table 5.

In South Africa, the largest segment of Eskom's coal-fired capacity (19.6 GW) is 10–20 years old; the two newest are 12–13 years old. There is 10.8 GW of capacity of 20–30 years age, and ~7 GW more than 30 years old. A number of Eskom plants are in the process of modernising and upgrading; Figure 10 shows the Komati station where there are nine units with a combined capacity of 1 GW. This was originally commissioned in 1961 and subsequently mothballed in 1990. It is now being upgraded, refurbished and recommissioned.

2.1.4 Environmental performance

Emission limits generally apply to all types of coal-fired power plant, although in practice, the majority in all three countries are based on various forms of PCC technology.

With the exception of mercury, environmental control technology on PCC units is mature, and the best installations perform highly effectively:

- Particulates – down to 5–10 mg/m^3 even with ESPs;
- SO_2 – limestone/gypsum FGD capable of getting SO_2 below 20 mg/m^3;
- NOx – combustion measures (low NOx burners and OFA) plus SCR, capable of NOx of 50–100 mg/m^3.

In practice, most PCC plants emit more than these levels because regulatory requirements do not do not usually require such high degrees of control, and cost is higher for deeper removal.

Historically, legislative requirements controlling plant emissions have differed between China, India, South Africa and OECD nations. Different approaches have been adopted by different countries to control the emission of pollutants such as SOx, NOx, and particulates. A range of technological responses has been introduced to control these emissions. However, over time, these have now largely converged, and techniques for end-of-pipe controls are now similar across most OECD countries. Recent years have seen increasingly stringent emission limits introduced in many countries although, in terms of emissions control measures and limits, some differences remain between China, India and South Africa. Emission standards are given in Table 6.

It is estimated that globally, over the next 12 years, some 800 GW of (new and existing) coal-fired boilers will be fitted with FGD systems. This will comprise more than 2000 individual units worldwide (McIlvaine, 2008); a typical example is shown under construction in Figure 11. China will continue to be the largest installer, followed by the USA where more than 150 projects are slated for start-up between 2008 and 2011; in 2009, an estimated 16 GW of capacity will be equipped with FGD in the USA. However, many other countries will also be investing in cleaner air. The major FGD system suppliers are the USA, Japan, and European companies. However, Chinese licensees are gaining experience in the field and are likely to become international suppliers. FGD systems are currently being built in China at less than 50% of the cost elsewhere in the world. Since 2004, effectively, all new Chinese coal-fired units have been required to install FGD. Since then, pollution levies for emissions of SO_2 (and NOx) have been increased and all units equipped with FGD now qualify for a power price incentive. During 2006 and 2007, FGD systems were installed at the remarkable rate of ~100 GW/y. In 2007, total capacity equipped with FGD reached 270 GW (48.7%). During the same year, 116 GW of new coal-fired capacity was added, with all units of >100 MW equipped with FGD. China's SO_2 emissions are now declining; in 2007 levels were 4.66% lower than in 2006 (reduction from 26 Mt to 24.7 Mt). The Government goal is for 60% of power plants to be deploying FGD by 2010.

Recent years have seen more demanding emissions standards applied in China and those for SO_2, NOx and particulates now fall within World Bank guidelines; SO_2 standards are now on a par with the OECD average (Smouse, 2009) although NOx standards are relatively modest compared to the OECD. In 1997, the first NOx emission limits were introduced for new large capacity PCC boilers. Revisions made in 2005 placed limits on all types of boiler, irrespective of age. Where applied, NOx control is mainly via combustion control systems, some of which originated from overseas technology suppliers. Increasingly, since the 1980s, low NOx burners,

Table 6 Emission standards for coal-fired plant (Mills, 2007; Wang and Zeng, 2008; Sloss, 2009)

	Particulates, mg/m³	SO_2, mg/m³	NOx, mg/m³
China	50	400–1200	450–1100 Dependent on coal: • 1100 (Vdaf<10%) • 650 (10% <Vdaf<20%) • 450 (Vdaf>20%)
India	• <210 MW – 350 • >210 MW – 150	None	None
South Africa	50	None	None
USA	30–50	400–800 New plants <100	210 New plants <100
EU LCPD for existing plants (>500 MWth)	50	400	500 200 (from 2016)
IPCC BAT for existing plant (>500 MWth)	5–20	20–200	90–200
Average for developed countries	30–50	100–850	200–400

Figure 11 Part of the new FGD facility being added to International Power's Rugeley B coal-fired power plant in the UK (courtesy Russell Mills Photography)

produced in China and tailored to the use of Chinese coals, have been retrofitted to coal-fired units of 100–300 MW. This trend continues (Wang and Zeng, 2008). Although NOx limits can often be met using low NOx burners, the import of both SCR and SNCR systems has begun. China is now operating or has under construction 30 GW of SCR systems and many more units are planned. By 2020, the country will be operating more SCR systems than any other country (Epoline, 2008).

In both India and South Africa, only limited efforts have been made to control SO_2 and NOx emissions, although the situation is gradually changing and in some cases, new legislation is in the pipeline. Indian coal-fired power plants are responsible for a high proportion of the country's SO_2 emissions, although the low sulphur content of Indian coals means that this is not generally considered a major issue. SO_2 abatement measures are generally limited to the provision of stacks of minimum height to ensure adequate local dispersion. At present, there do not appear to be any proposals for the introduction of more effective SO_2 control measures or more stringent legislation. Only one Indian power plant currently deploys FGD and a second one is being similarly equipped; both use seawater-based FGD systems. Similarly, Indian coal-fired power plants do not face any NOx emission limits and only a small number currently employ any form of NOx control technology; where used, these comprise overfire air systems and low NOx burners.

Historically, South African power plants were not designed with SO_2 control in mind. However, in 2004, a new Air Quality Act was introduced covering ambient levels of SO_2, NOx and particulates. The quantities of SO_2, NOx and CO_2 emitted from Eskom power stations are now calculated annually, based on coal characteristics and the power station design parameters. There is EU-type emissions legislation in the pipeline. The country is engaged in the process of further revising ambient air quality limits and is undertaking legislative reform (via the National Environmental Management: Air Quality Act – NEMAQA). This new legislation means that in future, plants will need to improve their environmental performance; the country's first FGD plant will be built at Eskom's new 4749 MW coal-fired Bravo station. Also, to date, only limited application of low NOx burners has been made. However, new stations will be suitably equipped, and some older stations such as Grootvlei are also being revamped with low NOx burners.

2.2 Fluidised bed combustion

Although PCC technology dominates power production in both OECD and non-OECD countries, there are also several other combustion systems in use for steam turbine generator and heat production plants. The most important of these commercially is atmospheric pressure circulating fluidised bed combustion, which is well-suited to low calorific value fuels, and uses direct addition of limestone to the combustion

Figure 12 Lagisza 460 MWe supercritical CFB power plant in Poland (courtesy Foster Wheeler)

system rather than downstream flue gas treatment to control SO_2 emissions. Further treatment can be used to reduce SO_2 to extremely low levels. Combustion takes place in a highly mobile bed, consisting mainly of ash, at more moderate temperatures than in PCC systems. Emissions of NOx are intrinsically quite low, even when SCR is not used.

Since the early 1990s, CFBC has been increasing in both size and steam conditions and numerous plants have now been built in the 200–400 MW range. The technology has reached the maturity and scale for supercritical designs to be offered. The first, a 460 MWe electricity generating unit at Lagisza in Poland (Figure 12), commenced operation in July 2009, and a second smaller project is being developed in Russia. Commercial designs for larger supercritical units have been produced by the major suppliers.

Both bubbling and circulating fluidised bed combustion systems are in use in China and India, although currently, not in South Africa. Some plants generate power or operate as cogeneration units, whereas others produce process steam or heat, often for industrial and commercial applications.

CFBC technology is widely used in China, and the number of plants continues to grow. The country has the largest number and greatest installed capacity of CFB boilers in the world. At the end of 2007, there were >2600 FBC units (total capacity 40 GW) in use. Most Chinese FBC technologies combine locally-developed and imported subcritical systems, often provided by via collaborative ventures with overseas technology suppliers such as Alstom. Technology development continues within China, with the aims of increasing efficiency and unit capacity. Part of the ongoing Chinese 863 Programme is developing a 600 MW SC CFB boiler, being built at the Baima power plant site (Mao, 2008). This will be anthracite-fired and use steam conditions of 25.4 MPa/571±5°C/569^{o}C±5°C. Concept designs have been completed and construction was due to start late 2008 (Mao, 2008).

In India, there are numerous small bubbling bed systems in operation, some of which are used for power generation purposes. There are also ~20 CFBC plants in use, the largest of which is 125 MWe. In both cases, many operate as captive power plants, providing electricity to industrial concerns that often lack reliable grid supply. Most units are less than 100 MW (Mills, 2007).

In South Africa, Eskom has investigated the use of CFBC for repowering one of its existing coal-fired power plants. This is not currently being pursued (van der Riet, 2007), although forecasts suggest that fluidised bed boilers could become viable by 2025. There are currently proposals by IPPs for the development of several CFB-based power and cogeneration projects and a number of feasibility studies have been undertaken. Some could be fired on coal discards. Several CFB-based projects have been proposed. For instance, Independent Power South Africa is proposing a coastal location for a 1000 MW CFBC power station. A second proposed plant of 540 MW could be operational by 2012.

2.3 Integrated gasification combined cycles (IGCC)

IGCC is not yet widely employed for coal-fired power generation but offers potential advantages over combustion systems. There are commercial demonstration plants operating in the USA, Europe and Japan and other plants are under construction in the USA, China and India. IGCC uses coal gasification, usually using oxygen in the presence of water or steam, to convert coal into a gaseous fuel that is cleaned while at pressure before it is fired in a combined cycle gas turbine. Gas cleaning consists of particulate removal, then cold gas scrubbing to take out NOx precursors and sulphur compounds. IGCC has very low emissions. Developments in gas turbines, together with other system improvements, will enable efficiencies without CO_2 capture to be raised beyond 50% (net, LHV) and give reductions in capital cost. New oxygen production technology is also being developed to further improve efficiency and costs.

As with CFBC, IGCC developments are under way in both China and India, but not South Africa. In China, there have been ambitious proposals for up to 12 coal-fuelled IGCC projects, of which two are making progress. The first is the GreenGen project in Tianjin, where a 250 MW demonstration plant is scheduled to be completed by the end of 2011. The second project is the 230 MW Huadian Banshan power plant project in Zhejiang Province, using the Chinese-developed opposed multi-burner (OMB) gasifier, with planned start-up in 2010.There are also a large number of coal gasifiers of various designs in China, although these are deployed mainly for the production of chemical feedstocks and SNG.

In India, the country’s first major coal-fuelled IGCC plant is being built in Andhra Pradesh by BHEL and APGenco. This 125 MW National Commercial Demonstration Project is using BHEL air-blown PFB gasification technology. A smaller lignite-fired IGCC plant using IGT/Enviropower gasification technology has also been operating for several years at a cement plant. Late in 2009, NTPC also announced plans for a 100 MW IGCC project to be fuelled on Indian coals. During Phase I of the project, NTPC plans to procure and develop fluidised bed gasification and gas cleanup technologies. In Phase II, a combined cycle system will be installed and integrated with the gasifier and other plant systems. Contracts for the project are expected to be awarded during the latter part of 2010. Reliance Energy also has plans for an IGCC plant to be operational in Jamnagar City in Gujarat by 2012. This will be fuelled on petcoke blended with 5% lignite. Around 80% of the syngas produced will be used for power generation.

In South Africa, Eskom is currently investigating the possibility of using underground coal gasification to cofire the existing Majuba power station; potentially, up to a third of its coal requirement could be replaced. In the longer term, UCG could feed a combined cycle plant. Sasol is also setting up a UCG demonstration project near Secunda to investigate accessing unmineable coal (gas to be used for power or liquids production). Twenty-seven other sites with the potential for using UCG technology are also being investigated.

2.4 National activities on CO_2 capture and storage

Technologies for CO_2 capture from combustion plant can be grouped into two main categories. The first involves using gas separation systems to remove the CO_2 from the flue gas stream of a relatively conventional combustion plant. The second, more radical, method uses a partially recycled flue gas/oxygen mixture for combustion of the coal, with off-take of CO_2 for storage after condensate removal ('oxyfuel' or 'oxy-coal' combustion).Thus, CO_2 capture systems may include chemical solvent scrubbing, oxy-coal combustion, and IGCC with carbon capture (shift reaction followed by pressure swing adsorption, electrical swing adsorption, gas separation membranes, or cryogenics). Most of these are being targeted mainly for application to power plants. However, other coal-fired industrial sectors also produce significant amounts of CO_2. For instance, 2 Gt of CO_2 is emitted annually by the global iron and steel industry (APP, 2007) and 1.8 Gt by the cement manufacturing sector. Although major applications of coal-to-liquids technology are currently limited to a few countries, CO_2 production from individual plants can be considerable, much higher than from conventional crude oil-to-liquids production. The technology will clearly need to incorporate CCS if it is to be acceptable. However, one of the effluent streams from a CTL plant is essentially a concentrated stream of CO_2 that would simply require compression and drying before transport to geological storage (NETL, 2009).

Compared to the OECD, the situation with CO_2 capture on steam plants and for industry is less advanced in China, India and South Africa as it is viewed as less urgent than increasing electricity supply and raising generation efficiency. However, although CCS-related activities are generally more limited in scale and scope, carbon capture is being considered in all three. China is the most advanced in this respect, and a number of initiatives are being developed. Several major Chinese R&D programmes are engaged in CCS-related

Table 7 Application of CCS in China

Project developers	Location	Technology	Fuel	CO_2 capture	Comment/status
Post-combustion capture					
CSIRO, Huaneng Group, TPRI	Huaneng Beijing Gaobeidian Cogen Plant	Amine scrubber	Coal	3000 t/y capture from sidestream	Pilot project launched in 2008. Larger (45 MWe) plant in the design phase
Huaneng Group	Shi-Dong-Kou power plant, North Shanghai	Amine scrubber	Coal	100,000 t/y CO_2 capture	Scale-up of Gaobeidian technology. May also include CO_2 storage trial
IGCC + CCS					
GreenGen Ltd Co	LiGang Industrial Park, Tianjin	Oxygen-blown, entrained flow gasification	Coal	Stage I – no CCS. Sidestream CO_2 capture starting at Stage II. Full scale CO_2 capture at Stage III	Stage I – 250 MW (2005-10). Plant construction began in 2009. Completion by 2010. Stage II – 400 MW (2010-15) to incorporate CCS by 2013. Stage III – 400 MW (2015-20) operational by 2017
Coal-to-liquids					
Shenua Group Corporation Ltd DCL project	Erdos City, Inner Mongolia	Direct liquefaction	Coal	~3.6 Mt/y CO_2 produced at Phase II. CCS option studies under way	Phase II completion in 2010 (three reactor trains). Over 6 Mt/y liquid products output

activities. There are also several pilot plants operating or planned (Table 7).

In India, apart from more general measures (such as reducing the impact of transport and increasing the use of renewable energies) most CCS-related activities are currently focused on the coal-fired power sector. Primarily, these are measures to improve the performance of the existing generating fleet and to install newer units of greater efficiency. Other CCS-related activities may be undertaken in the longer term (Mills, 2007). The government Planning Commission's *Integrated Energy Policy* (2006) notes that CCS will become crucial in the future (Stockwell, 2008). However, at present, there appears to be little government support for the application of CCS technologies in the country (Bloomberg, 2009). Focus remains firmly on meeting growing electricity demand.

Although the country is a member of the CSLF, to date, carbon capture and storage activities have been limited in South Africa. However, new initiatives are being put in place to address the county's CO_2 emissions of >400 Mt/y (the country is the 11th biggest global CO_2 emitter). Around 60% of this total is regarded as amenable to capture; most stems from power generation, industrial processes such as Sasol's CTL facilities (Figure 13), and general manufacturing. Some 85% of the large point sources of CO_2 considered suitable for carbon capture are owned by Eskom and Sasol. A Centre of Carbon Capture & Storage has recently been created within the South African National Energy Research Institute (SANERI). A detailed study is under way (2008-11) examining the potential for geological storage of CO_2. The South African Department of Environmental Affairs and Tourism's long-term mitigation scenario is to capture and store 5% of the country's carbon emissions. Preliminary studies suggest that the country has an available storage capacity of 100 Gt. There is a plan to implement a CO_2 injection experiment by 2016 and to develop a commercial CCS demonstration plant by 2020 (SANERI, 2009). Eskom, South Africa's major generator, aims to reduce its total carbon emissions by 2050 although levels are likely to rise in the mid term as new coal-fired capacity comes on line. In 2008, Eskom emitted 224 Mt of CO_2.

2.5 Technology transfer/knowledge sharing

Technology transfer has already played a major role in China and is playing an increasingly important one in India. Joint venture companies formed between international technology suppliers and local manufacturers have been important. As a result, since 2000, the majority of boilers and allied equipment for Chinese coal-fired power plants have been produced by Chinese manufacturers, with technical support from foreign partners who manufacture key components (such as parts for SC/USC systems). All of the major international power plant equipment suppliers have entered into some form of commercial alliance with Chinese manufacturers so that this can happen. Most now have manufacturing capacity within the country (Mills, 2008). Increasingly, there has been a tendency for such ventures to look beyond their respective local markets and to target those further afield.

Similarly, but on a smaller scale, Indian manufacturers are now entering into commercial alliances or joint ventures with major overseas technology providers. The growing market for SC PCC plants has so far been the main focus, although there is also increasing activity in the areas of fluidised bed boilers

Figure 13 Part of Sasol's Secunda CTL plant (courtesy World Petroleum Congress)

and gas and steam turbines. In South Africa, the two new SC PCC projects are currently being developed in conjunction with major overseas technology suppliers that include Alstom and Hitachi.

Recent years have seen increasing international collaboration with overseas development programmes and technology developers. China, India and South Africa are all engaged in various collaborative research, development and dissemination activities. For instance, China is actively engaged in a range of clean coal/CCS collaborative activities with the USA, Australia, and the European Union.

3 Iron and steel industry

Globally, nearly 600 Mt/y of coal are used by the iron and steel sector (World Steel Association, 2008b). Coal is important for iron and steel production in all three countries. In particular, in China and India, its use has increased dramatically over the past 10–20 years. In 2007, China's energy consumption was 186.1 Mtce for iron and steel production, India's was 26.0 Mtce, and South Africa's was 5.3 Mtce (IEA/OECD, 2009). In South Africa, coal consumption has remained essentially flat since the mid 1990s.

In 1996, OECD countries accounted for 60.6% of global steel production, although by 2006, this had fallen to 43.2%. Given additional planned capacity increases in China, India, Brazil and elsewhere, it is likely that the OECD share of world production will fall below 40% in the near future (Schultz, 2006). Between 1995 and 2005, China and India's steel production rates increased by nearly 14%/y and 5.6%/y, respectively. The Chinese industry is now the biggest in the world, in 2008 producing more than a third of global steel (Figure 14), and accounting for 15–16% of Chinese coal consumption. In the same year, India's steel output was 55.1 Mt. By 2011, production is expected to exceed 70 Mt/y, and India is forecast to become the world's second largest steel producer by 2016. South Africa ranks around 20th in the world in steel production.

3.1 National iron and steel sector makeup

Iron and steel production in China has expanded rapidly during the past decade, and between 1996 and 2006, output nearly tripled (Figure 15). The Chinese industry is now the biggest in world, in 2007, producing more than a third of global steel output. The sector is the second largest coal consumer after power generation. Significant new capacity has been added in recent years. However, the sector is now viewed as having over-capacity and central government is gradually closing down outdated inefficient units in line with the New Steel Policy issued in July 2005 (Zhu, 2008). The Chinese industry relies on imports for much of its iron ore, coke and scrap iron. In recent years, in order to stabilise costs, major industry players have made heavy investments in order to secure overseas supplies of raw materials.

Despite its size, the Chinese industry is fragmented, characterised by a handful of major producers, with numerous small- and medium-sized mills scattered throughout the country. In 2006, of China's output of 423 Mt, only 24% was produced by the top five producers combined. In the EU-25 nations, Japan, South Korea, and North America, the average level was ~60% (MacDonald, 2008). In China, until recently, three quarters of steel production was controlled by more than 40 individual mills. In contrast, a handful of companies dominate Europe, North America, Japan and South Korea, allowing them to control output and support prices. In Japan, six mills control 81% of the iron and steel industry (Yunyun,

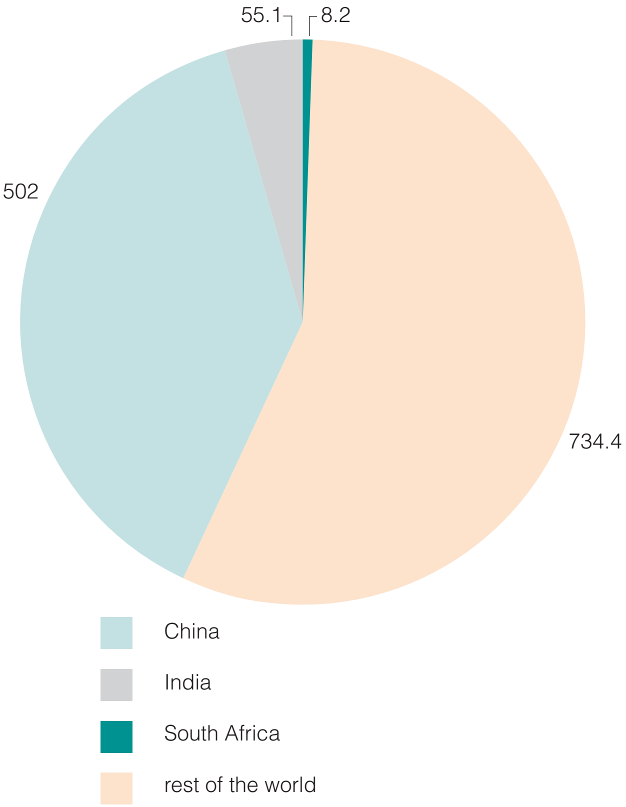

Figure 14 World steel production in 2008

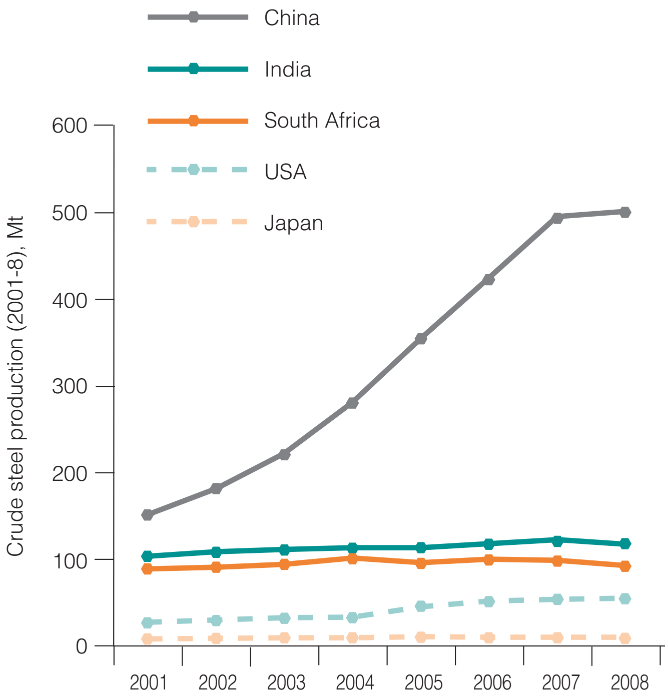

Figure 15 Crude steel production for selected countries (2001-08)

2008). However, as elsewhere, strategic consolidation is now taking place in China. Five of the largest mills in Europe now have an average capacity in excess of 20 Mt/y; Japan's Nippon Steel, the world's largest, has a capacity of 30 Mt/y. Several of the new Chinese conglomerates now approach these levels.

Since independence, India has experienced steady growth in the sector, annual steel output increasing from 14 Mt in 1992, to 58.6 Mt in 2008. The country has experienced a much higher production growth rate than many others. By 2011, steel production is expected to exceed 70 Mt/y and India is forecast to become the world's second largest steel producer by 2016. The industry is made up of a range of producers, varying considerably in size. The largest comprise large capacity integrated steel makers such as Tata Steel, SAIL, RINL, ESSAR, ISPAT and JVSL. Large integrated plants operate mainly in West Bengal, Chhattisgarh, Jharkhand and Orissa, the biggest with production capacities of 1–5 Mt/y. In 2007, these produced >75% of India's annual crude steel output of 58 Mt/y. There are also a large number of DRI (sponge iron) producers that use iron ore and non-coking coal to provide feedstock for steel producers. In addition, there are numerous mini blast furnaces, EAFs, induction furnaces and energy optimising furnaces in operation. India's share of global crude steel output is forecast to rise to just under 4% during the next decade (Perlitz, 2007). But, despite its impressive rise in recent years, parts of the sector remain constrained by a variety of factors that include limited investment in infrastructure, energy supply issues and electricity shortages, transport bottlenecks, and insufficient supplies of raw materials.

In terms of steel production, South Africa ranks around 20th in the world. The country produces ~0.8% of total global crude steel, but accounts for >50% of total African production. The iron and steel sector is responsible for ~4% of the country's annual domestic coal consumption. The biggest individual player is ArcelorMittal Steel South Africa, the continent's largest steel producer; the company operates from four major sites (Table 8). Here, as elsewhere, it is not uncommon to find different steel making technologies operated by the same manufacturer, sometimes on the same site. In 2007, South Africa as a whole produced ~9.37 Mt crude steel, of which, some 8.6 Mt was produced by ArcelorMittal.

3.2 Technologies used

3.2.1 Blast furnaces

Blast furnaces are used to for the production of more than 90% of world iron (APP, 2007) and, hence, indirectly, for the greatest proportion of steel. A blast furnace is a tall, refractory-lined vessel that is charged at intervals with iron ore (as lump, sinter, pellets or briquettes), coke and a fluxing agent (usually limestone) (Figure 16). Heat for the process comes from the combustion of the coke using hot air that is passed upwards through the bed. The CO_2 initially produced is reduced to carbon monoxide (CO) within the furnace, and the latter is the reducing agent that strips the oxygen from the ore. Liquid pig iron is tapped from the bottom of the furnace, and the off-gases consist mostly of a mixture of CO_2, CO and nitrogen. Of the 2 Gt of CO_2 that are emitted by the iron and steel industry globally (APP, 2007), 75% is released from blast furnaces (IEA, 2008).

Globally, some 65.5% of steel is produced via the blast furnace-BOF route, with much of the balance coming from electric arc furnaces (EAF). In the EU-25 nations, 59.5% comes from BOF plants and 40.5% from EAFs (Zhu, 2008). China has the highest dependence on blast furnace-BOF systems (87% of production) and the lowest on EAF (Figure 17). In some locations, greater adoption of the latter has been hampered by a shortage of electricity. There are currently ~800 companies operating blast furnaces, many of which have been built in recent years. Since 2004, the construction of smaller, less efficient units has been prohibited and all units less than 300 m^3 will be closed by 2010 (Zhu, 2008). Some of this lost capacity may eventually be replaced with more advanced processes such as Hismelt and Corex.

In 2007, Indian steel output consisted of 28 Mt from blast

Table 8 ArcelorMittal Steel South Africa production sites

Site	Major facilities	Comments
Vereeniging	Direct reduction plant, EAF	Vereeniging and Newcastle produce a total of 1.9 Mt/y rolled and forged steel products
Newcastle	Two coke oven batteries, Sinter plant, Blast furnace, BOF	Long steel production
Vanderbijlpark	Six coke oven batteries, two blast furnaces, Direct reduction plant (four kilns), three EAFs, three BOFs	Flat steel production. Produces 3.5 Mt/y liquid steel (84% of South Africa's requirements)
Saldanha	Corex furnace, Corex gas-based Direct reduction plant, Twin-shell Conarc process	Produces 1.2 Mt/y liquid steel. Only steel mill in the world using combined Corex/Midrex process for continuous casting chain – eliminates coke ovens and blast furnaces

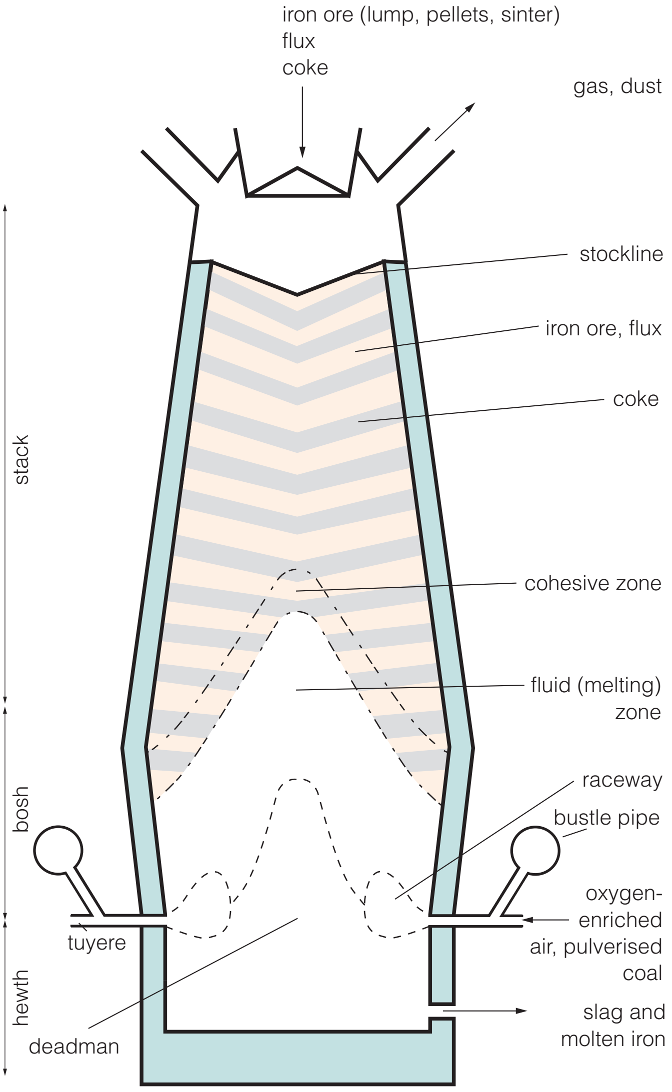

Figure 16 Section of a blast furnace (Carpenter, 2006)

furnace-BOF facilities, 24 Mt from other coal-based technologies, and 5.3 Mt from gas-fired units (Sreenivasamurthy, 2008). Blast furnaces are responsible for more than 45% of the country's output. However, there are significant differences between producers. For instance, SAIL currently produces ~70% of its steel using blast furnace technology, a level that is expected to increase to 80% once ongoing modernisation efforts have been completed. Blast furnace technologies are expected to maintain a significant role in India, despite the shortage of domestic metallurgical coal. As in China, there has been a trend towards the introduction of larger units. Eight large integrated blast furnace plants now produce >75% of India's crude steel. There are also around 40 medium-capacity units in operation; 25 are operated by SAIL and 7 by Tata Steel. In March 2009, India's largest individual blast furnace (capacity 2.8 Mt/y) came on line at JSW Steel. This advanced unit incorporates a Siemens two-stage cyclone-based separator to clean top gas which is this is then used for on-site heating.

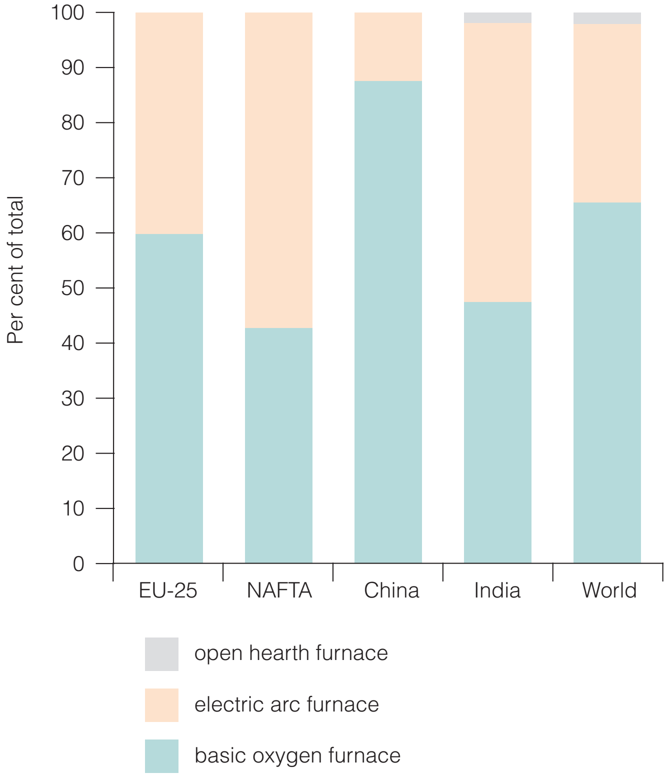

Figure 17 Steelmaking technologies deployed in 2006

The blast furnace also dominates in South Africa, although there is also some use of EAFs and rotary kiln (sponge iron) based processes. ArcelorMittal's Saldanha facility operates advanced processes based on Conarc and Corex technology. The plants at Vereeniging (DRI and EAF) and Newcastle (blast furnace-BOF) produce a total of 1.9 Mt/y. Vanderbijlpark (DRI, EAF and blast furnace-BOF) produces 3.5 Mt/y. The country's second largest producer (Highveld Steel & Vanadium) operates a combination of blast furnaces, EAFs and a rotary kiln-based system.

3.2.2 Direct reduced iron (DRI) production

There are a number of other systems for iron production, the most significant of which is direct reduction using a reducing gas. The iron is produced in solid form and known as direct reduced iron (DRI). The input fuel for producing the reducing gas is most commonly natural gas, but coal is also used. Sponge iron is a term sometimes applied to DRI, especially when it is produced using solid carbonaceous reductants such as charcoal, coke or coal. Iron from blast furnaces is converted to steel usually in basic oxygen furnaces.

In India, the scarcity of good quality coking coal has resulted in greater use of processes based on non-coking coals. These are being used increasingly in rotary kiln sponge iron making processes. The sponge iron produced is fed to both blast furnaces and EAFs. A high proportion of Indian sponge iron plants are coal-fired, with gas-fired production confined to some in the Western region. More than 200 sponge iron plants (with a total capacity of 19 Mt/y) are now in operation, many built since 2002. Individual capacities range from 0.03 to 0.3 Mt/y (Sreenivasamurthy, 2008). Additional units with a combined capacity of ~6 Mt/y are also under construction. India is now the world's largest producer of sponge iron. At present, steel demand consumes all output from both blast furnaces and sponge iron units, hence they are not yet in direct competition with one another. Coal-fired sponge iron plants can emit high levels of dust. Although technologies are available for their control (dedusting systems, ESPs and chemical sprays), because of cost implications, they are not universally applied, especially by smaller producers. They are used more widely at larger plants, some of which also employ heat recovery systems to raise steam for power generation purposes. Sponge iron is also produced in South Africa, although at a much lower level than in India.

Potentially, the efficiency of manufacture of sponge iron could be improved and pollution levels decreased by collection of the off-gases and utilisation of their energy content to preheat the incoming raw iron ore. Gases could subsequently be cleaned prior to release to atmosphere. Coal consumption per tonne of iron would be reduced, leading particularly to lower particulate and CO_2 emissions.

3.2.3 Electric Arc Furnace (EAF)

The other main route to steel is via the electric arc furnace (EAF), which usually uses scrap steel, together with a proportion of DRI, pig or sponge iron as raw materials. If scrap is available, the EAF method is more cost-effective and consumes fewer raw materials than the traditional blast furnace-BOF system. Globally, >34% of steel is produced in EAFs although the degree of application varies widely between countries. The use of the EAF is increasing in China, although only ~13% of the country's steel is currently produced in this way, the lowest for any major steel-producing nation. India has nearly 200 EAFs in operation, with a combined capacity of >12 Mt/y. However, the highest level of deployment is in the NAFTA countries (USA, Canada and Mexico) where 57.3% is produced by this means (Zhu, 2008).

3.2.4 Other steel making technologies

Open hearth techniques

Open hearth furnaces are a type of furnace where excess carbon and other impurities are burned out of pig iron to produce steel. Pig iron, limestone and iron ore are heated in the furnace to ~870°C. The limestone and ore form a slag that floats to the surface. Impurities, including carbon, are oxidised and transfer to the slag. The process is continued until the appropriate carbon content has been achieved. There are a number of variants of the technology, although globally, its use is declining. Most units had been closed by the early 1990s, not least because of their fuel inefficiency, being replaced by the BOF or EAF. In the USA, the last open hearth furnace closed in 1992, although the technology is still used in a few places such as the Ukraine. In India, nearly 6% of crude steel is still produced using the open-hearth process. This compares with the EU 25 level of only 0.3% (Perlitz, 2007). SAIL's corporate plan up to 2012 contains a variety of measures aimed at modernising its plant and processes; this includes the closure its remaining open-hearth facilities.

Advanced steel making systems

There are a number of potential alternative processes for producing iron and steel more efficiently. An example is the Finex iron-making process, introduced commercially in South Korea in 2007. However, higher costs have limited its application. Another example is ISARNA bath-smelting technology. This combines coal preheating and partial pyrolysis in a reactor, a melting cyclone for ore melting, and a smelter vessel for final ore reduction and iron production. Coal use is significantly reduced, and there is also potential for partial substitution by biomass. A 65 kt/y pilot plant is scheduled to become operational during 2009.

In South Africa, ArcelorMittal's Saldanha facility operates a unique advanced process based on Conarc technology. The process combines a converter and an EAF. This twin-shell unit mimics the geometry of a BOF vessel and is specially adapted to handle the large volumes of gas formed when using a carbon-rich feed. The plant also operates the Corex process. Essentially, this comprises a set of coke ovens and blast furnaces combined in one unit. The process uses lump ore and pellets to produce waste-free molten pig iron. Non-coking coal is used as reductant.

Use of biomass in iron and steelmaking is being developed in Australia by CSIRO and industry as a means of reducing net CO_2 emissions. Charcoal has been found to be as effective as high rank coals for the bath smelting of iron ore, and wood char has been shown to be a suitable replacement for coke breeze (APP, 2007).

3.3 Coke production

Coke is of vital importance to blast furnace operations and large quantities are produced in many parts of the world. It is produced by carbonisation of coal in coke ovens, a process which also leads to CO_2 emissions. Coke ovens may be recovery ovens (usually slot ovens), that collect hot gas for use in the plant in order to achieve energy savings, or non-recovery ovens (beehive-type ovens). The latter have lower costs but are less energy-efficient and more polluting. Within the OECD countries, slot-type ovens produce >90% of coke (Figure 18). In Japan and South Korea, there is 100% recovery, in the EU 15 it is 90%, in the USA, 60%, in China, 70% (METI, 2007). In general, slot ovens represent a mature technology, although there are a number of design and operational limitations. However, with the correct blend of coals and application of suitable operating practices, such units can consistently produce high quality coke, hence their continuing deployment in most major steel-producing countries. Japan and Germany have some of the world's most efficient plants. In 2008, OECD nations consumed 173.7 Mt of coke (IEA/OECD, 2008).

China is the world's biggest coke producer (60% of world total in 2008). In 2004, there were >1600 state-owned coke ovens with a combined capacity in excess of 165 Mt/y. Most are conventional slot oven batteries although beehive ovens still produce 20% of coke. In 2004, there were a further

Figure 18 UK coke-making operations

183 slot ovens under construction, with a combined capacity of 68 Mt/y (China Daily, 2004). There are still a significant number of older, smaller capacity units that require replacement. The current Chinese Five Year Plan notes the importance of adopting improved coke making technology. In 2008, Chinese coking coal consumption was 433 Mt. Some 10.3 Mt of this was imported (IEA/OECD, 2009).

Historically, the overall technological level of coke-making equipment in China (in terms of environmental protection and energy efficiency) has lagged behind that of the OECD (Minchener, 2004) although recent moves towards newer larger-capacity batteries and the adoption of Western operating practices is seeing this gap reduce. There can be significant differences in performance between some plants. However, the newest Chinese installations are performing at levels close or equal to many OECD units (UNEP, 2008).

In India, conventional by-product recovery coke ovens account for ~85% of coke production, the balance coming from non-energy recovery plants. Most Indian coke oven batteries are located in the eastern region of the country. As a result, coke consumers in the western and southern regions rely heavily on imports. In 2006-07, total estimated Indian coke demand was 25 Mt, much of this produced from imported coals. Annual imports have increased steadily for some years and in 2008, nearly 29 Mt of coking coal was imported (IEA/OECD, 2009).

Indian coke is produced in three ways:

- in captive coke ovens forming part of large integrated steel plants (such as those of Tata Steel, SAIL, and Jindal – there are currently ten such plants in operation, with a combined capacity of 4 Mt/y);
- in coke ovens in the public sector;
- in privately-owned facilities.

The average age of Indian coke-producing capacity, at 20 years, is below the global average (26 years) and that of Japan (35 years), the USA (31 years), and South Korea (22 years) (RAG, 2003). However, in India, there can be significant differences between individual plant performances. At some sites, improvements in production are being made through the introduction of stamp charging and dry quenching (*see below*) (Schultz, 2006). There is ongoing expansion in the sector, and the country's largest facility (the Hooghly Met Coke plant) is currently being commissioned. Once fully operational, this will be the largest stand-alone coke plant in India, and one of the largest in the world. It is using energy recovery coke ovens, designed to meet stringent environmental norms. Waste heat produced in the process will be used to generate electricity for the plant (20 MW) and the Grid (>100 MW).

In South Africa, the main producer (ArcelorMittal) operates several major coke oven batteries (with a combined output of >870 kt/y) at Newcastle, Pretoria, and Vanderbijlpark. The newest, commissioned in 2006, is a 450 kt/y state-of-the-art facility that reportedly conforms to the highest global environmental standards. In 2006, the country produced 1.84 Mt of coke in coke ovens. However, significant quantities of coke and coking coal continue to be imported. ArcelorMittal imports more than 60% of its coking coal requirements.

There are a number of ways in which coke production, potentially, can be improved. Important techniques include:

- **Coke dry quenching (CDQ) and coke stabilisation quenching (CSQ)**
  In CDQ, hot coke is cooled using inert gases rather than water. This improves coke quality, reducing energy demand in the blast furnace, and allows up to 80% of the sensible heat to be recovered. Coke consumption in the blast furnace is reduced by ~2%, saving 0.6 GJ/t of coke (Schultz, 2006). In Japan, more than 90% of coke is produced using CDQ technology and ~70% in South Korea. The Chinese level is ~ 25%. Levels are somewhat lower in the EU 15 and the USA (METI, 2007). CSQ technology (which brings the coke into contact with water from both above and below) has so far only been used in Germany.
- **Coke oven stamp charging**
  This technique, whereby the bulk density of the oven charge is increased by about a third via mechanical means, is used widely in Europe and elsewhere. The technique increases plant throughput, improves coke properties, and allows a portion of the coal to be replaced with inferior coking coal, coal fines, or petcoke, thus reducing costs. It is applied in some Chinese coke plants. China's largest stamp charged unit (at 2.2 Mt/y), also the third largest in the world, started up in 2007 at the Tangshan Jiahua Coal Chemical Processing Company site. Several major Indian producers (such as Tisco and Gujarat NRE Coke) also employ stamp charging. The latter uses imported Chinese technology. As part of its ongoing modernisation process, Tata Steel has adopted stamp charging and has built a Coke Dry Quenching facility (Prasad, 2007).
- **Coke oven gas recovery**
  Energy savings can be accrued by the recovery and use of gas from coke oven operations. In Japan and South Korea, there is 100% recovery, whereas in the EU 15 it is 90%, and the USA, 60%. China, at 70%, is ahead of the latter in this respect (METI, 2007).

3.4 Efficiency improvements to the steel making process

On the whole, steel industry efficiencies amongst OECD countries are now fairly similar (UNEP, 2008). Steel industry efficiencies of China and India fall some way behind most OECD countries (Figure 19). However, it is not uncommon anywhere to find facilities operating at best practice levels deployed alongside outdated systems.

Chinese average energy efficiency is lower due to the high proportion of small-capacity blast furnaces, the limited use of residual gases, and the use of low-quality iron ore and coke. However, the efficiency of newer Chinese blast furnace-based facilities is now on a par with the best producers elsewhere in the world. The Chinese Government has set a goal to reduce energy use and since 2000, particularly for larger producers, there has been a considerable reduction. This position should improve further as more outdated facilities are closed. The amount of coal consumed per tonne of steel produced has fallen from an average of ~930 kg in 2000, to 632 kg in 2007. Electricity demand has also been reduced. However, even though their numbers are decreasing (the Chinese government is in the process of closing all furnaces below 100 m^3 volume and those with a capacity of less than 20 tonnes. All units less than 300 m^3 will be closed by 2010 (Zhu, 2008) – many older units continue to operate with relatively low blast temperatures, high slag rates, and low top pressure. Because of this, their average coke requirement remains higher than that of operations elsewhere (Okuno, 2006). Generally, OECD units are more energy efficient and less polluting than many of their Chinese counterparts. However, the gap is shrinking, especially as smaller less efficient units are progressively closed.

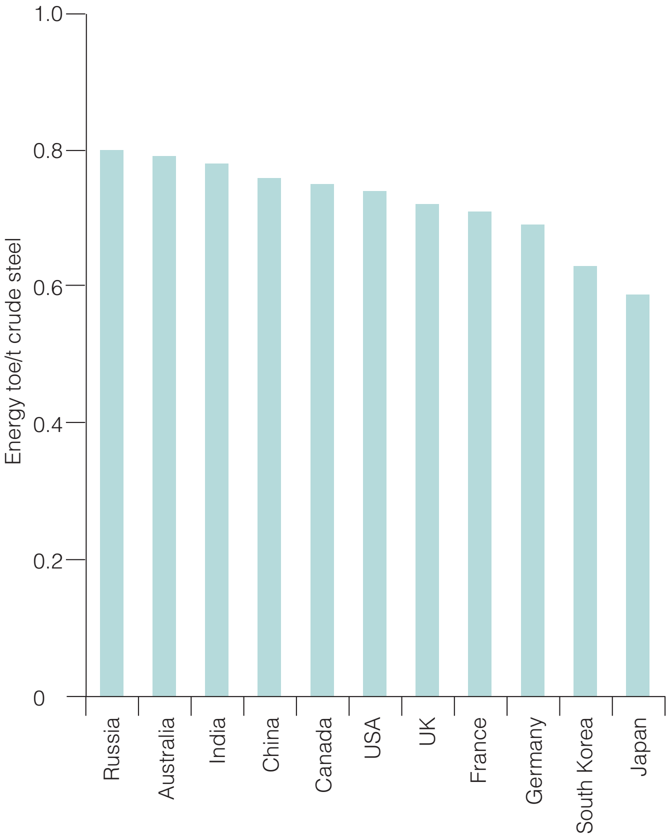

Figure 19 Energy requirements for steel production in selected countries (UNEP, 2008)

As elsewhere, the Indian iron and steel sector is an energy-intensive one, consuming annually ~10% of the country's total electricity and 27% of its industrial coal. Although, overall, energy requirements per tonne of steel have been decreasing and newer plants operate at efficiency comparable with world best, some still consume 44–64% more energy than equivalents elsewhere (Sreenivasamurthy, 2008). Many Indian producers are small – this limits the viability of adopting newer technologies and encourages the use of cheaper, less efficient systems. The technological performance of many Indian plants falls below existing international standards and the sector accounts for nearly 10% of the country's CO_2 emissions. Its energy efficiency and CO_2 emission intensity levels significantly exceed the OECD averages for primary steel making. Examples of energy requirements for different processes are given in Table 9. On average, Indian steel plants emit 2.5–3.0 tCO_2/t of steel produced compared to a world average of <2. There is a huge potential for improving energy consumption and reducing CO_2 emissions.

There are a number of techniques that can be applied to steel making systems to improve their performance or reduce their environmental impact. These include:

- **Pulverised coal injection (PCI) into blast furnaces**
  Since the 1960s, PCI has been deployed increasingly in global steel making. Instead of relying wholly on the use of coke, pulverised non-coking coal is fed into the blast furnace via tuyeres. Thus, cheaper coals can be used to replace a portion of the coking coal, reducing costs and energy requirements. There has been a general upward trend in PCI consumption for some years in most OECD nations. However, the largest consumer of PCI coal is now China which used >14 Mt in 2002 (Carpenter, 2006). Globally, PCI injection rates of 50–200 kg/thm are now possible. In China, specific PCI targets have been set, and some of the best Chinese facilities are now achieving world best practice levels.

Table 9 Comparison of specific energy requirements (Sreenivasamurthy, 2008)

Technology	Energy requirement, GJ/t crude steel
OECD – blast furnace-BOF	20
India – blast furnace-BOF	27.7
India – DRI-EF with waste heat recovery for power generation	30
India – DRI-EF with Grid power import	31
OECD – EAF scrap melting	1.5
India – EAF scrap melting	3

PCI use has also increased in India; annually, since 1998, the country has used between 2.1 and 2.4 Mt/y (IEA/OECD, 2009), being deployed by all major producers (Carpenter, 2006). India is the world's fifth biggest PCI user, behind France, Germany, Japan and South Korea. Asia in general is a major consumer of PCI coals and the extent of its use is expected to increase further. In South Africa, one large blast furnace has so far been equipped with PCI. PCI capability is nearly always fitted to new blast furnaces and is adopted as standard practice in Japan and South Korea, and for most full sized furnaces in China. Most Western European furnaces are similarly equipped, whilst in North America, just over half of the blast furnaces inject coal.

An alternative to PCI has been developed by NETL in the USA. This is called the Blast Furnace Granulated Coal Injection System (BFGCI) and injects granular coal instead of pulverised coal (the former costs less to produce). The system has been demonstrated in the USA and although blast furnace operating conditions required some adjustment, plant operation proved satisfactory and presented no major problems. The main conclusion from the demonstration was that granular coal injection on a large, modern blast furnace is technically sound and economically viable – coal could replace coke on an almost equal basis (NETL, 2000).

- **Waste energy recovery**
  The adoption of waste energy recovery systems tends to be more prevalent in countries with high energy prices, where the waste heat is recovered for power generation or other applications. There are several routes to energy recovery. One of the most important is the use of Top Pressure Recovery Turbines (TRTs). These utilise blast furnace gas to generate electricity. Typically, this can meet ~20% of plant requirements. TRTs are used widely in some countries; in Japan and South Korea, most units deploy TRTs. However, their degree of application is only ~13% in much of the EU and 5% in the USA. Around 25% of Chinese plants deploy TRTs, although the potential for further increase is considered to be high (METI, 2007).
- **Use of re-generative/recuperative burners**
  These recover heat from combustion gases to preheat the incoming combustion air. Preheating to within 150°C of the furnace chamber temperature is possible and energy efficiency improvements of up to 50% can be achieved. Recuperative burners incorporate a thermal medium to increase system fuel efficiency and increase flame temperatures. They differ from regenerative burners in that they cycle between firing and cooling operations. For the first half of the cycle, half of the burners are firing while the other half are off; the exhaust gas from the first set is fed through the second set, heating the thermal storage media, whilst that in the second set cools. The process then reverses. To date, there has been some deployment of the technology, mainly for application in steel reheating furnaces in some OECD countries.
- **Capture and use of coke oven gas (COG)**
  COG can be recovered and used for energy production. In Japan and South Korea, there is 100% recovery, in the EU it is 90%, and the USA, 60%. In China, less than half of coke-producing plants recover COG, thus there is considerable scope for its greater use (UNEP, 2008).

3.5 Sector environmental performance

Many European steel companies already operate with what are virtually the lowest emissions levels achievable with today's technology. This has been achieved via major technical innovations introduced by the steel industry over the last 25 years. However, depending on the location, type of technology and coal, emissions of SO_2 and particulates can be considerable, although recent years have seen significant improvements in many countries. Usually, newer plants generate lower levels of pollution; unlike smaller production units, it is often economically viable to adopt various emissions reduction techniques. Historically, the Chinese iron and steel sector has been a heavy polluter, although recent years have seen some improvements. Since 2000, significant reductions in pollutant levels have been achieved, particularly at larger plants, although in some locations, emissions of SO_2 and particulates remain high. This situation is expected to improve as outdated smaller facilities, high energy consumers and major sources of pollution, are closed. However, at the moment, there are still a significant number of small and medium-sized steel plants with much poorer technological standards and emissions performance (although this number is reducing).

In India, there are problems associated with the use of coal-fired sponge iron plants that often emit high levels of particulates. Although technologies are available for their control, because of cost, these are not universally applied. They are used by many larger producers, some of whom also employ heat recovery systems to raise steam for power generation.

More recently, the iron and steel industry's CO_2 emissions have become the focus of concern; globally, these are considerable. The greatest potential for CO_2 capture in iron production is in new designs of blast furnace that would use oxy-fuelling with recycle of part of the off-gas to reduce the coke rate. Retrofitting of blast furnaces would also in principle be possible (IPCC, 2005). PCI could be retained to further reduce the coke rate, together with oxygen-blowing. It would still be necessary to use physical solvent scrubbing to separate the CO_2. There are pilot tests at a number of locations (IEA, 2008a). An example is the Ultra Low CO_2 Steelmaking Project (ULCOS II). A pilot project is being set up in Germany during 2010-14, and a demonstration in France during 2011-15. Commercial deployment is expected after 2020.

Capture of the emissions from other parts of the steel-making process (such as basic oxygen furnaces and coke manufacture) appears far less promising as it would be prohibitively expensive (IEA, 2008a). However, technology is already available that allows harvesting of the gas leaving basic oxygen furnaces for heat recovery and utilisation as fuel gas (APP, 2007).

Capture from DRI processes has been identified by the IEA as a low cost CCS option, but scope for total CO_2 savings is limited by its degree of deployment. As in pre-combustion capture in IGCC, the reducing gas would be shift converted to hydrogen and CO_2 and the CO_2 captured. Hydrogen would then be used in the reduction process in place of the reducing gas (IPCC, 2005).

3.6 Technology transfer and knowledge sharing opportunities

Modern steel plants operate at close to the limits of efficiency. Advanced technologies maximise their operating efficiency and minimise CO_2 emissions. Integrated iron and steel mills in most parts of the OECD feed all waste gases produced back into the production process, increasing carbon efficiency, reducing external energy needs and minimising CO_2 emitted. However, this picture is not universal and many steel plants in other parts of the world operate at lower levels of efficiency. Only 39% of the world's steel production is located in countries that are party to the Kyoto Protocol (World Steel Association, 2008a).

Within the industry, technology transfer is viewed as essential in bringing all major steel-producing countries up to best practice standards. The aim is to encourage developing countries to upgrade their steel production sectors, without compromising their efforts to improve social and economic conditions. There are a number of initiatives in play. For instance, there is an ongoing initiative by the Asia Pacific Clean Development and Climate's (APPCDC) Steel Task Force where China, Australia, India, Japan, South Korea, and the USA (representing >50% of world steel production) has formed a partnership to encourage co-operation on the development and transfer of best practice technology with a view to promoting efficiency and reducing CO_2 emissions (Prasad, 2007).

Although there is already some deployment of modern systems and procedures in China, India and South Africa, there remains potential for much greater uptake. Some of the improvements so far made have resulted from overseas technology transfer initiatives, used to replace outdated capacity (Zhu, 2008). In the case of China, the biggest player, the preferred approach has been a mixture of commercial sales agreements with technology developers and vendors, supported by technology transfer initiatives. This will continue to be an important route in improving performance of equipment, operating systems and procedures, as well as helping drive down emissions of pollutants and CO_2 from the sector. Co-operation is also taking place directly between national steel organisations. For instance, the Japanese steel industry is closely involved with technology transfer activities via the China Iron and Steel Association. Steel industries in some developing countries are also active participants in the Clean Development Mechanism. Globally, the promotion of the best available technologies is viewed as crucial for efficient technology diffusion and commercialisation. This will require the continued co-operation, in particular technological co-operation, between steel industries in developed and developing countries

4 Cement manufacturing industry

Nearly half of the world's cement is manufactured in China. In 2005, global cement production grew to 2.284 Gt, with the vast majority of growth taking place in developing economies, especially China. In 2005, China produced 1.06 Gt of cement (47% of the world total). By 2006, output had increased to ~1.2 Gt and in 2008, it reached ~1.3 Gt. Over the past few decades, local and provincial government agencies have played a key role in expanding the cement sector. However, it remains fragmented and lacks strong organisational structure from the centre. China has the largest number of cement plants in the world, estimated at between 8000 and 9000 of various sizes. Typically, in an industrialised nation, there may be 40–50 major producers, with individual capacities of up to 4 Mt/y. Around 570 Chinese suppliers have production capacities of between 275 kt/y and 1 Mt/y and forty have capacities in excess of 1 Mt/y. About half of China's cement plants are located in rural townships (UNEP, 2008).

The cement sector is one of India's core industries. Recent years have seen enormous expansion and the country is now the second largest global producer. Production capacity now exceeds 180 Mt/y, more than 90% in the form of larger manufacturing plants (of 1.2–2.5 Mt/y capacity). There are a total of 140 large and ~365 small cement manufacturing units in the country. Nearly 90 of the larger plants have capacities of >1 Mt/y. By 2010, Indian production is forecast to reach 210 Mt/y. Between 2002 and 2007, the market share of the five largest producers increased from 42% to 56%.

There has been significant investment in new Indian cement plants. The situation is that the sector now encompasses some of the world's least energy efficient plants, but also others based on world best practice. The current ongoing challenge is to modernise or phase out the older, inefficient plants whilst acquiring the best possible technologies (Sathare and others, 2005). Annually, the sector consumes >20 Mt/y of coal, ~4.5% of India's total coal demand. By 2011-12, coal requirement is forecast to increase to 24 Mt/y. However, ongoing shortages of suitable domestic coal have resulted in some companies importing coal, purchasing supplies on the open market, or adopting alternative fuels such as petcoke or lignite (sometimes blended with bituminous coal). Rising coal imports have become a feature of the cement industry in recent years. Captive power plants at cement works consume a further 2 Mt/y of coal. Based on current manufacturing capacity, total sector electricity requirement is ~2.3 GW.

In South Africa, general industrial use accounts for ~8% of the country's annual coal consumption, with the cement and building products industry being the biggest consumers. Recent years have seen the cement industry expand to meet increasing demand. Cement production is currently in excess of 14 Mt/y. This is forecast to increase to 24 Mt/y by 2014. The cement industry comprises four major producers (Pretoria Portland Cement PPC, Holcim South Africa, Lafarge South Africa, and Natal Portland Cement NPC). Through the investment of global cement companies in South Africa, there has been a notable improvement in efficiency and quality control at all cement plants.

4.1 Technologies deployed

Globally, most newer plants use large capacity dry feed rotary kilns with pre-calciners (Figure 20), although the makeup of the sector varies between countries. For example, in the USA, the sector has 65% dry kilns and 33% wet types (58% coal-fired, 13% gas, 28% other fuels), while in Japan only dry kilns are used (94% coal-fired) (Taylor and others, 2006). Similarly, in China, several types of cement kiln are used, around 94% coal fired – mechanised vertical kiln systems (55%) and dry types (43%) dominate. But modernisation is under way. In 1995, the output from NSP kilns (New Suspension Preheater – modern rotary kilns featuring suspension pre-calcining) in China was only 6% of the total, and large-medium scale kilns accounted for only 33% of total output. However, by 2004, output from NSP kilns had increased to ~45%, and the contribution from larger plants had grown to 63% (Yanjia, 2006). By 2010, output from large scale NSP kilns should reach 80%, increasing to 95% by 2030, reducing the contribution from traditional shaft kilns to just 5%. Between 2007 and 2010, China aims to close down 250 Mt of outdated cement producing capacity (mainly vertical kiln units). This will be followed by a second wave of closures (between 2010 and 2012) aimed at closing a further 600 Mt of outdated capacity. This will reduce some of the current overcapacity and help increase overall sector efficiency. More than 200 new cement production lines are currently under construction (with a combined capacity in excess of 200 Mt).

In India, the cement industry uses plants that range from mini to large capacity units (10 to 7500 t/d). Some 94% of production comes from larger plants (>600 t/d output). There are currently >130 large rotary kiln plants in operation with an installed capacity in excess of 184 Mt/y. There are also >350 mini cement plants with a combined capacity of ~11 Mt/y. Currently, around 93% of Indian capacity is based on modern dry process technologies, with only ~7% using older wet and semi-dry systems.

The industry in South Africa is characterised by a range of plant types of differing age and capacity. However, rotary kiln technology dominates production. The newer, larger facilities are considered to be on a par with some of the world's best plants. There is an ongoing process to improve the sector's performance and gradually phase out older outdated plant. Activities are focused on the retrofitting of kilns, upgrading of milling plants, the addition of additional pre-calciners, and the use of improved intelligent software programmes for plant operations. These moves are improving fuel efficiencies and reducing coal requirement per tonne of product.

4.2 Fuels used

In some OECD countries, alternative fuels are co-combusted with coal in large quantities. These can be gaseous (coke oven

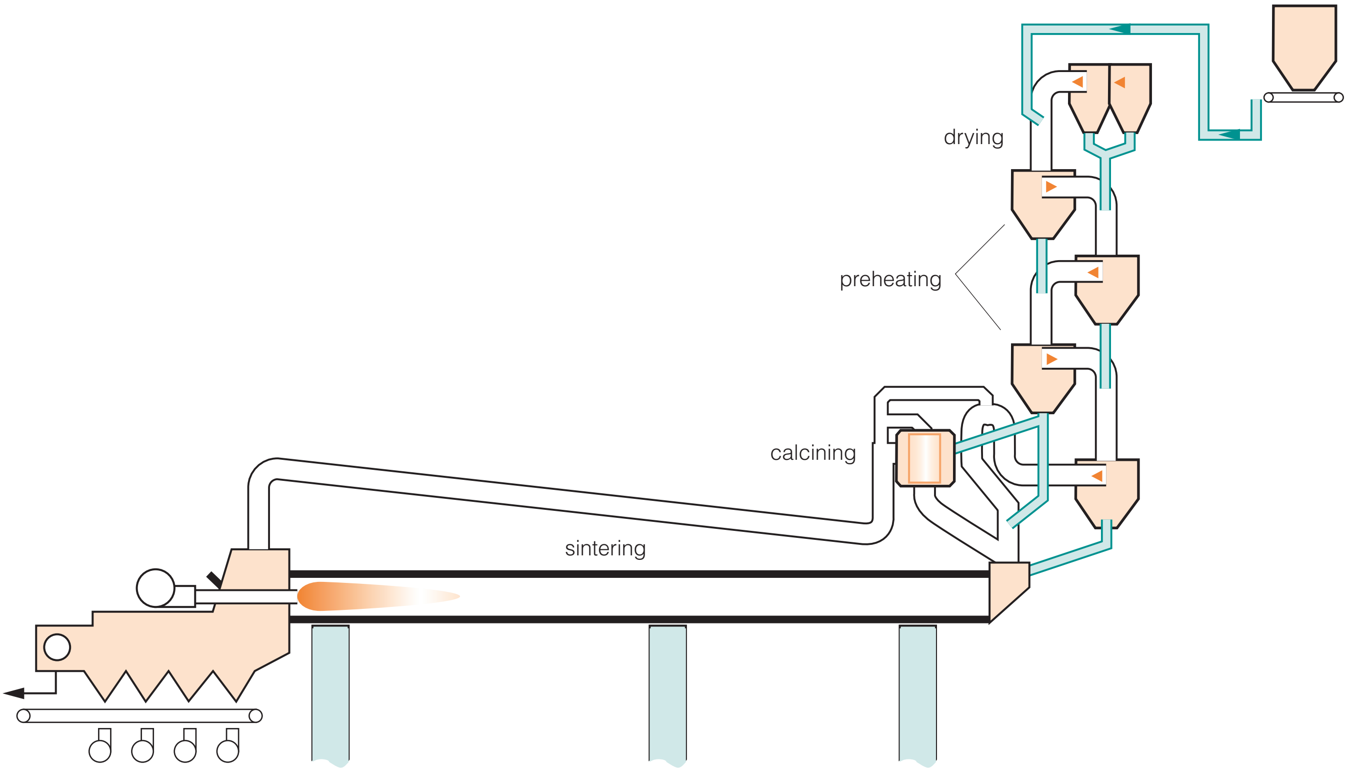

Figure 20 Cement rotary kiln and pre-calciner

gases), liquids (spent solvents), or solids (tyre-derived-fuels (TDF)). Some cement producers in Belgium, France, Germany, The Netherlands and Switzerland have reached average substitution rates of 35–70% of the total energy used, and some individual plants have achieved 100% substitution of coal or natural gas (Asthana and Patil, 2006; Murray and Price, 2008). However, the level of application can be affected by factors such as local availability of alternative fuels. The US and Japanese cement industries burn large (and increasing) numbers of used tyres (58 million a year in the USA). Potentially, each tonne of TDF can replace 1.25 tonne of coal, although operational issues limit the maximum level of substitution to around 20% (Portland Cement Association, 2008). Japan also burns 450 kt of waste oil, 340 kt of wood chips and 300 kt of waste plastic. According to IEA statistics, in 2003, the OECD cement industry used 66 PJ of combustible renewables and waste, split evenly between industrial wastes and wood waste. However, at the moment, such use appears to be limited largely to the OECD.

Potentially, China has large quantities of industrial and other wastes that could be suitable for cement production. These include granulated blast furnace slag, fly ash, coal gangue, steel slag, and carbide slag that could be utilised as cement raw materials and additives (estimated total of 0.8 Gt/y). There is also a huge potential for the co-processing of municipal waste in cement kilns, but so far, only small trials have been undertaken.

Coal is also the main energy source for cement manufacture in India, although limited efforts are under way to explore the use of alternatives (such as lignite, petcoke, TDF, rice husks, and groundnut shells). The Indian Central Pollution Control Board is encouraging the use of high CV hazardous wastes; India generates ~4.4 Mt/y, some of which are potentially suitable as kiln fuel. Within EU countries, there are >250 cement plants that, between them, utilise more than 3 Mt/y of hazardous wastes – around 10% of the total fuel input. In India, only a few cofiring trials, involving a handful of cement producers, have so far been undertaken using TDF, and only limited investment has been made in the collection, handling and processing systems for its production. In the UK, up to 20% TDF is used in cement manufacture, and other plants operate similarly in The Netherlands, Germany and Norway.

Coal also dominates cement production in South Africa, being the only economically-available fuel source. An ongoing programme is investigating the use of non-coal fuels, with the aim of reducing coal use by up to 35%. These will comprise selected waste products sourced from various industrial and domestic sources; examples include TDF, paper waste, waste oils, waste wood, paper sludge, sewage sludge, plastics and spent solvents.

4.3 Energy efficiency

Cement production is an energy-intensive process. Most of the energy used is in the form of fuel for the production of cement clinker, and electricity for grinding the raw materials and finished cement. Globally, there has been a general improvement in the efficient use of energy within the industry, as older inefficient plants (often small regional units) have been replaced with newer technology. New plants in developing countries actually tend to be larger, cleaner and more efficient than those built 10–30 years ago in the more developed countries.

Cement can be manufactured using several different technologies (wet, semi-wet/semi-dry, and dry). Energy intensity of these ranges from 3.4 to 5.3 GJ/t, with wet production being the most energy intensive and the dry process the least; the latter consumes about half of the energy of the wet process (UNEP, 2008). A weighted global average of the total amount of primary energy required to produce a tonne of cement suggests a level of ~4.5 GJ/t; China is mid way amongst major cement producing countries with an average around this level. Japan and Germany are the lowest at ~3.5 GJ/t (METI, 2007). However, Chinese cement kilns are characterised by a range of efficiencies, as some continue to depend on outdated technology. A considerable amount of electricity is also consumed during manufacture. Typically, ~100 kWh/t of clinker is consumed in rotary kilns for grinding raw materials, at the kiln, and for grinding the cement. Current best practice levels are ~75–80 kWh/t of clinker. However, there is some variation between countries, reflecting local circumstances. The Chinese national average is ~100–110 kWh.

In 2007, the Chinese Ministry of Construction published the first energy-saving standards for cement manufacturing plants to further increase the industry's energy efficiency. These standards cover all aspects of cement manufacturing, including plant construction, manufacturing technology, power systems and equipment use. They form part of the End-Use Energy Efficiency Programme of the Chinese government, run in co-operation with the United Nations Development Programme. The ultimate goal is to reduce energy consumption by 15% and to reduce pollutant emissions accordingly.

In India, whilst some modern units are approach world best practice levels, overall, the sector lags behind; the Indian cement sector uses energy more intensively than most industrialised countries. However, improvements have been made in the past 10–15 years and some plants have reduced energy requirements by 25–30%. Materials consumption has been reduced by the introduction of more advanced technologies and there has been a move away from less efficient wet kilns, toward semi-dry and dry kilns. More than 80% of India's cement-manufacturing capacity is now based on modern dry processes. But, whilst some plants compare favourably with best practice, there remains potential for further improvement, especially of smaller plants. In many cases, average energy consumption remains higher than the best practice value. Examples of individual process stages and their energy requirements are shown in Table 10.

There is also potential for the utilisation of waste heat from the exit gases of pre-heaters and grate coolers; this can be used for on-site co-generation. An average plant potential of between 3 and >5.5 MW has been identified. In 45 Indian plants that produce 1 Mt/y or more of cement, the total cogeneration potential is ~200 MW. More advanced equipment is also available that would help reduce energy intensity (such as high efficiency fans and separators, vertical roller mills, pre-grinder/roller presses, low pressure pre-heater cyclones, fuzzy logic/expert kiln control system, and high efficiency grate coolers) (Sathare and others, 2005).

As elsewhere, in South Africa, there is an ongoing process of phasing out of older facilities, and replacing them with more modern systems. This process has focused on the retrofitting of kilns, upgrading of milling plants, the addition of pre-calciners, and the use of intelligent software programmes for plant operations. These moves have improved fuel efficiencies. Savings in raw materials such as limestone and coal are also being made through the increasing use of power station fly ash in the production of building materials. At the moment, the biggest user is Lafarge Cement – the company produces a range of building products that incorporate fly ash.

4.4 Environmental performance

SO_2 emissions from cement kilns can be controlled using FGD, and NOx, with SCR and SNCR systems; both are in use on cement kilns in several OECD countries. In Europe, SO_2 emission limits vary between 200 and 1200 mg/m^3, depending on factors such as location, plant type, capacity, and fuels used. NOx limits range between 800 and 3000 mg/m^3. China has a goal of reducing pollution from cement plants by 10% by 2011. At a particularly well-performing new unit owned by Jinan Shanshui Group, SO_2 emissions are only ~22 mg /m^3, achieved mainly through the use of low sulphur coal. However, emissions can vary widely and depending on local circumstances, SO_2 emissions can be much higher. NOx levels also vary considerably, averaging 594 mg/m^3. This is similar to the World Bank limit of 600 mg NOx/m^3. In Europe, cement plants conform to a particulates limit of 70 mg/m^3 although this is being reduced further to the World Bank limit of 50 mg/m^3. Since 2000, particulate emission

Table 10 Average Indian and Best Practice energy consumption for selected stages in cement production (Sathare and others, 2005)

Process	Unit	India average	World Best Practice
Raw materials preparation – coal mill	kWh/t clinker	8	2.4
Raw materials preparation – crushing	kWh/t clinker	2	1
Clinker production – kiln and cooler	kcal/kg clinker	770	680
Clinker production – cement mill	kWh/t clinker	30	25
Total electricity requirement	kWh/t cement	95	77

from Chinese cement plants have been limited to 100 mg/m^3. Some larger Chinese producers aim to achieve significant reductions in major emissions. For instance, between 2005 and 2012, Lafarge Shui On aims to reduce its particulate emissions by 45%, NOx emissions by 35%, and SO_2 emissions by 20%.

Chinese cement plants using the older vertical shaft kilns are a source of dioxin and furan emissions because, unlike the modern rotary kiln systems with suspension preheaters/ pre-calciners, these do not quickly cool the off-gases. Mercury and heavy metals may also be released. Cement production is China's third largest mercury emitter behind non-ferrous metal smelting and coal combustion (Cho and Giannini-Spohn, 2007).

In India, depending on factors such as plant capacity, SO_2 emissions from cement plants are limited to 300–2300 mg/m^3, and NOx to 200–2500 mg/m^3. However, there are often big differences between individual plants. Particulate limits are dependent largely on plant capacity and location. Control systems deployed are generally multi-cyclones, ESPs and bag filters.

In South Africa, emission limits are being tightened. A programme of environmental compliance inspections is under way and most major cement producers aim to reduce particulate levels as part of their efforts to reduce energy consumption and minimise emissions.

4.4.1 CO_2 emissions

Although the global cement industry emits large quantities of CO_2, modern plants with pre-calciners and rotary kilns have high energy efficiencies, and the scope to reduce CO_2 emissions by efficiency improvements at such plants is small. However, because not all plants use the best available technologies, globally, the cement industry actually has greater potential for reducing CO_2 emissions than any other industrial sector. By adopting best available technology industry-wide, it has been estimated that the industry could reduce its total energy use by 28–33% and CO_2 emissions by 480–520 Mt/y (UNEP, 2008). Energy efficiency and CO_2 reduction potentials for the cement industry in several important regions are given in Table 11.

A recent IEA Greenhouse Gas R&D Programme study assessed CO_2 capture, both by post-combustion scrubbing using MEA and by oxy-combustion, for new cement plants (Barker and others, 2009).

Table 11 Energy efficiency and CO_2 reduction potentials (Price and Worrell, 2006)

Region	Energy efficiency improvement, %	CO_2 reduction potential, %
Western Europe	17	8
USA	33	17
China	<35	18

Two-thirds of the CO_2 produced during cement manufacture is released by the limestone as it is calcined in a series of cyclones in the first stage of the cement production process. In 2007, cement production was responsible for 9% of China's total CO_2 emissions of 6200 Mt/y (Marland and others, 2008). The next largest emitter was the USA. A measure of the efficiency of production can be gauged from the amount of CO_2 emitted per unit of cement produced. China ranks midway between major cement producing countries (India is somewhat higher) (Table 12). However, this masks the wide variations between plants, with the country's numerous small, inefficient plants consuming more fuel and emitting more CO_2 and pollution than international norms.

Despite efficiency improvements achieved in recent years, as a result of increased production, China's CO_2 emissions from the cement sector have increased. In contrast, emission levels from some OECD countries have fallen. This has been achieved through the replacement of primary raw materials and fossil fuels with wastes and by-products, coupled with increased efficiency.

One South African cement producer (Afrisam) has recently introduced a carbon dioxide rating stamp which now appears on every bag of cement sold. It indicates how many kilograms of CO_2 (on a 'cradle-to-gate' basis) were emitted for the production of each kilogram of cement. The current world average emission is estimated at 890 gm. So far, this is the only South African producer to adopt this approach.

4.5 Technology transfer and knowledge sharing opportunities

As with other major coal-using sectors, these activities can have an important role to play in increasing the efficiency of production and minimising levels of pollutants and CO_2. However, many of the industry's most modern cement

Table 12 CO_2 emissions from cement production in selected countries (2000) (UNEP, 2008)

Country	CO_2 emissions/t cement
Japan	0.73
Australia and New Zealand	0.79
Former Soviet Union	0.81
Western Europe	0.84
China	0.90
South Korea	0.90
Canada	0.91
India	0.93
USA	0.99

production systems were developed and in place by the 1980s and are now in use throughout the world. New technology has spread relatively quickly through parts of the industry, often via international collaboration. For instance, there have been a number of collaborative development efforts between Japan and China (improved particle separators, suspension preheaters, and waste heat power generation systems). Since the 1980s, technology transfer has therefore played an important role in increasing the efficiency of production and minimising levels of pollutants and CO_2. Intellectual property rights in many cases no longer apply, and local manufacturers are now designing and supplying equivalent systems (Izumi, 2008). There are a number of means by which production efficiency and emissions can nevertheless be improved (Price and Worrell, 2006; Sathare and others, 2005). These include:

- Replacement of old equipment with new more efficient systems such as rotary kilns with pre-calciners, and increased use of high efficiency fans, vertical roller mills, pre-grinder/roller presses.
- Improving the electrical efficiency of plants through the use of systems to recover heat from the exit gases of pre-heaters and grate coolers for on-site electricity generation. Potentially, a typical cement plant could generate between 3 and >5.5 MW of electricity.
- Increasing the share of biomass or other fuel sources such as wastes. The use of biomass or wastes in cement kilns is still low outside the OECD nations.
- Increased utilisation of materials such as steel making slags and fly ash, as in Europe, to produce cement using less clinker. Blast furnace slag is now being used increasingly as a clinker substitute in China, reducing raw material requirements and CO_2 emissions (Zhu, 2008). There are also similar initiatives in India and South Africa.
- Adoption of improved energy management and process control optimisation, which often requires little financial investment.

5 Brick production

Clay bricks can be made by hand or machine and are used throughout the world. The world's two biggest producers of bricks are China and India. Handmade brick production in the developing economies amounts to an estimated 1266 billion bricks a year. Two countries predominate, namely China (55.3% of global total) and India (11.3%), with the balance coming from other parts of Asia, Africa, South America and Mexico (33.4%). China relies heavily on handmade bricks, whereas in most OECD nations, the industry is dominated by machine made equivalents. Although fewer in number, production facilities in the latter tend to be much larger than those in the developing economies. For instance, output from a typical Chinese TVE (Town and Village Enterprise) kiln ranges from 6 to 36 million bricks each year, with the largest producing 120 million (UNEP, 2008). In contrast, a single modern tunnel kiln (used widely in the OECD) can produce, in a continuous process, between 40 and 80 million bricks a year. Worldwide, machine made brick production using automated kilns amounts to ~125 billion bricks. An example of a typical modern gas-fired tunnel-type brick kiln is shown in Figure 21.

Chinese brick makers consume ~100 Mt of coal each year to produce an estimated 700 to 830 billion handmade bricks and 100 billion machine made bricks (Hablakilns, 2007). In China, coal remains the dominant fuel for firing brick kilns, whereas natural gas is preferred in many OECD nations. Brick production times vary significantly between the different technologies. Coal-fired clamp kiln bricks can take up to three weeks or more to fire adequately (and are often operated only seasonally) whereas a gas-fired tunnel oven can take only 48 hours.

Many Chinese brick making operations comprise small provincial facilities located in townships and villages. There are thousands of such enterprises that vary considerably in production capacity. This contrasts with, for instance, the USA, where around 80 manufacturers operate 200 plants (with a combined capacity of 9.5 billion bricks/y). Some 82% of US production comes from just ten manufacturers (American Brick Association, 2008). Around 90% of Chinese TVE-produced bricks are made in annular kilns, although some larger enterprises use continuous (tunnel-type) kilns. These are more fuel efficient as they employ direct stoking into the bricks and utilise waste heat to dry and preheat the green bricks before firing. They also have the capacity to fire very large quantities evenly and with minimal wastage. However, they are expensive to build and maintain, and occupy a large amount of space. As a result, many Chinese units are smaller and in this respect, Chinese-developed technology, in the form of the Vertical Shaft Brick Kiln (VSBK) is being applied increasingly. This cost-effective, coal-fired system has proved to be energy efficient (reportedly 40–50% lower than traditional clamp processes), with relatively low emissions; it is now used widely in China (>50,000 kilns). The technology has begun to make inroads into brick making sectors elsewhere, and is being exported to Indian, Bangladesh and several South American countries (UNDP, 2003).

Figure 21 Modern gas-fired tunnel brick kiln (courtesy US Brick Industry Association)

India is the second largest global brick producer after China. Annual coal consumption is between 20 and 24 Mt. Brick-making is a traditional, disorganised industry, generally confined to rural and semi-urban areas. It comprises mainly small-medium concerns (>100,000), most of whom produce hand made bricks using traditional fire clay, simple techniques and clamp kilns. An estimated 144 billion hand made bricks (11.3% of world's total) are produced in this manner. It is one of the largest labour-generating industries, employing around 5 million workers. The level of mechanisation is low and labour intensity is high. Emissions of CO_2, SO_2 and particulates can be considerable.

There is considerable scope for improving the efficiency of the traditional low efficiency Indian clamp kiln, used widely. To date, efforts to improve production efficiency have concentrated on two techniques – the World Bank is involved with both initiatives. These are:

- Adoption of Chinese VSBK technology. This is being promoted particularly in the states of Chattishgarh, Madhya Pradesh, Rajasthan, Orissa, Jharkhand, Uttar Pradesh and West Bengal. This technology is both cleaner and more energy efficient than clamp kilns. Its specific energy consumption is between 0.8 and 1.0 MJ/kg of fired brick, much lower than that of a clamp kiln (1.5 to 2.5 MJ/kg). In an Indian context, initial investment costs are ~US$10,000 for a production capacity of ~5000 bricks/d. Technology and Action for Rural Advancement, the agency that provides VSBK technology in the country, plans to set up ~125 VSBK plants throughout India (Maithel and others, nd).
- The FaL-G project. This aims to replace traditional burnt clay bricks with fly ash brick, manufactured using available industrial wastes/by-products as basic raw materials. Fly ash, the key ingredient of FaL-G technology, is abundantly available in India. This is

> mixed with lime (as a by-product of the acetylene industry) and gypsum from chemical plants. The technology does not require a sintering process to produce bricks and no thermal energy is required. Around ~100 micro industrial plants are planned in the states of Tamil Nadu, Kanataka, Orissa and Uttar Pradesh. This type of production can be carried out year round, as opposed to the sometimes seasonal operations of clamp kilns.

In South Africa, the industry produces an estimated 4.5 billion bricks and blocks a year. In recent years, output has increased significantly, with coal as the dominant energy source. This is used widely for firing various designs of kiln and brick driers. The sector also uses considerable amounts of electricity, generated mainly by coal-fired power plants. Corobrik, with 14 major brick-making factories, is the country’s largest manufacturer, accounting for >70% of the country’s production. Some South African facilities operate several different brick-making technologies side by side. Three types of kilns are currently used: Hoffman-type, tunnel and clamp kilns. For instance, Makana Brick’s Grahamstown plant uses both traditional clamp kilns alongside a new state-of-the-art (Hassler) tunnel-type kiln. The latter is claimed to be >20% more efficient than other South African plants. Although coal dominates brick making, several programmes are under way investigating the use of alternative fuels such as wastes and biomass. The use of natural gas has also been increasing.

6 Coal-to-liquids (transport fuels)

Not currently a major coal market in most countries, there is a strong possibility that coal-to-liquids plants could be constructed more widely if oil/coal price relativities remain high over an extended period. Unconventional liquids production is expected to become increasingly important over the next 20 years (Lindsay and others, 2009). There are two main processing routes to liquids. One (indirect liquefaction) uses gasification in an initial stage to produce synthesis gas. This is then processed to form liquid products. The other means (direct liquefaction) uses hydrogen addition to the coal in the presence of catalysts to form liquids more directly.

Coal's potential as a feedstock for producing liquid transport fuels is greatest in China, the USA and India, all of which possess considerable coal reserves but have insufficient oil and natural gas (Couch, 2008). At present, operational CTL plants are limited to a handful of facilities in South Africa and China. However, within the OECD, there are a growing number of plants proposed (mostly in the USA). Most are currently at the feasibility stage (Table 13).

Potentially, coal-to-liquids production could be of major significance to China. At ~368 Mt/y, the country is the world's second largest oil consumer. Consumption is forecast to reach 653 Mt/y by 2020. Currently, national oil production is ~187 Mt/y (BP, 2008) so nearly half of demand is met by imports. Under the WEO (2009) *Reference Scenario*, by 2030, OECD oil imports will be lower than today. In contrast, those of China (and India) are expected to be much higher. The *Reference Scenario* projections imply a persistently high level of spending on oil and gas imports. China overtakes the USA soon after 2025, to become the world's biggest spender on oil and gas imports, while India surpasses Japan soon after 2020 to take third place (IEA, 2009).

Table 13 CTL proposals in OECD countries (Couch, 2008; Carpenter, 2008)

Developer	Location	Country	Capacity, bbl/d
DKRW, Rentech, GE ExxonMobil	Medicine Bow, Wyoming	USA	15,000–20,000
WMPI, Shell, Sasol, US DOE	Gilberton, Pennsylvania	USA	5000
American Clean Coal Fuels	Oakland, Illinois	USA	30,000
Alaska IDEA	Beluga Cook Inlet, Alaska	USA	80,000
Peabody/Rentech	Massachusetts	USA	10,000–30,000
Peabody/Rentech	Illinois, Indiana or Kentucky	USA	10,000–30,000
Rentech	Natchez, Mississippi	USA	10,000
Rentech, KEC WorleyParsons	Illinois	USA	1800
Rentech	Mingo County, West Virginia	USA	10,000–20,000
Baard Energy	Wellsville, Ohio	USA	35,000–50,000
Synfuels Inc/ GE, Haldor-Topsoe, NACC, ExxonMobil	na	USA	na
Headwaters, Hopi Tribe	Arizona	USA	10,000–50,000
Headwaters, NACC, GRE, Falkirk Mining	North Dakota	USA	40,000
Fuel Frontiers	Kentucky	USA	na
Pikeville County	Kentucky	USA	50,000
Australian-American Energy	Massachusetts	USA	25,000
American Lignite Energy	North Dakota	USA	32,000
Atlantic Energy Ventures	Ohio	USA	50,000
Alter NRG	Alberta	Canada	40,000
Monash Energy (Anglo Coal, Shell)	Victoria (Note: Project on hold December 2008)	Australia	60,000
Arckaringa Project (ConocoPhillips/Rentech)	South Australia	Australia	30,000
Schwarze Pumpe	Spreetal	Germany	3000 (Phase I) 20,000 (Phase II)

As part of its national energy policy, China has pursued the development of CTL processes with the aim of having a national CTL capacity of 50 Mt/y by 2020. Forecasts have suggested that by this date, the country could meet a tenth of its needs via this route. However, most Chinese projects have been cancelled or delayed recently on economic and environmental grounds. An important issue was the high level of CO_2 emissions produced. Conversely, the number of Chinese plants producing chemicals from coal (see below) continues to increase (Henley, 2007). Two Chinese CTL projects are currently progressing. These are:

- **Shenua Group Corporation Ltd DCL project, Erdos City, Inner Mongolia**
  The liquefaction technology adopted has integrated technologies from the USA, Germany and Japan, with in-house innovations. Shell gasification technology is used although more than 60% of the plant's equipment was produced domestically (China Daily, 2008). When the second phase is completed in 2010, the facility will have three reactor trains and once fully operational, will have an output in excess of 6 Mt/y. The plant will produce ~3.6 Mt/y CO_2 (3.1 Mt CO_2 from hydrogen production, with the balance from heating, flaring and power generation) and CCS activities are planned. Ongoing feasibility studies are exploring options for EOR applications and/or storage in deep unmineable coal seams and deep saline aquifers (Sun, 2008). Some CO_2 is reportedly already being used for EOR purposes. Initial commercial operations began in 2009.
- **Shenua Ningxia Coal Industry Group-Sasol joint venture, Ningxia Autonomous Region**
  This project is currently at Stage II of the feasibility process, the results of which will serve as the main decision-making basis for the development of a 3.6 Mt/y (80,000 bbl/d) capacity facility. The feasibility studies also involve Foster Wheeler Energy Ltd and Wuhuan Engineering. The proposed project is expected to attract US$ 5–7 billion of investment, shared equally between Shenua and Sasol. An official report, which will include CCS options, is due to be presented to the NDRC in 2010. Reportedly, there has been strong support for Sasol's aspiration to integrate CCS into the design of the facility.

India is also a major oil consumer and importer. In 2007, the country produced 37.3 Mt of crude oil but consumed 128.5 Mt. Since 2000, oil imports have increased significantly, exceeding 90 Mt in 2007 (BP, 2008). Although there are no CTL plants currently operating, a number of projects are proposed. The most recent involves Jindal Steel & Power Ltd (JSPL) and Sasol. This will produce SNG that will then be used in a JSPL steel plant and to feed an 80,000 bbl/d facility for motor fuels. There is also a pre-feasibility study under way for a plant involving Tata and Sasol (as Strategic Energy Technology Systems joint venture). Fischer-Tropsch technology will be used to convert ~30 Mt/y of high-ash opencast coal into 80,000 bbl/d of liquid products (diesel, naphtha, jet fuel, and LPG). The project will also generate 1500 MW of electricity. Reliance Industries, allied with Coal India, has also proposed an US$8 billion indirect coal liquefaction project based on US technology. This would use up to 30 Mt/y of Mahanadi coal to produce 80,000 bbl/d of synthetic oil products.

South Africa has only small deposits of oil and natural gas. In 2007, the country's oil demand was 25.8 Mt (BP, 2008) and approximately two thirds of this was met by imports. The remainder (36%) was produced from coal and natural gas by Sasol. Around 24% of South Africa's indigenous coal production is used by Sasol's CTL and other operations. Sasol Mining supplies most of the feedstock coal required for the company's large Secunda petrochemicals plants. This comes from a number of different collieries and seams and requires careful blending in order to achieve consistent operating conditions. The coals for Secunda contain about 28% ash (Couch, 2008). The Secunda plant converts 120 kt/d of coal (via Sasol-Lurgi gasification and Fischer-Tropsch technologies) into 150,000 bbl/d of liquid fuels that include petrol, diesel, jet fuel, illuminating paraffin, liquefied petroleum gas, and fuel oils. Liquid fuels are produced through Sasol's combined operations at Secunda and Sasolburg.

Sasol employs two systems based on Fischer Tropsch technologies, namely the High Temperature Fischer Tropsch (HTFT) process used at Secunda, (producing mainly liquid fuels and chemicals) and the Low Temperature Fischer Tropsch (LTFT) process, used at Sasolburg (mainly for gas-to-liquids operations). At Secunda, the production process is carried out in a multi-unit gasification plant where coal is gasified using around 80 Lurgi-Sasol gasifiers to produce crude syngas. These operate with lump coal (coal fines are used for power generation, both on site and for export to the Eskom grid). Once cleaned, syngas is fed to a suite of nine reactors where it reacts (under pressure and in the presence of an iron-based catalyst at ~350°C) to yield hydrocarbons, mainly in the C1 to C20 range. These are cooled progressively in a product recovery plant until most are liquefied. They are then separated via fractionation to produce separate hydrocarbon-rich fractions and methane-rich gas; most of the latter is converted into syngas via autothermal reforming for further internal processing, and the balance is sold as pipeline fuel gas.

There are longer-term proposals to increase the capacity of the Secunda plant by 20% (30,000 bbl/d) and for the construction of a new 80,000 bbl/d plant. If both proceed, coal demand could increase by ~25 Mt/y. However, the latter is currently on hold pending the outcome of further investigations into water availability, carbon capture and storage, and other infrastructure requirements.

6.1 CO_2 emissions

Both processing routes (direct and indirect) are currently expected to result in the production of large quantities of CO_2 in the absence of CCS. Life cycle (production plus utilisation) estimates of CO_2 emissions without CCS indicate up to twice the life cycle estimates from crude oil-to-liquids. The technology will clearly need to incorporate CCS if it is to be acceptable. However, it would be a relatively simple modification to include CCS, because one of the effluent

Figure 22 Slurry reactor forming part of Sasol's extensive Secunda CTL plant, reportedly the world's single largest point source of CO_2 (courtesy World Petroleum Congress)

streams from a CTL plant would consist of a concentrated stream of CO_2 that would simply require compression and drying before transport to geological storage (NETL, 2009). A recent paper indicated that incorporation of CCS would add only 8% to the capital cost of a polygeneration (liquids plus electricity producing) plant (Mantripragada and Rubin, 2009).

Because of the high costs and high levels of CO_2 produced by CTL processes, there will likely only be niche deployment on projects where there is substantial government support and where CO_2 produced will be captured and stored (Couch, 2008). Most Chinese CTL projects recently proposed were shelved or cancelled because of economic and environmental (CO_2 emissions) issues. CO_2 capture should actually in principle be simple and economic on CTL plants, and both of the ongoing Chinese projects are currently reviewing this option.

In South Africa, Sasol's Secunda CTL plant (Figure 22) is cited as being the world's single largest point source of CO_2. In 2007, the company reportedly produced 71 Mt of CO_2; this equates to >3 tonne of CO_2 for every tonne of saleable product. This level has fallen from a level of 3.45 t in 2004 and there is a target to reduce this to 2.85 t by 2014. The company is examining different options to achieve this, including the possibility of planting large acreages of plants to absorb CO_2, as well as the application of CCS. There are plans in the longer term for several new large-scale Sasol facilities to be added, and the company's current policy is that any new plants will be built carbon capture ready.

7 Coal-to-chemicals

A number of different production technologies are used to manufacture chemicals in different parts of the world. The products and choice of technologies adopted often reflect local circumstances such as particular market requirements and the availability and cost of certain feedstocks. In parts of the world where coal is readily available, and natural gas is expensive or scarce, major increases are being made in coal-based capacity. Coal's potential is the greatest in China, the USA and India. Traditionally, producers in North America and Western Europe have relied heavily on natural gas for chemicals production.

China in particular, depends heavily on coal for chemicals production, much more than, for instance, the USA (the world's largest chemicals producer). In 2007, the sector's energy requirement was 47.9 Mtce, an amount that has been increasing steadily since 2000 (IEA/OECD, 2009). There are a growing number of coal-based Chinese production facilities (natural gas is expensive and relatively scarce), unlike the OECD nations, where there are only a handful of major commercial projects operating or proposed, mostly in the USA (Table 14). Currently, around 30 new Chinese coal-to-chemical projects are believed to be under construction. However, recent announcements suggest that there may be a three-year moratorium on the construction of new chemical plants and some existing facilities will be restructured. This is to avoid over-capacity in the sector and to reduce its environmental impact.

In South Africa, significant amounts of coal are used by Sasol to produce a wide range of chemical products and derivatives. Some are marketed predominantly within the country whereas others are sold worldwide. In contrast, a relatively small amount of coal-derived chemical products are produced in India; currently, a total of around 2.5 Mtce is used for chemicals production, a level that has decreased in recent years (IEA/OECD, 2009).

7.1 Technologies deployed

The handful of coal-based production plants within the OECD has mostly adopted gasification technology from Lurgi, Texaco or GE. The sector is much larger in China where, historically, a wide range of gasifier types have been deployed. In 2007, there were nearly 140 gasification plants operating in China (>400 individual gasifiers) used predominantly for chemicals and SNG production. Around 55% of these were coal-fuelled. Many have been supplied or built under licence from overseas vendors such as Kellogg, Texaco, Lurgi, GSP, Shell, Siemens and GE Energy (UNESCO, 2007). GE claims to have signed more gasification licences (fourteen) for chemicals than any other supplier (seven for methanol, DME and chemicals production and seven for ammonia). In October 2009, Hangzhou Jinjiang Group selected GE gasification technology to help expand its chemicals production. GE is licensing its technology to the

Table 14 Major OECD coal-based chemical plants and proposals (Tullo and Tremblay, 2008; plus data from the Gasification Technologies Council, USA)

Developer	Location	Start-up date	Gasification technology	Products
Dakota Gasification	Great Plains, Beulah, North Dakota, USA	1984	Sasol Lurgi Dry Ash Process	400 kt/y ammonia, 110 kt/y ammonium sulphate, cresylic acid, phenol
Eastman Chemical Co	Kingsport, Tennessee, USA	1983	Texaco quench gasifiers	145 kt/y methanol and acetyl chemicals
Beaumont Chemical Facility	Texas, USA	2011	GE	Chemicals
Faustina Hydrogen Products LLC/Eastman	Louisiana, USA	2010	GE	Ammonia, methanol, CO_2
Southeast Idaho Energy	Idaho, USA	Post 2012	GE (coal + petcoke)	5 kt/d ammonia, 1800 t/d urea, 1600 t/d ammonium nitrate
Agrium	Alaska, USA	na – evaluating change from natural gas to coal	na	Nitrogen fertilisers
Ube City ammonia plant	Japan	1984	GE	1250 t/d ammonia
Schwarze Pumpe	Germany	~1995	BGL, GSP, FDV	Up to 130 kt/y methanol*

* produced from combinations of coal and various wastes

Group for a new chemicals production plant to be developed in Hangzhou. This will be fed with more than 2.1 million m^3 of SNG a day. Coal will come from the Xinjiang Hongshan region. Shell also has a significant presence in China, with a number of major plants operating or under construction (six for methanol and eight for fertilisers) (van Holthoon, 2007). Recent developments have also seen the first delivery of Siemens gasifiers to China. During 2008, the first two of an order of five 500 MWth gasifiers were delivered to Shenhua Ningxia Coal Industry Group Co Ltd. These will be used for a coal-to-polypropylene plant in Ningxia Province.

Many smaller Chinese plants use domestically-developed fixed bed gasification systems, often characterised by high energy consumption and high levels of pollution. However, there is a gradual move away from this type of technology towards more efficient entrained flow units. A growing number of plants are relying on newer Chinese-developed technology, such as the opposed multi-burner (OMB) gasification system, developed by the Institute of Clean Coal and the East China University of Science and Technology (Yu, 2007). There are currently thirteen projects deploying a total of 33 OMB gasifiers (Wang and Guo, 2008). Examples of major projects and proposals are presented in Table 15.

During the 1980s, several coal-based fertiliser plants were operating in India, but later closed, mainly because of technical difficulties. However, there are currently several proposals for new coal-based projects. GAIL India and Rashtriya Chemicals and Fertilizers are investigating a coal gasification-based fertiliser plant in Orissa. This would produce 3000 t/d of ammonia and 3500 t/d of urea. Also, a Sasol-Lurgi gasification joint venture is developing a gasification-based direct reduced iron project for Jindal Steel & Power in Orissa. This project will use seven gasifiers and represents the first integration of DRI and coal gasification. The plant will gasify low-rank, high ash coal for the production of ammonia, phenol and sulphur, as well as produce syngas for the DRI process. It is scheduled for start-up late in 2009.

Sasol of South Africa is the largest individual coal-to-chemicals producer in the world. As already noted, coal is a major feedstock for the production of syngas via Sasol-Lurgi gasification technology. More than 80 gasifiers convert ~40 Mt/y of coal to syngas. Using Fischer-Tropsch technologies, this is converted into a wide range of liquid and solid products.

7.2 Feedstocks

Globally, a variety of chemicals production processes are in operation, using feedstocks that include coal, natural gas, fuel oil and naphtha. Coal is of particular importance in China, although only limited use is currently made in India where other hydrocarbon feedstocks predominate (naphtha, natural gas, furnace oil, or combinations of these). Coal and natural gas dominate South African operations. In all three countries, some chemical products are also derived from coke production by-products. These generally comprise coal tar pitches, distilled and treated to produce a range of useful feedstocks and products.

7.3 Products

Potentially, a wide range of chemical species can be derived from coal although in practice, bulk markets are dominated by a relatively small number of products. Most are currently

Table 15 Projects using Chinese opposed multi-burner (OMB) coal gasification technology (Yu, 2007; Wang and Guo, 2008)

Project developer	Location	Products	Start-up date
Hualu Hengshen Chemical Co Ltd		Methanol, 750 t/d ammonia	2004
Yankuang Cathay Coal Chemical Co	Tengzhou City, Shandong Province	1150 t/d methanol	2005
Tengzhou Fenghuang Fertilizer Plant Co	Tengzhou City, Shandong Province	300 kt/y methanol	2008
Yankuang Lunan Fertilizer Plant	Tengzhou City, Shandong Province	Methanol, 240 kt/y ammonia	2009
Jiangsu SOPO Group	Zhengjiang City, Jiangsu Province	600 kt/y methanol, acetic acid	2009
Jiangsu Linggu Chemical Co	Yixing City, Jiangsu Province	450 kt/y ammonia	2009
Ningbo Wanhua Polyurethane Co	Ningbo City, Zhejiang Province	240 kt/y methanol, 80 kt/y ammonia, + CO and H_2	2010
Shenghua Ningxia Coal Group	Yinchuan City, Ningxia Province	750 kt/y methanol	2009
Shenua Ningmei		1900 t/d DME	2009
Shengda Ningdong		2000 t/d methanol	2010
Shandong Jiutai		2000 t/d methanol	2010
Anhui Huayi		1500 t/d methanol	2010

produced in China and South Africa. The most important are:

Methanol

In China, methanol's main use is as a feedstock for chemical production, with the remainder mixed into gasoline (Couch, 2008). Methanol is also used in the production of formaldehyde, acetic acid and methyl methacrylate, and is used as a solvent for many applications. It is also used to produce MTBE, used as an octane-booster or as a gasoline component. With government encouragement, there has been a considerable increase in China's methanol output in recent years. In 2007, production reached 10.8 Mt but new projects are expected to boost this. The NDRC suggests outputs of 19.3 Mt/y by 2009, 38 Mt/y by 2015, and 66 Mt/y by 2020. Currently, coal-based methanol production accounts for ~80% of national supply, with the balance coming from oil and natural gas (Wang and Guo, 2008). As the country's primary energy resource, coal will remain the main focus for future development activities in the production of chemicals such as methanol (Market Avenue, 2008).

Dimethyl ether (DME)

DME is produced either by direct synthesis from coal-derived syngas or via methanol dehydration. It can be derived in a two-step process from syngas to methanol, which is then dewatered to produce DME. It is easily liquefied and has physical and chemical properties similar to LPG. It can be used as a diesel replacement and has potential to replace some LPG for residential use (Couch, 2008). There are currently >20 major Chinese units producing methanol and DME from coal. Several are being enlarged. The largest project is expected to eventually have a production capacity of 4.2 Mt/y of methanol and 3 Mt/y of DME.

Olefins

Olefins (such as polyethylene and polypropylene) can be produced directly from coal or via methanol synthesis/ dehydration. Both technologies are currently deployed commercially in China and a number of other projects are being developed. These include the Shaanxi Coal Chemical/Dalian Institute of Chemical Physics DME/methanol-to-olefin 10 kt/y demonstration plant (ethylene and propylene), the Shenhua Group project in Inner Mongolia (1.8 Mt/y methanol, 300 kt/y polyethylene and 300 kt/y polypropylene), and the Shenhua Ningxia Coal Industry Group project in Ningxia Province (polypropylene). Current Chinese production of olefins is around 3 Mt/y. Industry expansion is expected to increase this by a further Mt/y in the near future.

In South Africa, Sasol Polymers produces a range of polymers that include low density polyethylene. The C2-rich stream produced during operations at Secunda is split into ethylene and ethane. The ethane is then cracked via a process of thermal decomposition, to produce ethylene. This is purified and converted downstream into polyethylene. Propylene from the light hydrocarbon gases is also purified to provide feedstock for Secunda's two polypropylene plants and Sasolburg's butanol and acrylates plants. Some ethylene and propylene produced is sold to third-party polymer producers. Hexene and octene is also produced and used for the production of co-monomers; these are used for the manufacture of speciality grades of polymers. Between them, the Secunda and Sasolburg plants supply ethylene, propylene, polyethylene, linear low density polyethylene, polypropylene and polyvinyl chloride to domestic and international customers.

Ammonia and fertilisers

Globally, anhydrous ammonia is produced in around 80 countries. During the 1970s, the developing countries accounted for 27% of global ammonia capacity; today, it is >50%. The choice of feedstock influences energy efficiency of the process. For instance, using coke to manufacture ammonia consumes ~70% more energy than using natural gas. China produces 66% of its synthetic ammonia using coke, whereas the USA produces 98% of its ammonia using natural gas (Marulanda, 2007). Production in China is dominated by small-medium coal- or coke-fuelled plants. Energy consumption per unit output for small plants can be more than 75% higher than that of large plants. Smaller plants produce two thirds of national output, and up to 90% use coal as feedstock. Annual Chinese ammonia production in recent years has been >34 Mt.

In China, ammonia is the largest volume chemical produced by the gasification of coal and is a key intermediate for fertilisers such as urea, ammonium nitrate and ammonium phosphate. In the process, coal is gasified to produce syngas, which is then shifted, cleaned and used for the synthesis of ammonia. Much is used for the production of nitrogenous fertilisers (China is the world's biggest producer). The ammonia sector is the country's biggest employer of gasification technology. Coal-based synthetic ammonia accounts for 75% of total output and annually, ~50 Mt of coal is used in this way (Wang and Guo, 2008). There are currently >500 production plants scattered throughout the country, operated by more than 400 producers. Larger facilities have individual outputs of between 300 kt/y and 1 Mt/y although smaller, less efficient, more polluting plants continue to produce a significant proportion of national output. Many rely on obsolete technology at a production scale too low to be economic (Minchener, 2004).

There are several types of fertiliser produced in India, of which, nitrogenous fertilisers (predominantly urea) constitute >80%, and phosphatic fertilisers most of the balance. Ammonia is the basic raw material used for nitrogenous fertiliser production and is currently synthesised from a number of non-coal feedstocks. Coal is used indirectly in some Indian chemical and fertiliser plants as a boiler fuel in conventional captive (both PCC- and FBC-based) power generation and cogeneration plants that form integral parts of such production facilities. Between 4 and 5 Mt/y of coal is consumed in this way (Mills, 2007). In a recent development, the India government announced that it was exploring the concept of creating integrated power and fertiliser complexes. CO_2 would be captured from coal-fired power plants and used in the synthesis of ammonia for urea production. The project is at a preliminary stage.

In South Africa, alongside its range of liquid fuels, Sasol produces more than 120 chemical products that include ammonia, ammonium sulphate, ammonium nitrate and urea. Other products include alcohols, acetic acid, ketones, esters, acrylic acid esters, ethyl acetate, ethers, propionic acid, acid, alpha olefins, co-monomers, mining chemicals, detergents, surfactants, inorganic speciality chemicals, oleochemicals, waxes, petroleum jellies, liquid paraffins, oils, sulphur and phenols. Many are marketed worldwide.

Coke oven by-product-derived chemicals

Chemical products can be produced directly and indirectly from coal. They can also be produced from various chemical species generated as by-products from the manufacture of coke in coke ovens – a major product is coal tar pitch. This can be distilled into various fractions and treated to produce a number of chemical building blocks such as naphthalene, phenanthrene, and anthracene. These can be used directly in, for instance, resin and surface coating applications. There are a range of uses for coal tar distillation pitches and oils. Major ones include as electrode binders for aluminium and electro-steel production, refractory materials, carbon black production, and timber impregnating oils. Where species (such as aromatic base chemicals) are further isolated, they are used for the production of antiseptics, drugs, dyes, explosives, inks, pesticides, plasticisers, solvents and surfactants. Various coal tar-derived chemicals are produced in China, India and South Africa. For instance, in the latter, ArcelorMittal’s Coke & Chemical Division produces coke for the ferro-alloy industry from two coke batteries at Pretoria and Vanderbijlpark and also processes coal tar pitch generated from coke-making. This is sold to Southern African aluminium producers. The company’s tar distillation plant (located at the Vanderbijlpark site) processes >150 kt/y of coal tar based products. Other applications include the production of wood preservatives, road binders, paints, primary raw materials, absorbents, and blast furnace fuels.

Similarly, in both China and India, a number of major manufacturers supply a range of products derived from coke oven operations. These include benzene, toluene, xylene, naphthalene, coal tars, coal tar enamels, creosote oil, pitches, ammonium sulphate, benzol and pyridine.

8 Coal use in residential and commercial buildings

Of India, South Africa and China, only the latter uses significant quantities of coal for residential heating. The level of use is also much greater than in most OECD countries (Table 16). In China, a significant amount of coal is used for cooking and water and space heating, predominantly in central and northern parts of the country. Particularly during winter, emissions from coal-fired heating units are a major cause of air pollution in cities, and are a major public health concern. Most medium and large northern cities rely on coal-fired centralised heating systems, with small coal stoves heating older buildings in small towns, villages, and outlying areas. Centralised heating systems are often based on old Soviet-era technology and operate with largely ineffective pollution control equipment. Many smaller stoves also operate inefficiently and are highly polluting, producing high indoor concentrations of SO_2, CO, particulates and other pollutants (Metz, 2007). Often, low quality coal is used. In order to improve local environments, coal-free zones have been created in some towns and cities, where the use of coal for household and residential use is now banned. The phase out of coal for residential heating in urban areas is set to increase (IEA, 2008b) and many smaller residential and commercial coal-fired units have been switched to LPG, gas-firing or electricity. However, in the northern regions, coal use remains significant. Due to its low cost and a lack of alternatives, coal is expected to remain the dominant fuel for central heating systems for some time, although it may eventually reduce if alternative fuels become more readily available.

China is the world's largest builder of housing with an annual construction rate of 200 to 300 million m^2 (2.5 to 3.7 million dwelling units) in urban areas, and 700 million m^2 in rural areas. The Chinese housing stock, that currently stands at >30 billion m^2, is expected to continue growing for at least a decade.

Between 1978 and 2005, the rate of urbanisation increased from 18% to 40%; urban population has tripled in 25 years (now 520 million from a total population of ~1.3 billion). By 2030, the number of urban dwellers is expected to be 870 million. China's urban residential building stock is expected to more than double in the next 20 years.

Energy demands in the Chinese residential sector are determined largely by the climate: heating requirements are high in the northern and central regions (Heilongjiang, Liaoning and Beijing). In Harbin in Heilongjiang, the country's northernmost province, the mean daytime temperature in January is -25°C (FFEM, 2009). Typically, energy consumption in buildings accounts for 25% of total energy consumption in China. However, in the colder northern regions, it accounts for 30–40%. In these regions there are 3.1 billion m^2 of heating area, 35% of which is heated by central heating systems and 65% by stoves. Annually, in these colder regions, ~180 Mt of coal is used for space heating in urban residential and commercial buildings. In recent years, an estimated 80 Mt/y has been used directly in households.

Generally, Chinese buildings tend to be inefficient in terms of heat utilisation. Compared to buildings elsewhere with comparable climates, heat losses are substantially higher (Clemson, nd). The Government estimates that energy use per unit floor area in new residential buildings can be halved, compared with the existing building stock, if compliance with the current energy code is ensured (Feller, 2008). Despite regulations on heating first issued in 1985 and revised regularly since, only a relatively small proportion of the existing housing stock is adequately insulated. As part of the ongoing 11th Five-Year Plan (2006-10), for Northern China, the government aims to reduce building energy consumption per unit of GDP by 4% per annum.

Table 16 Solid fuels used for residential purposes in selected countries (kt/y) (IEA, 2006)

Country	Anthracite	Bituminous coal	Subbituminous coal	Lignite/brown coal	Patent fuels	Total
China		74,817			9064	83,881
India		5604				5604
South Africa		4941				4941
OECD countries						
Canada		32	5	50		87
Czech Republic			119	1720		1839
Hungary		90	305	115		510
Germany	85	75			55 (+ 895 peat)	1110
Spain	270	40				310
UK		547			257	804

Although there is a move away from coal in some parts of China, in some regions, its use will remain widespread. Where coal burning continues in residential and commercial buildings, it will be important to improve the efficiency of coal-fired heating systems and operating practices. There is significant potential for the introduction of more advanced designs capable of improving efficiency of combustion and reducing emission levels. Globally, a wide range of products is available that include innumerable variants of coal-fired domestic stoves, room heaters and water heaters. Options include manual and automatic feeding. Some are now available with advanced control systems to help maintain efficient combustion under a range of operating conditions.

Previously widely-used in parts of India, in some regions, coal use for domestic heating, water heating and cooking has declined, being replaced progressively with electricity (but not yet available in all parts of the country) or other fuels such as kerosene, LPG and biomass. Where alternatives are readily available, coal use has fallen. Most households in urban areas now rely on electrical energy to meet energy demands. More affluent households tend to use electricity for water heating. However, apart from in and around cities, use of electricity for lighting remains comparatively low. Unlike European households, its use for cooking is not widespread. In coal-producing regions such as the northern belt states of West Bengal and Bihar, and Eastern part of Maharashtra, coal use remains higher. In 2006, 5.6 Mt of coal were reportedly used for residential purposes (IEA/OECD, 2008). However, this may be significantly under-reported; it is difficult to determine precisely the amount of coal used as much is supplied via informal arrangements and goes unrecorded.

In South Africa, the residential sector can be sub-divided into urban and rural areas; the latter are defined largely as squatter camps or informal settlements. Households in urban areas rely heavily on the use of electricity, whereas rural dwellers tend to use various fuels such as wood, bagasse, coal, kerosene and LPG. In 2006, 4.9 Mt of coal was reportedly used for residential purposes (IEA/OECD, 2008). Some estimates suggest that each family in a squatter camp uses about a tonne of coal each year. But much is this of very poor quality and some is even blended with discards reclaimed from dumps.

In some locations, household coal burning is the largest contributor to local air pollution. There is a tradition of retaining older outdated stoves and other appliances, rather than replacing them, even in electrified households. Stoves are often in poor condition, operating inefficiently and adding to localised pollution. Inside pollution levels can also be excessive. However, coal will continue to be used by many lower income families as it is generally easily available and forms the cheapest option. There is a need for the use of better grades of coal, as well as the introduction of newer improved designs of stoves and other appliances. The transfer of such clean coal stove technology would help to alleviate the significant health and environmental impacts of current practices (CIAB, 2002).

9 Concluding remarks

China, India and South Africa all have significant coal reserves, and each relies heavily on coal for electricity generation and various industrial applications. In all three, despite ongoing efforts to diversify, coal continues to play an important role in supplying energy to the power generation sector and a number of major industries. This situation will continue for some years.

Each country generates a significant proportion of its electricity from coal-fired power plants. For instance, 93% of South Africa's electricity is produced from coal. However, each country suffers electricity shortages and is in the process of adding further, more advanced coal-fired capacity. At present, the dominant technology is subcritical PCC. However, the situation is changing as all three are adding supercritical PCC-based plants. China is the most advanced in this respect, although the first Indian projects are expected to come on line soon.

The use of circulating fluidised bed combustion plants is growing in China and India. China has the largest number of CFB units operating in the world, and the number in India is also increasing. These are used for power generation, cogeneration and various industrial applications. Coal-fuelled IGCC technology is also being actively developed in both. In China, the GreenGen IGCC + CCS project is now under way and in India, initial construction of an IGCC demonstration plant has begun.

A number of major industrial sectors in each country depend on coal as a source of energy. These include iron and steel production. Here, China is the world's biggest player, producing more than a third of global output. India is forecast to become the second largest producer by 2016. There are marked differences between the types of technologies deployed in each country. For example, China has the highest global dependence on blast furnace based systems and the lowest on electric arc furnaces. The reverse is true in India, where greater use of the latter is made. In all three countries, coal use is expected to remain significant for some years.

Overall, steel industry efficiencies of China and India fall some way behind most OECD countries. However, it is not uncommon anywhere to find facilities operating at best practice levels deployed alongside outdated systems. Each country has plants where performance and efficiency is on a par with the best in the world. However, such application is not necessarily universal and there are often big differences between the best and worst performers. These differences are generally greater than in OECD nations.

The cement industry is a major coal user. Nearly half of the world's cement is manufactured in China. In both China and India, recent years have seen enormous expansion (much of it coal-based) and the latter is now the second largest global producer. The industry in South Africa, although smaller, has also seen major growth. In all three, coal remains the main choice of fuel. However, various initiatives are in hand (although, generally at an early stage) exploring the use of waste-derived fuels as partial replacements for coal. As with the iron and steel sector, in each country, there can be significant differences between the best and worst performing plants. Although the general situation is improving, the current challenge is for the sector is to modernise or phase out older, inefficient plants whilst acquiring the best possible technologies.

Clay bricks are used in huge numbers throughout the world, many produced in coal-fired kilns. The world's two biggest producers are China and India. Some production techniques differ from those used in OECD nations, having been developed to meet local requirements and conditions; Chinese-developed technology is now being exported to a number of other developing economies. Overall, there is considerable scope within the sector for improving efficiency, although, again, it is not uncommon to find outdated plants operating alongside modern, very efficient facilities. Coal will remain an important source of energy for many years.

Although not currently a major coal market in most countries, there is a strong possibility that coal-to-liquids plants (CTL) could be constructed more widely if oil/coal price relativities remain high over an extended period. Coal's potential as a feedstock for producing liquid transport fuels is greatest in China, the USA and India, all of which possess considerable coal reserves but have limited oil and natural gas. At present, operational CTL plants are limited to a handful of facilities in South Africa and China. They are of particular importance in the former as the country relies heavily on CTL for its transport fuels and other chemical feedstocks. Potentially, CTL production could be of major significance to China, although most Chinese projects have been cancelled or delayed recently on economic and environmental grounds (particularly high CO_2 emissions). However, two Chinese projects are currently progressing. Conversely, the number of Chinese plants producing chemicals from coal continues to increase. In India, several major projects involving overseas technology developers have been proposed are being explored.

Under the WEO (2009) *Reference Scenario*, OECD CO_2 emissions in 2030 are 3% lower than in 2007. In contrast, CO_2 emissions of major non-OECD countries such as China and India increase. Of the 11 Gt growth in global emissions between 2007 and 2030, China accounts for 6 Gt and India for 2 Gt (IEA, 2009). China, India and South Africa are all engaged in various ways and to differing degrees with efforts to control CO_2 emissions from their respective coal-fired power generation and industrial sectors. However, compared to the OECD, the situation with CO_2 capture on steam plants and for industry is less advanced as it is viewed as less urgent than increasing electricity supply and raising generation efficiency. However, although CCS-related activities are generally more limited in scope and scale, carbon capture is being considered in all three. China is the most advanced in this respect, and a number of initiatives are being developed.

Although at present, in India, focus remains firmly on meeting growing electricity demand and there appears to be little government support for the application of CCS technologies, there is some agreement that it will become increasingly important in the future. In South Africa, a Centre of Carbon Capture and Storage has recently been created within the South African National Energy Research Institute and a number of projects have been proposed.

Potentially, in all three countries, there are opportunities for the increased adoption of more advanced technologies for power generation and/or industrial applications. Greater deployment of advanced systems would help increase sector efficiency, resulting in reduced coal use and hence, lower emissions of classic pollutants and CO_2.

10 References

American Brick Association (2008) *The American brick industry*. Available at: http://www.gobrick.com/html/biaoverview.html, Reston, Virginia, USA, 1 pp (2008)

APP (2007) *The State–of-the-Art Clean Technologies (SOACT) for Steelmaking Handbook*. Asia Pacific Partnership for Clean Development and Climate. Prepared for the APP, US Department of State, and US Department of Energy by Lawrence Berkeley National Laboratory, Berkeley, CA and the American Iron and Steel Institute, Washington, DC, USA (Dec 2007)

Asthana S R, Patil R K (2006) *Use of alternative fuels in Indian cement industry*. Available at: http://www.ese.iitb.ac.in/~aer2006/papers/ASR_147.doc, Bombay, India, Indian Institute of Technology, 4 pp (2006)

Barker D J, Turner S A, Napier-Moore P A, Clark M, Davison J E (2009) CO_2 Capture in the cement industry. *Energy Procedia*; **1** (8); 87-94 (Feb 2009)

Bhattacharya S (2008) Coal-fired power generation, Replacement/retrofitting of older plants, *Workshop on fuel options for power generation in ASEAN*, Bangkok, Thailand, 16 pp, 22-23 Sept (2008)

Bloomberg (2009) *India opposes carbon storage as climate change tool, Saran says*. Available at: http://www.bloomberg.com/apps/news?pid=20601130&sid=aEMIishWO_VA (Apr 2009)

Blue Wave (2007) *Supercritical and ultrasupercritical coal power plants*. Report to NRECA Cooperative Research Network by Bluewave Resources LLC, McLean, Virginia, USA, and IEA Clean Coal Centre, London, UK. 100 pp (Dec 2007)

BP (2008) *Statistical review of world energy (2008)*. Available at: http://www.bp.com/ (2008)

BP (2009) *Statistical review of world energy (2009)*. Available at: http://www.bp.com/ (2009)

Carpenter A M (2006) *Use of PCI in blast furnaces*, CCC/116, IEA Clean Coal Centre, London, UK, 66 pp (Oct 2006)

Carpenter A M (2008) *Polygeneration from coal*, CCC/139, IEA Clean Coal Centre, London, UK, 96pp (Oct 2008)

China Daily (2004) *Gov't warns of overheating in coke industry* (24 May 2004)

China Daily (2008) *China to produce liquid fuel from coal* (30 Mar 2008)

Cho J-M, Giannini-Spohn S (2007) *A China environmental health research brief. Environmental and health threats from cement production in China*. China Environment Forum partnership with Western Kentucky University on the US AID-supported China Environmental Health Project. Available at: http://www.wilsoncenter.org/index.cfm?topic_id=1421&fuseaction=topics.item&news_id=274782 (Aug 2007)

CIAB (2002) Coal and sustainable development – achieving balance in priorities. Position paper by CIAB. *World summit on sustainable development*, Johannesburg, South Africa, 18 pp (Aug 2002). Available at: http://www.iea.org/Textbase/Papers/2002/COAL.pdf (2002)

Clemson (nd) Miscellaneous Industries: Case 5 - Residential Building Construction in Beijing. Available from: http://cherokee.agecon.clemson.edu/China_case9.pdf, Clemson, South Carolina, USA, University of Clemson, 6 pp (nd)

CoalPower, IEA Clean Coal Centre, London, UK. Available on-line from www.iea-coal.org

Couch G (2008) *Coal to liquids*, CCC/132, IEA Clean Coal Centre, London, UK, 114 pp (Mar 2008)

Epoline (2008) *McIlvaine reports desulfurization system market at $200 B*. Available at: http://www.eponline.com/articles/68631/, Dallas, Texas, USA, Environmental Protection online (23 Oct 2008)

Eskom (2009) *Power stations and pumped storage schemes*. Details of individual Eskom plants. Available at: http://www.eskom.co.za/live/content.php?Item_ID=137 (2009)

Feller G (2008) *China's Coal. The reality of energy development in China*. Available at: http://ecoworld.com/features/2008/01/21/chinas-coal/, Eco World Journal (Jan 2008)

FFEM (2009) *Energy efficiency and sustainable development, combating the greenhouse effect and climate change*. France, Paris, French Global Environment Facility, 24 pp (2009)

Hablakilns (2007) *The Brick Industry*. Available at: http://www.hablakilns.com/industry.htm, Hawthorn East Victoria, Australia, Habla Kilns Ltd (2007)

Henley J P (2007), *Overview of China's lead in coal gasification implementation.* Coal Gasification in China. Available at: http://www.gasification.org/Docs/Legis/2007%20China%20Roundtable/Senate%20RT%20Review%20DOW% 20JPH%202007%2003%2023.pdf, The Dow Chemical Company, 21 pp, 23 Mar (2007)

IEA (2006) *Key World Energy Statistics*. International Energy Agency, Paris, France. 82 pp (2006)

IEA (2008a) *CO_2 Capture and Storage: A key abatement option*. International Energy Agency, Paris, France, 266 pp (2008)

IEA (2008b) *World Energy Outlook 2008*. International Energy Agency, Paris, France. 578 pp (Nov 2008)

IEA (2009) *World Energy Outlook 2009*. International Energy Agency, Paris, France. 696 pp (Nov 2009)

IEA/OECD (2006) *Focus on Asia, Focus on Clean Coal*. Working paper. Available at: http://www.iea.org/, International Energy Agency, Paris, France (Nov 2006)

IEA/OECD (2007) *Fossil fuel-fired power generation. Case studies of recently constructed coal- and gas-fired power plants*. Paris, France, International Energy Agency, 171 pp (2007)

IEA/OECD (2008) *Coal Information 2008*. International Energy Agency, Paris, France, IEA/OECD, 514 pp (2008)

IEA/OECD (2009) *Coal Information 2009*, International Energy Agency, Paris, France, 498pp (2009)

IPCC (2005) *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. De Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp. (2005)

Izumi Y (2008) *Technology transfer in the cement sector*. Available at: http://www.asiapacificpartnership.org/pdf/vancouver/Stakeholder1_03.pdf, Japan Cement Association, 12 pp (30 Oct 2008)

Lindsay I, Lowe C, Reddy S, Bhakta M, Balkenende S (2009) Designing a climate friendly hydrogen plant. *Energy Procedia*; **1** (1); 4095-4102 (Feb 2009)

MacDonald S (2008) *Consolidation in the world steel industry*. OECD DSTI/SU/SC(2007)24, 62nd OECD Steel Committee meeting and round table on consolidation in the world steel industry, Istanbul, Turkey, 10 pp,17-18 May (2007)

Maithel S, Mueller H, Singh R (nd) *Experiences in transfer and diffusion of efficient technologies in Indian brick industry*. Available at: http://www.resourcesaver.com/file/toolmanager/O105UF862.pdf. New Delhi, India, TERI; Nepal, Pokhara, Swiss Centre for Development Cooperation in Technology and Management; New Delhi, India, Priya Brick Technology Consultancy Services, 9 pp (nd)

Mantripragada H C, Rubin E S (2009) CO_2 reduction potential of coal-to-liquids (CTL) plants *Energy Procedia*; **1** (1); 4331-4338 (Feb 2009)

Mao J (2008) CFB boilers in China. *Cleaner Coal Workshop*, Halong City, Vietnam, 19-21 Aug 2008. 27 pp. Available at: http://www.egcfe.ewg.apec.org/publications/proceedings/CleanerCoal/HaLong_2008/Day%202%20Session%20%205%20-%20Jianxiong%20Mao%20CFB%20Boilers%20in%20China.pdf (2008)

Market Avenue (2008) Report on China's Coal-to-Methanol Industry, 11 July 2008. Available at: http://www.marketavenue.cn/upload/ChinaMarketReports/REPORTS_1010.htm, Beijing, PR China, 63 pp (2008)

Marland G, Boden T A, Andres R J (2008) *Cement Manufacture, and Gas Flaring. Global, regional, and national CO_2 emissions*. In trends: A compendium of data on global change. Available at: http://cdiac.ornl.gov/ftp/trends/emissions/saf.dat, Tennessee, USA, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory (Aug 2008)

Marulanda C (2007) *Sustainable chemical management - Exploring opportunities for the global chemical industry. Linking sound chemicals management to the development agenda*. Available at: http://siteresources.worldbank.org/INTPOPS/Resources/CMChemsAndEnergy.pdf, The World Bank, 15 pp, 28 Mar (2007)

McIlvaine (2008) *NOx Control: World Markets. China will help drive the NOx control market to $5 billion/year*. Available from: http://www.mcilvainecompany.com, The McIlvaine Company, 24 Oct (2007)

METI (2007) FY 2007 Annual energy report. Available at: http://www.enercho.meti.go.jp/english/report/19fy_outline.pdf, Japan, Ministry of Economy, Trade and Industry, 42pp (2007)

Metz B (2007) *Climate change 2007. Mitigation of climate change*. Working Group III contribution for the 4th assessment register of the IPCC, 115 pp (2007)

Mills S J (2007) *Prospects for coal and clean coal technologies in India*. CCC/129, IEA Clean Coal Centre, London, UK, 73 pp (Dec 2007)

Mills S J (2008) *Meeting the demand for new coal-fired power plants*. CCC/141. IEA Clean Coal Centre, London, UK, 66pp (Nov 2008)

Minchener A J (2004) *Coal in China*. CCC/87, IEA Clean Coal Centre, London, UK, 59 pp (July 2004)

Minchener A J (2009) IEA Clean Coal Centre, London, UK. *Personal communication* (9 Sept 2009)

Murray A, Price L (2008) *Use of alternative fuels in cement manufacture, Analysis of fuel characteristics and feasibility for use in the Chinese cement sector.* Lawrence Berkeley National Laboratory, Berkeley, California, USA. LBNL-525E, 63pp (2008)

NETL (2000) *Blast Furnace Granulated Coal Injection System Demonstration Project: A DOE assessment*, DOE/NETL-2000/1126. Morgantown, West Virginia, USA. 45pp (June 2000)

NETL (2009) *Affordable, Low-Carbon Diesel Fuel from Domestic Coal and Biomass*, US DOE. Report No. DOE/NETL-2009/1349. Morgantown, West Virginia, USA. 126pp (Jan 2009)

Okuno Y (2006) *Prospects of iron and steel production and progress of blast furnace route in China*, Technical report No 94.UDC 669.1.012.4 (510): 669.162. Available at: http://www.nsc.co.jp/en/tech/report/pdf/n9403.pdf. Japan, Nippon Steel, 7 pp (July 2006)

Perlitz U (2007) *Steel market in Indian*, Frankfurt am Main, Germany, Deutsche Bank Research, 12 pp, 27 Sept (2007)

Portland Cement Association (2008) *Tire Derived Fuel*. Portland Cement Association, Skokie, Illinois, USA. 5pp (2008)

Prasad S B (2007) Climate change and steel sector. *IPCC Working Group III's dissemination workshop on Fourth Assessment Report*, Kolkata, India, 11-12 Oct (2007)

Price L, Worrell E (2006) Global energy use, CO_2 emissions and the potential for reduction in the cement industry. In: *Cement energy efficiency workshop*. Organised by IEA in co-operation with WBCSD, Paris, France, 4-5 Sept 2006, 20 pp (2006)

RAG (2003) The international market for metallurgical coke. RAG Trading GmbH, *International Pig Iron Secretariat, 37th Members` Meeting*, Lausanne, Switzerland, 11-13 June 2003. Available at: http://www.pigiron.org.uk/getlibrarydoc.php?id=36&docnum=1&type=pdf (2003)

Ricketts B (2006) Focus on clean coal, Working paper, Focus on Asia Pacific, IEA/OECD, Paris, France (Nov 2006)

SANERI (2009) *Business plan 2009/14*, Centre for Carbon Capture & Storage, South African National Energy Research Institute, Working draft, 86 pp (Mar 2009)

Sathare J, Price L, de la Rue du Can S, Fridley D (2005) *Assessment of energy use and energy savings potential in selected industrial sectors in India.* Report LBNL-57293, Berkeley, California, USA, Lawrence Berkeley National Laboratory, 100 pp (2005)

Schultz J D (2006) *Regional Perspectives – NAFTA*, Regional ISS perspective - American Iron and Steel Institute, DSTI/SU/SC(2006)61, OECD Directorate for science, technology and industry steel committee meeting, Paris, France,11 pp, 7-8 Nov (2006)

Sinha A K (2006) The need for graduation to larger unit sizes. Towards mega-growth and cleaner environment. *International summit and expo power India 2006*, Mumbai, India, 12-15 October (2006)

Sloss L (2009) *Impact of emissions legislation on coal-fired power plants*. CCC/145. IEA Clean Coal Centre, London, UK, 51pp (Feb 2009)

Smouse S (2009) Pittsburgh, PA, USA, U.S. Department of

Energy, National Energy Technology Laboratory, *Personal communication* (7 May 2009)

Sreenivasamurthy U (2008) *Domestic climate policy for the steel sector, India. International support for domestic climate policies*. Cambridge, UK, Electricity Policy Research Group, University of Cambridge, 29 pp (Nov 2008)

Srivastava N K (2008) *Perspective, policies and technical issues on renovation and modernisation programme in India – NTPC Ltd*. Cleaner coal workshop, Ha Long City, Vietnam, 22 pp, 19-21 Aug (2008) Available at: http://www.egcfe.ewg.apec.org/ (2008)

Stockwell D (2008) *Carbon capture and storage in developing countries*. Available at: http://ukinhungary.fco.gov.uk/resources/en/power-point/3898777/3898786/ccs-debbie-stockwell, UK Department for Environment, Food and Rural Affairs - International Climate Change Division, 22 pp (2008)

Sun Q (2008) *CTL Development in China*. Washington DC, USA, US-China Energy Center, West Virginia University, Congressional Noontime Briefing, Rayburn House Office Building, 24 Apr (2008)

Taylor M, Tam C, Gielen D (2006) Energy efficiency and CO_2 emissions from the global cement industry. *IEA-WBCSD workshop, Energy efficiency and CO_2 emission reduction potentials and policies in the cement industry*, Paris, France, 12 pp, 4-5 Sept (2006)

Tian J (2008) *Implementing energy efficiency programs in China's power generation sector. Case study of recent policy initiative*. Working paper. Available at: http://www.adb.org/Documents/events/2008/ACEF/session19-Tian.pdf, Asian Development Bank, 26 pp, 30 May (2008)

Topper J (2008) *Coal for power world wide and the work of the IEA CCC*. Available at: http://www.iea.org/textbase/work/2008/neet_russia/Topper_Clean_Coal_Center.pdf. Moscow, Russia, FASI-IEA NEET Workshop on Energy Technology Collaboration, 29 pp, 30 Sept (2008)

Tullo A H and Tremblay J-F (2007) Coal: the new black. *Chemical & Engineering News*; 15 (17 Mar 2008)

Wang F and Guo X (2008) Opposed multi-burner (OMB) gasification technology. *Gasification technologies conference*, Washington DC, USA, 8 Oct (2008). Available at: http://www.gasification.org/Docs/conferences/2008/37WANG.pdf (2008)

Wang Y and Zeng S (2008) Environment protection regulations and practices on emission reduction of coal-fired power plants in China. *Cleaner coal workshop on solutions to Asia's growing energy and environmental challenges*, Ha Long City, Vietnam, 29 pp, 19-21 Aug (2008)

World Steel Association (2008a) Technology transfer, Spreading industry best practice. Fact sheet. Available from: http://www.worldsteel.org (Oct 2008)

World Steel Association (2008b) Raw materials. Fact sheet. 2 pp. Available from: http://www.worldsteel.org (Oct 2008)

UNDP (2003) *Improving kiln efficiency in the brick making industry in Bangladesh. Proposed GEF Implementing Agency*. Available at: http://www.gefonline.org/, Global Environment Facility (2003)

UNEP (2008) *Green jobs: Towards decent work in a sustainable, low-carbon world. Basic industry*. Available at: http://www.unep.org/PDF/UNEPGreenjobs_report08.pdf Nairobi, Kenya, United Nations Environment Programme, 376 pp (Sep 2008)

UNESCO (2007) *Report on applying coal gasification technology in China's coal chemical industry*. Available at: http://unesdoc.unesco.org/images/0015/001516/151688e.pdf Beijing, PR China, Natural Sciences Sector, UNESCO Office Beijing, UNESCO/Shell Chair in Coal Gasification Technology, 58 pp (2007)

van der Riet M (2007) Clean coal technologies for power generation - a South African perspective. Available from: http://www.iea.org/textbase/work/2007/neet/van_der_riet.pdf South Africa, SANERI, 20 pp (Feb 2007)

van der Riet M, Begg J H (2003) *Clean coal technologies for South Africa*, ESI Africa (2). Available from: http://www.esi-africa.com (2003)

van Holthoon E (2007) Shell gasification processes, *Gasification technology conference*, San Francisco, USA, 18 pp, 14-17 Oct (2007)

Yanjia W (2006) China's energy efficiency policy in industry, Contribution of mitigation policies to sustainable development, Goals in non-annex I. *Working together to respond to climate change*. Annex I - Expert group seminar in conjunction with the OECD Global Forum on Sustainable Development, Paris, France, 27-28 Mar (2006)

Yu Z (2007) *Opposed multi-burner gasification technology burner gasification technology - seven new projects in China*. Gasification technologies conference 2007, San Francisco, USA, 14-17 Oct 2007, 17 pp. Available from: www.gasification.org/Docs/Conferences/2007/14ZHOU.pdf (2007)

Yunyun L (2008) Steel mills: Coping with surging costs. *Beijing Review*, 10 Mar (2008). Available at: http://www.radio86.co.uk/china-insight/from-chinese-media/5475/steel-mills-coping-with-surging-costs (2008)

Zhu Y (2008) *Sectoral Study on the Iron and Steel Industry, Interdependencies on Energy and Climate Security*. Environment Energy and Development Programme, Chatham House, London, UK, 31 pp (Feb 2008). Available at: http://www.eu-china-energy-climate.net/documents/Iron%20and%20Steel%20Report.pdf (2008)

Zongrang Z (2007) Development of 1000-MW ultra supercritical coal-fired units in China. *Clean coal as a sustainable energy development strategy*, Hanoi, Vietnam, 7 Feb (2007). Available at: http://www.egcfe.ewg.apec.org/publications/proceedings/CFE/Hanoi_2007/5-3Zongrang.pdf (2007)