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**Working Paper**

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# CO$_2$ emission reduction potential of large-scale energy efficiency measures in heavy industry in China, India, Brazil, Indonesia and South Africa

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# CO$_2$ emission reduction potential of large-scale energy efficiency measures in heavy industry in China, India, Brazil, Indonesia and South Africa

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**Abstract:** We quantify the theoretical potential for CDM projects to improve energy-efficiency in selected heavy industrial sectors (iron and steel, cement, aluminium, pulp and paper and ammonia) in China, India, Brazil, Indonesia and South Africa and discuss the likelihood of the potential emission reductions materialising under CDM. Promising project types are: near net shape casting and pulverized coal / natural gas injection in iron and steel, cement blending, changes in aluminium smelter technology from Söderberg to prebaked anodes, continuous digestion process in pulp and paper, complete process integration in ammonia production. The total annual emission reduction potential of the iron and steel, cement and aluminium could reach more than 800 million CERs for China, India, Brazil and South Africa. While industrial boiler refurbishment could be widely replicated, reductions per boiler are relatively limited and overall potential is difficult to estimate.

# Contents

# 1.    Introduction

The manufacturing industry is a relevant greenhouse gas (GHG) emitter. As a whole, it accounted for about 7.1 billion t of $CO_2$ equivalent emissions in 1990. The heavy industries - iron and steel, cement, aluminium, pulp and paper and ammonia - account for a large proportion of worldwide GHG emissions of the manufacturing industry (see IPCC 2001). PFCs are directly emitted in the process of aluminium production while cement productionleads to $CO_2$ emissions. Steam and heat which are necessary for many industrial processes lead to direct emissions from fuel combustion. Indirect emissions are due to electricity consumption. Several studies have shown that the fossil fuel-based power sector in developing countries offers enormous potential for $CO_2$ emission reductions both through energy-efficiency improvements in existing plants as well as utilisation of state-of-the-art technology for new capacity additions (see IPCC 2001, Böhme et al. 2005). We thus only discuss energy savings in heavy industry in this paper.

The Clean Development Mechanism (CDM) could potentially help energy-efficiency projects in the heavy industry in developing countries to become economically attractive or remove barriers for implementation of state-of-the art technology in this area. The volume of CERs that potentially accrue from such project types is potentially huge.

This paper assesses the theoretical potential for energy-efficiency CDM projects using best available technology (BAT) in selected sectors of the heavy industry (iron and steel, cement, aluminium, pulp and paper and ammonia) in China, India, Brazil, Indonesia and South Africa and discusses which share of the potential emission reductions could actually materialise under the CDM.

The following chapter analyses the production processes for the selected heavy industries and the related energy use. Chapter 3 determines demand-side energy efficiency potential and resulting $CO_2$ emission reduction of a number of large-scale technology options on the basis of model energy-efficiency projects for each industry.  The fourth chapter analysis the energy efficiency potential of industrial steam supply based on model projects.  The aim of these chapters is to identify energy-efficiency project types that seem promising for CDM projects due to their emission reduction volume. Chapter 5 gives a rough estimation of total achievable emission reductions for the iron and steel, cement and aluminium industry in China, India, Brazil and South Africa[1]. Chapter 6 discusses the likelihood of the identified promising project types to materialise under CDM. The results of the paper are summarised in chapter 6.

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[1] For Indonesia sufficient data was not available. That was also the case for the pulp and paper and the ammonia industry in all countries.

# 2.    Process description of heavy industries

This section describes production processes of selected heavy industrial sectors: iron and steel, cement, aluminium, pulp and paper, and ammonia.

## 2.1    Iron and steel industry

Steel production accounts for approximately 5% of the global energy demand (see Phylipsen et al. 1998). The steel industry can be grouped in two different modes of production: "primary steel production" from iron ore (and a fraction of scrap), and "secondary steel production" from scrap only (see Figure 1). Primary steel production consists of three main production steps. First iron ore is reduced to iron. Depending on which of the three possible reduction processes is used, the output is either pig iron, directly reduced iron or smelted iron. Iron reduction is the production step with the highest energy intensity of all steel making processes (see Kim et al. 2002). Afterwards, the iron is processed to steel in open hearth (OHF) or basic oxygen furnaces (BOF). Finally, the steel is cast and rolled. In secondary steel production, scrap or directly reduced iron (DRI) is processed in electric arc furnaces to steel and cast and rolled afterwards.

The world average specific energy consumption (SEC) of steel production in 2002/2003 was 19 GJ/tonne of crude steel (see IISI 2005b). There is a technical long term potential to reduce the SEC to 12.5 and 3.5 GJ/t respectively (see de Beer et al. 1998).

**Figure 1: Iron and steel manufacturing process and major types of energy consumed**
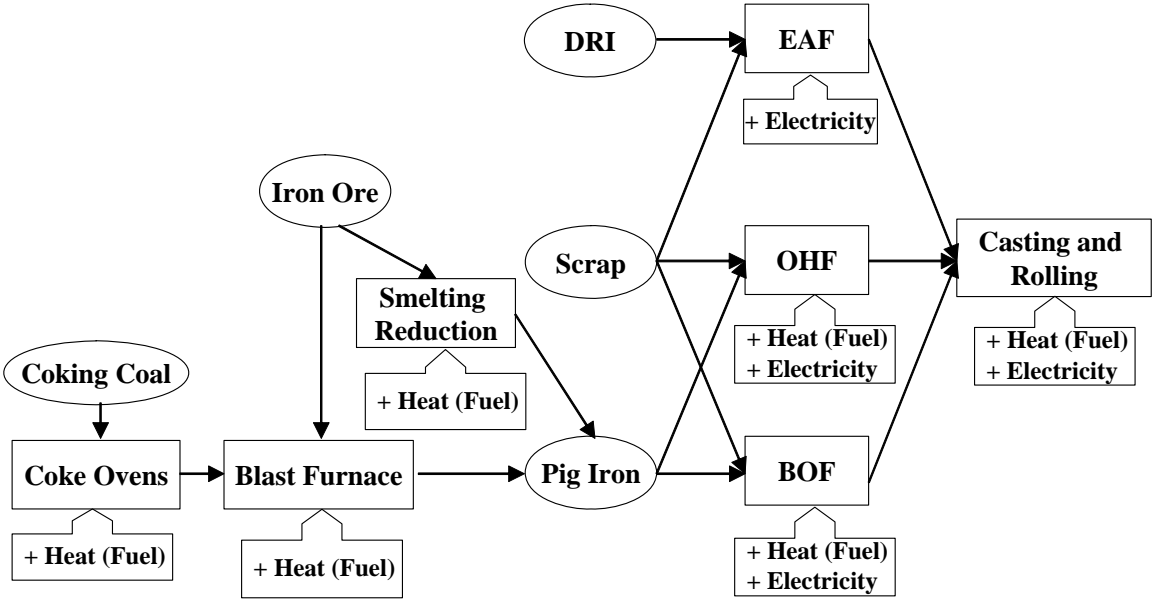
### 2.1.1 Iron making from ore

There are mainly three different methods to make iron: traditional pig iron production, smelting reduction, and direct reduction. Among the three, pig iron production is the most common way. Each technique is described below.

#### 2.1.1.1 *Traditional pig iron production*

Pig iron consists of approximately 95% iron, 3-4% carbon and traces of manganese, phosphorus, sulphur and silicon. The world production of pig iron was 717.7 Mt in 2004 (see IISI 2005a). The traditional pig iron production process involves the following three steps: 1) coke production, 2) sintering of iron ore, and 3) pig iron production in blast furnace

##### 2.1.1.1.1 *Coke production*

Coke is needed for iron ore reduction in blast furnaces. The most common process for producing coke from (bituminous) coal is the by-product process. In this process coal is heated to high temperatures in absence of oxygen (pyrolysis). The coke leaving the coke oven has to be cooled from around 1,100°C to 200°C

##### 2.1.1.1.2 *Processing of iron ore*

There are two kinds of iron ore, hematite and magnetite. Before they can be used to produce pig iron it has to be sintered or pelletised. For sintering, the ore is crushed and mixed with coke and lime dust. A thin tier of the resulting fines is ignited from above on a circulating grate. This causes the ore granules to agglomerate (see IEHK 2004).

##### 2.1.1.1.3 *Pig iron production*

Pig iron is produced in a blast furnace with limited oxygen. The capacity of blast furnaces for pig iron production ranges from 75 kilotonnes to four megatonnes per year (see Worrell et al. 1997).  In the furnace, the coke is mixed with sintered or pelletised iron ore and lime, and burnt at temperature of approximately 1,500°C.  The iron ore is reduced to pig iron producing by-products such as blast furnace slag and blast furnace gas.

#### 2.1.1.2 *Smelting reduction*

In some countries, e.g. South Africa, hard coal is abundant, but not coking coal. In such a case, smelting reduction technique can be an alternative to reduce iron ore to pig iron. Coal is gasified during the melting reduction of iron ore, which is pre-reduced with the gas from the gasification process. Surplus gas can be used as fuel e.g. for electricity generation or direct reduction of iron ore (see Ruth et al. 2001).

#### 2.1.1.3 *Direct reduction*

Iron can be reduced from iron ore at temperatures below the melting point of iron. The fuel for this process is in most cases natural gas. Unlike pig iron, direct reduced iron (DRI), known as sponge iron, can be used for secondary steel production as a substitute for scrap of high quality. Typical DRI plants have small capacities of less than one million tonnes per year (see Worrell et al. 1997).

### 2.1.2    Steel production – integrated plants

There are mainly three ways to produce steel from pig iron or DRI: OHF, BOF, and EAF. Steel scrap can be fed into all kinds of furnace to produce secondary steel. EAF is the most common technology for secondary steel production while OHF and BOF for primary steel production.

#### 2.1.2.1   *Open hearth furnace*

OHF represent a traditional and inefficient steel production technique. In an OHF, scrap and iron are melted in a pan lined with refractory bricks. The fuel and the combustion air are preheated below the melting pan in order to reach sufficient temperatures (1,650°C) when they are burnt directly over the steel. Excess carbon is removed by reducing rusty scrap ($Fe_2O_3$) to iron and carbon monoxide, which is oxidised to $CO_2$ using atmospheric oxygen. OHFs are nowadays continuously being replaced by basic oxygen furnaces (BOF) and the OHF share in world steel production is constantly decreasing. In 2004 only 3.2% of the global steel production came from open hearth furnaces and the largest shares could be found in Russia and the Ukraine (see IISI 2005a).

#### 2.1.2.2   *Basic oxygen furnace*

BOF uses the same technique as the OHF, but for carbon oxidation pure oxygen is used instead of air. This significantly reduces process duration and thus leads to a much higher level of energy efficiency and productivity. Apart from the lower energy intensity, BOF also have lower capital intensity than OHF, which supports the rapid replacement of OHF with BOF (see Worrell et al 1997). The share of scrap in BOF loads is usually 10 to 25%. The drawback of BOF compared to OHF is the lower possible scrap concentration (see Price et al. 2001). BOF technology accounted for 63% of world steel production in 2004 (see IISIa 2005).

#### 2.1.2.3   *Electric arc furnace*

Mini mills for secondary steel production normally use EAF. They were introduced for the production of special steel alloys, nowadays they serve to produce e.g. long products (e.g. wires, tubes etc.), mainly from a feedstock of scrap (see Poveromo 2003). They can also be used for steel production from direct reduced iron. The primary energy consumption is much lower than for integrated mills, because the pig iron production and coking are avoided. Direct reduced iron (DRI) can be used in exchange for high quality scrap. Using DRI as a feedstock leads to a slightly higher energy consumption of the EAF process due to the higher content of unwanted non-metal components (see Considine et al. 2000). The main energy source for electric arc furnaces is electricity, but the electricity consumption can be reduced by injecting fuels (see Worrell et al. 1997). 33.8% of the world steel production came from EAF processes in 2004 (see IISI 2005a).

### 2.1.3    Casting and rolling

Traditionally, the steel is cast into ingots. The ingot casting process is being replaced by approximately ten times more energy efficient continuous casting. An even more advanced casting technique is thin slab (near net shape) casting. It reduces the need for hot rolling because products are initially cast closer to their final shape (see Price et al. 2001).

After casting most of the steel is rolled. In hot rolling mills the steel is heated and fed through roller presses in order to reduce thickness. Typical energy consumption of hot rolling is 5.4 GJ/t of crude

steel. After hot rolling additional cold rolling can be carried out, the final step is optional finishing. Cold rolling and finishing account for another 1.85 GJ/t (see Price et al. 2001). In Brazil, India and Mexico the share of cold rolled products is increasing, causing additional energy consumption (see Price et al. 2001).

The actual primary energy intensity of the processes involved in steel making mainly depends on size and load of the plant, maintenance, how the plant is run and how the electricity and fuels are supplied. Table 1 shows typical energy intensity ranges for the most common processes in iron and steel making.

**Table 1: Typical SEC of each steel production process**

| Process | SEC [GJ/t steel] |
|---|---|
| Iron making – pig iron[1] | 12.7-18.6 |
| Iron making – smelting reduction[1] | 13.0-18.0 |
| Iron making – DRI[1,2] | 10.9-16.9 |
| Steel making – OHF | 3.9-5.0 |
| Steel making – BOF | 0.7-1.0 |
| Steel making – DRI + EAF[2] | 4.0-6.7 |
| Steel making – scrap + EAF | 4.0-6.5 |
| Casting – ingot casting | 1.2-3.2 |
| Casting – continuous casting | 0.1-0.3 |
| Casting – thin slab casting | 0.6-0.9 |
| Rolling – hot rolling | 2.3-5.4 |
| Rolling – cold rolling | 1.6-2.8 |
| [1] Includes energy for coke making and ore preparation [2] 80% DRI, 20% scrap | |

Source: see Price et al. (2001)

Different combinations of steel production routes cause different energy intensities for the production process. Using the median of each production step's energy intensity range from Table 1, Price et al. (2001) estimated some examples for some possible combinations (see Table 2)

Table 2: Typical SEC of steelmaking process combinations

| Process combinations | Primary energy intensity (GJ/t steel) |
|---|---|
| Pig iron – OHF – ingot casting – hot rolling | 26.2 |
| Pig iron – BOF – ingot casting – hot rolling | 22.6 |
| Pig iron – BOF – continuous casting – hot rolling | 20.6 |
| Pig iron – BOF – thin slab casting | 17.3 |
| Smelting reduction – BOF – ingot casting – hot rolling | 22.4 |
| Smelting reduction – BOF – continuous casting – hot rolling | 20.4 |
| Smelting reduction – BOF – thin slab casting | 17.1 |
| DRI – EAF – continuous casting – hot rolling | 23.3 |
| DRI – EAF – thin slab casting | 20.0 |
| EAF – continuous casting – hot rolling | 9.3 |
| EAF – thin slab casting | 6.0 |

Source: see Price et al. (2001)

## 2.2 Cement industry

The cement industry is one of the most energy intensive industries, especially in developing countries. Energy consumption causes 20-25% of the production cost (see Mohanty 1997). For cement production (see Figure 2), lime, silica and coal (amongst others) are ground and then processed in a kiln (pyro-processing). The lime (calcium carbonate, $CaCO_3$) is "calcined" to calcium oxide (CaO) at 800-900°C. In this process heat is consumed and $CO_2$ is emitted. From the CaO and other components like iron oxides and aluminium oxides, clinker is produced in the kiln, consuming heat at 1,350-1,450°C (see Hersel 2002). After leaving the kiln, the clinker needs to be cooled (see Hendriks et al. 2004). The clinker is ground and mixed with additives, e.g. gypsum, fly ash or blast furnace slag (see Hendriks et al. 2004). The clinker/cement (C/C) ratio determines the cement type, hardness and curing time; the most common cement type is Portland cement with a clinker/cement ratio of 0.95 (see Hendriks et al. 2004).

Figure 2: Cement manufacturing process and major types of energy consumed
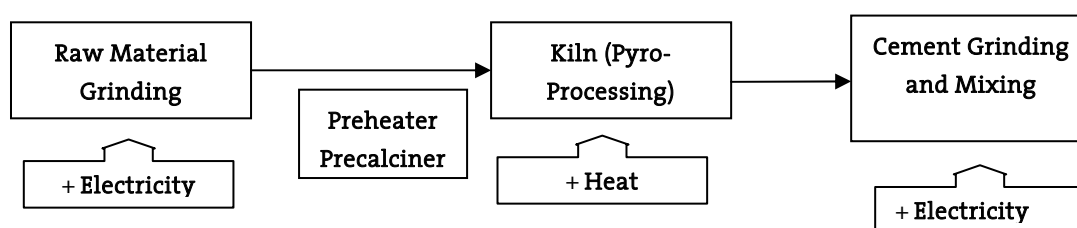


As table 3 shows, primary energy demand for cement production in 1994 ranges from approximately 3.5 GJ/t for a dry rotary kiln with four-stage preheating to around 7 GJ/t where inefficient wet kiln processes are used (see Hendriks et al. 2004).

Table 3: Global carbon emissions from cement production in 1994

| Region/ Country | Cement Production | C/C Ratio | Primary Intensity (Cement) | Primary Energy | Process Carbon Emissions | Carbon Emissions Energy Use | Total Carbon Emissions |
|---|---|---|---|---|---|---|---|
| | Mt | % | GJ/t | PJ | Mt $CO_2$ | Mt $CO_2$ | Mt $CO_2$ |
| China | 423 | 83 | 5.0 | 2,117 | 175 | 197 | 372 |
| Europe | 182 | | 4.1 | 749 | 73 | 56 | 129 |
| OECD Pacific | 151 | | 3.5 | 533 | 65 | 41 | 105 |
| Other Asia | 124 | | 4.9 | 613 | 56 | 179 | 105 |
| Middle East | 111 | | 5.1 | 563 | 51 | 44 | 95 |
| North America | 88 | | 5.4 | 480 | 39 | 40 | 78 |
| EE/FSU | 101 | | 5.5 | 558 | 42 | 38 | 80 |
| Latin America | 97 | | 4.7 | 462 | 41 | 30 | 71 |
| India | 62 | 89 | 5.0 | 309 | 28 | 30 | 60 |
| Africa | 41 | | 4.9 | 201 | 18 | 15 | 33 |
| World Total | 1,381 | | 4.8 | 6,585 | 587 | 830 | 1,126 |

Source: see Hendriks et al. (2004)

Opportunities for energy saving by increasing the efficiency of cement production can be found in two different energy-intensive processes: i) the calcination and clinker production (pyro-processing), and ii) raw material/cement grinding/mixing processes. Those processes are further examined in the following.

### 2.2.1   Pyro-processing

The pyro-processing stage consumes large amounts of heat generally supplied by burning of (fossil) fuels. Pyro-processing accounts for up to 87% of the primary energy needed in the cement production process (see Mohanty 1997). There are basically three types of clinker production methods: dry, semi-dry (or semi-wet) and wet kiln processes. Wet kiln processes consume more energy than the dry process because additional heat is needed to dry the slurry in the kiln before calcination and sintering can take place. Although the energy efficiency improvement potential of wet-to-dry-conversion is significant, such measures are not considered in this study because nowadays almost all cement plants (except for the U.S.) use dry processes (see Table 4).

Table 4: The influence of process type on energy efficiency (1995 data)

| Kiln Type | Brazil | China | India | Mexico | South Korea | USA | Typical primary intensity (GJ/t clinker) |
|---|---|---|---|---|---|---|---|
| Wet | 8% | 8% | 14% | 1% | 1% | 27% | 6.2 |
| Semi-Dry | 3% | 0% | 3% | 0% | 0% | 1% | 3.9 |
| Dry | 14% | 7% | 6% | 29% | 0% | 21% | 4.5 |
| Dry with preheaters | 37% | 2% | 16% | 4% | 15% | 19% | 3.6 |
| Dry with preheaters/ precalciners | 38% | 4% | 53% | 67% | 84% | 33% | 3.4 |
| Shaft | 0% | 79% | 8% | 0% | 0% | 0% | 5.3 |
| C/C ratio | 80% | 82% | 90% | 88% | 94% | 88% | |
| Weighted typical primary intensity (GJ/t cement) | 3.7 | 4.8 | 4.2 | 3.9 | 3.8 | 4.5 | |

Source: Adopted from Phylipsen et al. (2002) for process shares (1995 data), and Hendriks et al. (1999) for typical primary intensity values.

### 2.2.1.1 Kiln type

There are two main kiln types available for clinker production: vertical shaft and rotary kilns. Vertical shaft kilns calcine and sinter the raw meal in an upright kiln with the hot combustion gases flowing in counter current direction. In spite of some exceptions, vertical kilns usually have lower fuel efficiency. The clinker is generally of a lower quality than clinker from rotary kilns. Another kiln technology is a rotary kiln. Rotary kilns are used in most countries. They have lining of fire resistant bricks and slope of 3-6°. Ground raw materials are fed into the kiln at the upper end. At the lower end there is a flame to heat up the inside of the kiln (see Mohanty 1997). The combustion gas enters the kiln at a temperature of approximately 2,000 °C (see Hersel 2002) and moves upwards in counter current with the material that tumbles down the kiln, being dried and calcined (where necessary) and then sintered to form clinker.

### 2.2.1.2 Preheaters and precalciners

Apart from using raw material that is as dry as possible, the use of preheaters and precalciners are possibilities for increasing energy efficiency. They also increase the plant capacity as a side effect. Because drying, heating and calcination takes place in the preheaters and precalciners, kilns are only needed for clinkerisation (sintering). Heat for these pre-treatment steps can be provided by heat recovery from cooling the clinker and by using the kiln's exhaust gases. Precalciners usually have an additional burner, for which (alternative) fuels with a lower heating value can be used.

Nowadays a rotary kiln with five stage preheater and precalciner (capacity 3000 t/d) can achieve a SEC of 2.9 - 3.2 GJ/t clinker (see Ruth et al. 2000).

### 2.2.2 Grinding and crushing

Grinding and mixing stages use a lot of electricity. The factors that influence the electricity consumption most are mill types used as well as hardness and composition of the materials ground. The total electricity consumption varies between 90-130 kWh/t cement (see Cembureau 1999).

#### 2.2.2.1 *Raw material grinding*

Different types of mills have different designs and energy intensities (see Table 5). Tube mills (ball mills) are usually less energy efficient than horizontal or vertical roller mills (VRMs) and roller presses, which have the highest energy efficiency. Tube mills have a specific electricity consumption of 17-20 kWh/t raw material (see Ruth et al. 2000). The electricity consumption of VRMs is 25-30% lower than of tube mills, horizontal roller mills are 30-35% more energy efficient, and roller presses need 35-50% less electricity than tube mills. The main advantage of tube mills is that operating and maintenance costs are lower, which can make up for the lower energy efficiency, where electricity is cheap (see Ruth et al 2000). The best available technology for raw material preparation is the roller press with static V-separator for raw material preparation which has a specific electricity consumption of 10-11 kWh/t (see Ruth et al. 2000).

**Table 5: SEC of each raw material grinding technology in dry cement making**

| Technology | SEC (kWh/t raw material) |
|---|---|
| Center discharge tube mill | 17-20 |
| Airswept tube (ball) mill | 17-20 |
| VRM | 13-14 |
| Roller press, static V-separator | 10-11 |

Source: see Ruth et al. (2000)

#### 2.2.2.2 *Cement grinding and mixing*

About 40% of the electricity used in a cement plant is consumed in the final cement grinding process (see UNIDO 1994) where clinker and additives are ground until they have reached the desired grade of fineness.

Specific electricity consumption for cement grinding and mixing of an open system (without a separator) with tube mills can be as much as 55 kWh/t (see Mohanty 1997). When using roller press and a separator the SEC can be reduced to be around 28 kWh/t (see Mohanty 1997, p.15). A high-efficiency separator is estimated to further reduce the electricity consumption at this stage by 1.7-2.3 kWh/t cement (see Ruth et al. 2000, p.4). The best available technology (closed system based on a roller press with high-efficiency separator) has potential to achieve 25 kWh/t cement (see Ruth et al. 2000, p. 10).

Table 6: Energy use of different configurations of the cement grinding process

| Technology | SEC (kWh/t cement) |
|---|---|
| Open system with ball mills[1] | 55 |
| Closed system with ball mills and a separator for recycling[1] | 47 |
| Closed system with pre-grinding of clinker into an energy efficient roller mill with recirculation[1] | 41 |
| Closed system based on roller press, a ball mill and separator[1] | 39 |
| Closed system only based on a roller press and separator[1] | 28 |
| Closed system only based on a roller press and high-efficiency separator[2] | 25 |

Source: see Mohanty (1997)[1] and see Ruth et al. (2000)[2]

## 2.3    Aluminium industry

Energy represents about 25% of the costs associated with primary aluminium production (see EAA 2003). The aluminium industry can be grouped into two different modes of production process: "primary aluminium" from alumina which is converted from bauxite, and "secondary aluminium" from recycled metal (see Figure 3). In the primary aluminium industry, the main processes are alumina production and aluminium production. In alumina production, also known as alumina refining, bauxite (aluminium containing ore) is converted to alumina ($Al_2O_3$) by treating it with sodium hydroxide at elevated temperatures and pressure (the Bayer process). Alumina is electrolytically reduced to primary aluminium in the Hall-Héroult process. Electrolysis, also known as aluminium smelting, takes place in a so-called primary smelter. In the electrolysis, carbon anodes are used, produced by baking pitch and/or petrol cokes. After electrolysis the electrodes are partly recycled. Finally, the crude aluminium can be cast into intermediate products. The most energy consuming process steps are the production of alumina, the production of anodes (including anode feedstock), and the electrolysis. Of these steps, electrolysis is by far the most important one, accounting for about 85% of primary energy consumption (see Phylipsen et al. 1998).  Table 7 shows the significant energy consumption of the electrolysis process, leading to the biggest amount of GHG emission.

Table 7: GHG emission from primary aluminium production processes (kg-CO$_2$ per t process output and kg-CO$_2$/t Al)

| | Alumina refining | Anode production | Electrolysis | Casting |
|---|---|---|---|---|
| Process | 0 | 388 | 1,626 | 0 |
| Electricity | 58 | 63 | 5,801 | 77 |
| Fossil Fuel | 789 | 135 | 133 | 155 |
| Transport | 61 | 8 | 4 | 136 |
| Ancillary | 84 | 255 | 0 | 0 |
| PFC | 0 | 0 | 2,226 | 0 |
| Per t process output | 991 | 849 | 9,789 | 368 |
| Per t Al | 1,908 | 374 | 9,789 | 368 |

Source: Adopted from IAI (2003a)

Another route to produce aluminium is recycling and remelting aluminium scrap. Since this process does not require either alumina production or electrolysis, it saves up to 95% of the energy required for the production of primary aluminium (see EAA 2003).

Liquid aluminium is drained from the primary or secondary smelter and cast into buns, ingots, slabs or rods, using ovens. There is no significant difference in energy consumption among different types of products. A difference in SEC may arise if products are further processed by extrusion or rolling (see Phylipsen et al. 1998).

Figure 3: Aluminium manufacturing process and major types of energy consumed
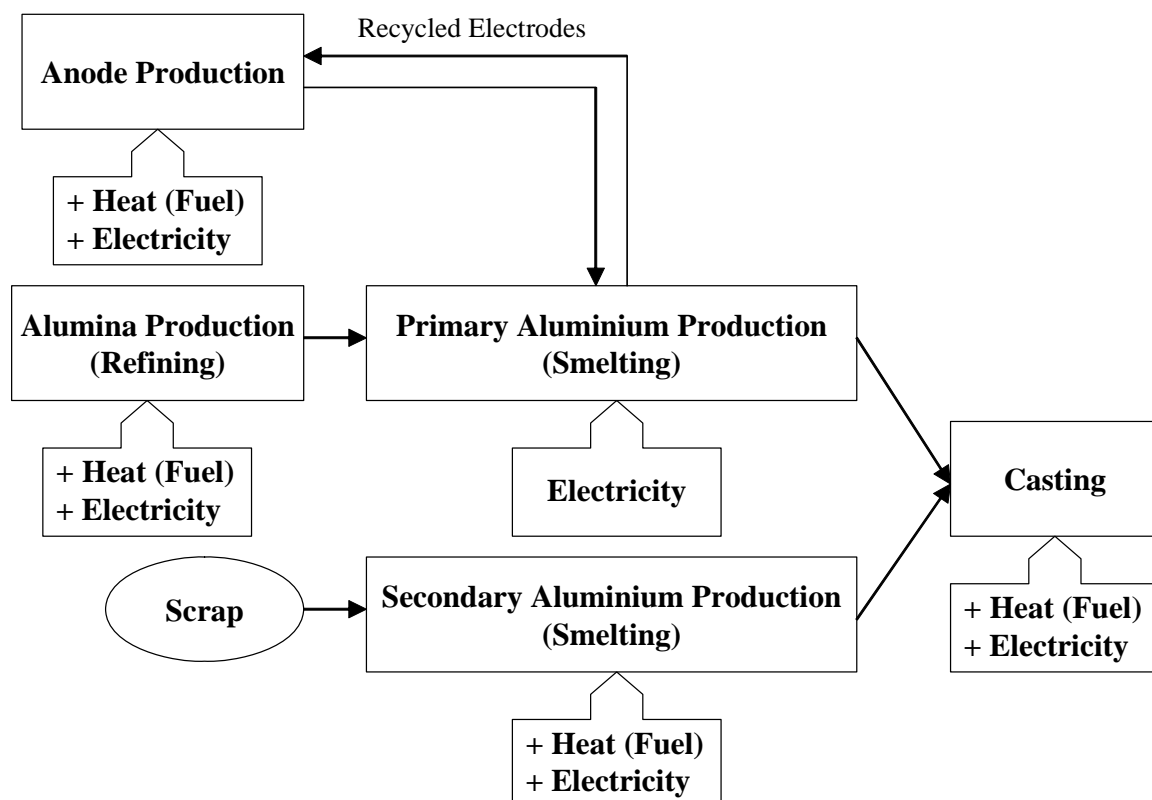
Table 8 shows specific electricity consumption in the electrolysis process, the most energy-intensive part, in different world regions.

Table 8: Specific electricity consumption in the electrolysis process in each region in 2003

| Region | SEC (MWh/t Al) |
|---|---|
| Africa | 14.3 |
| North America | 15.5 |
| Latin America | 15.4 |
| Asia | 15.4 |
| Europe | 15.1 |
| Oceania | 14.8 |
| World average | 15.2 |

Source: see IAI 2004

The following part describes each process of aluminium production and typical SECs. Technologies for energy efficiency improvement are also identified.

### 2.3.1 Alumina production

In alumina production, bauxite is converted to aluminium oxide using the Bayer process, which uses caustic soda and calcined lime as input reactants. The slurry is heated and pumped to digesters, which are heated pressure tanks. In digestion, iron and silicon impurities form insoluble oxides called bauxite residue. The bauxite residue settles out and a rich concentration of sodium aluminate is filtered and seeded to form hydrate alumina crystals in precipitators. These crystals area then heated in a calcining process. The major differences in processing are at the calcinations stage. There are two types of kilns: rotary and fluid bed. The fluid bed or stationary kiln is newer and significantly more energy efficient (see IAI 2003a). Improving alumina refining by replacing rotary kilns with fluid bed kilns would cut energy demand of this stage by 60% (see Gale et al. 2000).

The energy requirement for alumina production was estimated to be 3.76 kWh/kg of alumina or 7.27 kWh/kg of primary aluminium in the U.S. (see Choate and Green 2003). The world best practice SEC in 1998 was estimated to be about 9.5 GJ/t of alumina (see ISR). The Alumina Technology Roadmap set a long-term target to reduce energy consumption in the refining process to 25% below current best practice by 2020 through better chemical process knowledge, waste heat utilization, and cogeneration (see DOE 2001).

### 2.3.2 Primary aluminium production

In the primary aluminium production process molten aluminium is produced from alumina by the Hall-Héroult process that dissolves the alumina in a molten cryolite bath and passes current through this solution, thereby decomposing the alumina into aluminium and oxygen. Aluminium is tapped out of the reduction cell at daily intervals and the oxygen combines with the carbon of the anode to form $CO_2$. The cell consists of a steel shell lined with refractory materials insulation and with a hearth of carbon. This is known as cathode. The cathode is filled with a cryolite bath and alumina and an anode is suspended in the bath to complete the circuit for the pot. Once started, a cell will run

continuously for the life of the cathode, which may last for in excess of 10 years. At the end of its life each cell is completely refurbished (see IAI 2003a).

Since electricity consumption is the major energy aspect of the electrolysis process, the following part of this section will focus on only electricity use. In 2003, the world average electricity SEC of the electrolysis process in primary aluminium production was 15.2 MWh/t (see IAI 2004). The best available technology had an electricity SEC of 13 kWh/t in 1999 (see IAI 2001a). The energy efficiency of the process can be below 50% due to limitations in cell design imposed by the materials available today (see Nora 2002). Opportunities for energy savings can be found in electrode types used for electrolysis and electrolysis process itself.

### 2.3.3    Anode and cathode types

Energy efficiency of this process can be significantly improved by inert anode and wetted cathode technology.  As opposed to the current consumable carbon anodes, inert anodes are made from materials that are not consumed during the electrolysis reaction.  Inert anodes allow for a closer anode/cathode distance and reduce electrolysis energy consumption.  Wetted cathodes refer to cell designs that use new cathode materials such as titanium diboride ($TiB_2$) that are wetted by aluminium. They improve energy efficiency by reducing an anode/cathode distance and magnetically induced turbulence during the operation (see Martin et al. 2000). The combination of inert anodes and wetted cathodes is estimated to reduce energy requirements in the electrolysis and anode manufacturing processes by 3.05 MWh/t and $CO_2$ emissions by 1.65 t per t aluminium compared to the typical modern Hall-Héroult technology (see Choate et al. 2003). Both inert anodes and wetted cathodes are nearly commercial (see Martin et al. 2000).

### 2.3.4    Electrolysis process

There are two types of aluminium smelting technologies that are distinguished by the type of anode used: Söderberg and Prebake. Söderberg technology uses a continuous anode which is delivered to the cell in the form of a paste, and which bakes in the pot itself. On the other hand, prebake technology uses multiple anodes in each cell. These anodes are pre-baked in a separate facility and then suspended in the cell. Söderberg is the oldest technology and is being phased out in favour of Prebake (see Bergsdal et al. 2004). Table 9 shows SEC and global production share of each primary aluminium smelter technology.

Table 9: SEC and global production share of each primary aluminium smelter technology

| Technology | SEC (MWh/t Al)[1] | Global production share (%)[2] |
|---|---|---|
| PFPB (Point Feeder Prebake) | 13.3 (Greenfield expansion) 13.8 (Upgrading and brownfield expansion) 14.4 | 58 |
| CWPB (Center Work Prebake) | 15.5 | 9 |
| SWPB (Side Work Prebake) | 14.6 | 6 |
| HSS (Horizontal Stud Söderberg) | 16.6 (Söderberg average) | 9 |
| VSS (Vertical Stud Söderberg) | | 18 |

Sources: see Schwartz et al. (2000)[1] and see IAI (2003b)[2]

In addition to the high electricity saving potential, the electrolysis process has a great potential of PFC emission reduction. Two PFC ($CF_4$ and $C_2F_6$) contribute about 48% of primary aluminium GHG emissions (see EAA 2002). Emissions of PFCs are strictly the result of electrolytic reduction. They are formed only during the so-called anode effect when the electrolyte becomes depleted in alumina (see Harnisch et al. 1998). Manufacturers have been trying to reduce anode effects as they reduce productivity. Table 10 shows specific PFC ($CF_4$ and $C_2F_6$) emissions of each primary aluminium smelter technology. A shift from older smelter technologies to newer technologies improves energy efficiency while reducing PFC emissions.

Table 10: Specific PFC emissions and global production share of each primary aluminium smelter technology

| Technology | Specific PFC ($CF_4$ and $C_2F_6$) emissions in 2000 (t-$CO_2$/t Al)[1] | Global production share (%)[2] |
|---|---|---|
| PFPB | 0.84 | 58 |
| CWPB | 1.61 | 9 |
| SWPB | 7.89 | 6 |
| HSS | 3.78 | 9 |
| VSS | 2.49 | 18 |
| Note: Global Warming Potential of 6500 and 9200 were used for $CF_4$ and $C_2F_6$ respectively | | |

Source: IAI (2001b)[1] and IAI (2003b)[2]

### 2.3.5    Secondary aluminium production

Secondary aluminium is important since the energy demand of its production process is only 5-10% of the one of primary aluminium production. The aluminium recycling industry is growing faster than the primary industry. Secondary aluminium is now meeting over 25% of current world aluminium demand and could provide up to 50% of the aluminium metal supply within 20 years (see IAI 2003). Several new technologies have emerged that help to improve the recovery or processing of scrap or reduce energy use in the preparing and melting of scrap. However, opportunities for energy efficiency projects in the secondary aluminium production process are limited since the process is much less energy-intensive by nature.

### 2.3.6   Casting

Currently, the casting and rolling stage of aluminium production is a multi-step process involving ingot casting, transportation, reheating of the ingots and rolling into the desired shape (see Jaccard & Associates 2004).

## 2.4   Pulp and paper industry

The paper production process can be divided into two main process steps: the pulping and the paper production (see Figure 4). Plants which carry out both steps are called integrated paper mills. It is still very common that pulp and paper production steps are carried out in separated plants. Plants that do only produce pulp are called pulp mills - those plants that get pulp delivered from pulp mills for paper production are called paper mills. Pulp mills have a higher energy consumption per t of pulp than paper mills have per t of paper as pulping production is more energy-intensive than paper production (see Farahani et al. 2004).

After paper production the paper is dried[2]. The range of raw materials is wide (from wood over bagasse to rice straw), but they all contain substantial amounts of cellulose, hemicellulose (polysaccharides) and lignin.

**Figure 4: Paper and pulp manufacturing process and major types of energy consumed**
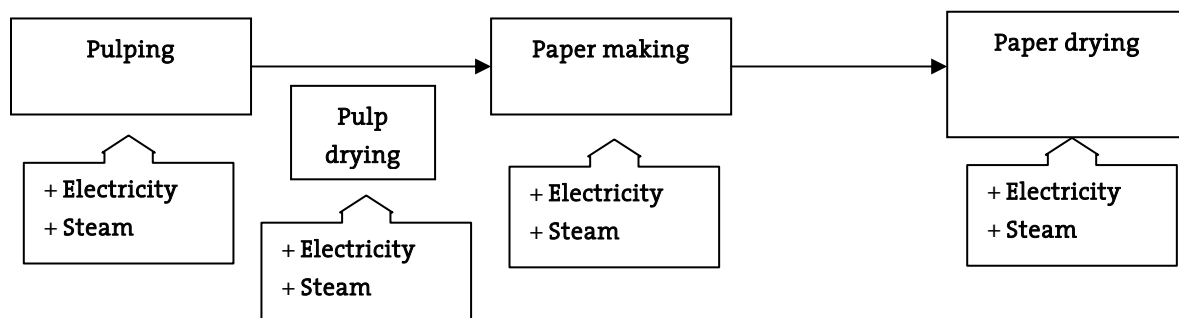


The share of steam in the pulp and paper industry amounts to ~ 70 to 80% of the total primary energy consumption (see Mohanty 1997b). The fuel for steam generation can be of fossil origin (coal, fuel oil, natural gas), but also waste materials from the pulp and paper making processes such as waste feedstock, waste paper or concentrated black liquor. Often steam and electricity are produced simultaneously in a cogeneration plant. Tables 10-11 show estimates for the shares of different paper making process steps in total steam and electricity consumption in an integrated mill. Pulping and drying are the most energy consuming processes by far.

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[2] Pulp also needs to be dried for transportation if produced in a pulp mill.

**Table 10: Shares of steam consumption in an integrated paper mill (typical average)**

| Process | Steam consumption [%] |
|---|---|
| Pulping | 40 |
| Drying | 33 |
| Bleaching | 21 |
| Hot water making | 5 |
| Others | 1 |

Source: Mohanty 1997b

**Table 11: Shares of electricity consumption in an integrated paper mill (typical average)**

| Process | Electricity consumption [%] |
|---|---|
| Paper forming | 40 |
| Pulping | 22 |
| Chemical plant | 11 |
| Boiler house | 13 |
| Water treatment | 12 |
| Others | 2 |

Source: Mohanty 1997b

In Europe, the average total SEC including thermal energy for electricity generation is around 16.1 GJ/t[3] of paper (see CEPI 2004). The thermal energy demand was 11.8 GJ/t including thermal energy for electricity generation and the electricity demand was 1.14 MWh/t. In 2003, 51% of thermal energy used stem from biomass (see CEPI 2004). Table 12 gives average SEC estimates for India, China, Indonesia, Japan and Netherlands for around 1990[4].

**Table 12: SEC in pulp and paper production in selected countries**

| Country | SEC (GJ/t) | Year |
|---|---|---|
| India | 30-55 | 1984 |
| China | 30-35 | 1992 |
| Indonesia | 10-20 | 1989 |
| Japan | 22 | 1992 |
| Netherlands | 17 | 1988 |

Source: see Phylipsen et al. (1998)

The average SEC values given above have limited explanatory power as the final energy consumption very much depends on the design of the plant (pulp, paper or integrated), the pulping process, characteristics of the raw material as well as the grade of the finished product. For example,

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[3] This value has been calculated based on total European paper production. The exact share of pulp, paper and integrated mills is not given. However, annual European pulp production was 40,981 kt and paper production 95,217 which, when assuming a ratio of ~1tpulp/1tpaper, shows that a substantial share of plants were paper mills that have imported their pulp from outside of Europe.

[4] Share of pulp, paper and integrated mills not given.

the energy demand for wastepaper pulping is only approx. 1/3 of wood pulping, so the SEC is lower where wastepaper pulp has a bigger share in total pulp production (see Mohanty 1997b).

The following table shows typical average steam[5] and electricity consumptions for pulp and paper mills (non-integrated) in Sweden and the US as well as BAT model plants. The model plant has been assumed to consist of the best technologies that have been built into Swedish pulp and paper mills so far. Table 13 also shows the specific consumption values of a pulp mill using waste paper as raw material only.

Table 13: Typical steam and electricity consumption of selected pulp and paper mills

|  | Sweden | | US | | BAT model | | Waste paper |
|---|---|---|---|---|---|---|---|
| Steam consumption (GJ/t) | 15.4 | 8.4 | 20.2 | 10.7 | 10.4 | 6.9 | 0.4 |
| Electricity consumption (kWh/t) | 854 | 760 | 780 | 588 | 588 | 760 | 390 |

Source: see Farahani et al. (2004)

In the following the most energy-intensive paper production steps are described and typical SEC values given.

### 2.4.1   Pulping

The pulping process serves to decompose raw materials and yield pure cellulose (fibers). The most common pulping processes can be divided into chemical and mechanical pulping processes. The following tables show the typical energy consumption found in the US and Europe for the most common processes.

Table 14: "Good practice" SEC of the most common chemical pulping processes in the EU and US

| Process | SEC | |
|---|---|---|
| | Steam (GJ/t) | Electricity (kWh/t) |
| Kraft pulping | | |
| *Conventional batch digester* | *3.5-4.4* | *325* |
| *Continous batch digester* | *1.7-2.7* | *400* |
| *Displacement batch digester* | *1.7-2.2* | *400* |
| Sulfite Pulping | 4.2 | 572 |

Source: see Rein (2002) and see Martin et al. (2000) and own assumptions

Table 15: "Good practice" SEC of the most common mechanical pulping processes

| Process | SEC | |
|---|---|---|
| | Steam (GJ/t) | Electricity (kWh/t) |
| Thermomechanical pulping | 0.9 | 2000-3500 |
| Grinding (stonegroundwood) | - | 1650 |
| Refiner pulping | - | 2000 |

Source: see Rein (2002) and see Martin et al. (2000)

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[5] Primary energy consumption was not given. It depends on the conversion efficiency of the steam boilers used as well the steam parameters.

In chemical pulping the raw material is cooked in digesters and therefore the process consumes a large amount of steam compared to the mechanical process where the raw material is grinded down to fibers. The steam in chemical pulping is usually produced by a recovery boiler ("Tomlinson boiler") that also separates the dissolved wood residues from the cooking chemicals. Produces steam by burning the residues. The boiler can be part of a CHP system (usually back-pressure steam turbine). Some recovery boilers can be fired with up to 80% black liquor (see Rein 2002). Black liquor is the mix of highly alkaline solution and dissolved contaminants remaining from the pulping process after the fibres and cooking chemicals have been removed. The cooking chemicals can be extracted and recovered for re-use on a chemical recovery process.

### 2.4.2    Pulp drying

In pulp mills the pulp also needs to be dried before it is transported to paper mills. It is estimated that in a US plant drying requires 4.5 GJ/t of steam and 155 kWh of electricity. Modern flash dryers are much more energy efficient. They use natural gas-fired air heaters and steam for drying the pulp. SEC is 1.7 GJ/t of natural gas and 0.7 GJ/t (see Rein 2002).

### 2.4.3    Papermaking

In the paper mill, the pulp is mixed with hot water and several additives. After screening, the liquid pulp is applied to a circulating mesh and dewatered, first by gravity and air suction, then by pressing. The pressing section is an obvious candidate for energy-efficiency measures as the drier the paper the less energy is consumed during paper drying. Estimates for technological options for pressing are not available. Martin et al. (2000) estimate a reduction in steam consumption by 1.6 GJ/t of paper when switching from a conventional roller press to a shoe press.

### 2.4.4    Paper drying

In the drying section the most common process is contact drying with steam heated cylinders. As the energy required for drying will depend on the dryness of the paper the energy demand should be expressed in GJ/t water removed. A "good practice" value is 3.2 GJ/t water which is 4.5 GJ steam per t when assuming that 1.4 kg steam is required for evaporating 1 kg of water (Rein 2002). Martin et al. (2002) estimate an energy consumption of 10 GJ/t and 21 kWh/t for a US plant. A condebelt dryer has almost the same steam consumption as a contact dryer but does allow for better heat recovery which makes them more energy-efficient (see Martin et al. 2000). The recovered heat can be utilised elsewhere in the process. In some paper mills additional gas-fired infrared dryers are used.

## 2.5    Ammonia industry

Ammonia is an important input for production in the nitrogen fertilizer industry, phosphate fertilizer industry and potash industry. Ammonia is synthesized by reacting nitrogen with hydrogen. Nitrogen is taken from ambient air and hydrogen is derived from calalytic reforming of hydrocarbon fuels (e.g. natural gas, fuel oils, naphta or coal). Pure $CO_2$ is a by-product from ammonia production and ammonia plants are often integrated with urea plants which process the $CO_2$ for nitrogen fertilizer production (see Windridge et al. 1998).

The following three main types of the ammonia production exist:
- steam reforming of natural gas or other light hydrocarbons
- partial oxidation of heavy fuel oil, vacuum residue or light hydrocarbon fuels
- coal gasification

During ammonia production the bulk of energy is consumed in form of the hydrocarbon fuel feedstock, except for steam reforming where a large quantity of fuel is burned in the reformer furnace. In steam reforming the amount of fuel burned is approximately 40-50% of the total fuel input into the process (see Windridge et al. 1998).

All process types have in common that they require a considerable amount of heat and/or steam to sustain the production process. The major share of heat and steam demand is usually supplied by waste heat recovery boilers. Modern steam reforming plants are net steam exporters while plants based on other process types usually need to operate additional steam boilers or import steam from external sources.

About 85% of current world ammonia production is based on steam reforming concepts (see Windridge et al. 1998). Coal gasification is not in use in Europe and the US anymore as in regions where natural gas is available the process is not economical because of its high specific energy intensity (see Rafiqul et al. 2005). In China, the majority of ammonia comes from medium and small sized ammonia plants that use the coal gasification process (see Price et al. 2000). In contrast, in India 87% of production capacity built after 1981 were natural gas based steam reforming plants (see Schumacher et al. 1999). In general, recent capacity additions world-wide tend to be based on steam reforming as the specific energy intensity is considerable lower than for other process types – unless no natural gas is available. In Indonesia, for example ammonia plants have witnessed a natural gas supply shortage in recent years (see Rabobank 2005).

Table shows typical SEC of ammonia plants surveyed in the US, EU and in India. It clearly illustrates that the SEC for steam reforming are significantly lower than for other process types.

Table 16: SEC surveyed in ammonia plants in selected countries

| Year | Country | SEC (GJ/t, NCV) including feedstock | | | | |
|---|---|---|---|---|---|---|
| | | Natural gas | Naptha | Heavy fuel oil | Coal | Average |
| 1980 | US | 40.1 | | | | |
| 1985 | US | 38.7 | | | | |
| 1990 | North America | 37.7 | | | | |
| 1995 | North America | 37.1 | | | | |
| 1998 | North America | 36.7 | | | | |
| 1994-1996 | US | | | | | 39.3-41.3[a] |
| 1979-1980 | India | | | | | 61.9 |
| 1986-1987 | India | | | | | 56.0 |
| 1991-1992 | India | 40.1 | 48.9 | 56.4 | 165.9 | |
| 1994-1995 | India | 38.7 | 47.2 | 59.8 | | |
| 1995-1996 | India | | | | | 45.6 |
| 1994-1996 | South Asia | | | | | 39.6 |
| 1989-1990 | EU | | | | | 35.5 |
| 1994-1996 | EU | | | | | 34.0-38.7[b] |
| a Average figures for different regions in the US | | | | | | |
| b Average figures for different regions in the EU | | | | | | |

Source: see Rafiqul et al. 2005

In China, the bandwidth of SEC of ammonia plants is very broad (39–65 GJ/t) due to the large share of gasification ammonia plants (see Price et al. 2002).

The theoretical minimum SEC for steam reforming plants is 19.4 GJ/t. In Europe, average SEC in 1998 was 35.5 GJ/t (see Rafiqul et al. 2005). The most energy-efficiency steam-reforming ammonia plant built so far is operating in China and is achieving a SEC of 26.8 GJ/t (see Rafiqul et al. 2005).

In the following we limit our analysis to natural gas based steam reforming plants for three reasons. First, with few exceptions they constitute the majority of plants that have been built in developing countries during the last 20 years due to their economic attractiveness. Second, they are the only plant type that uses considerable amounts of fuel as non-feedstock. Although a reduction in feedstock consumption does reduce the SEC of the plant, it does not reduce $CO_2$ emissions as all $CO_2$ produced is usually captured and used for fertilizer production or other industrial purposes (see Rafiqul et al. 2005). Third, recent studies on concrete energy saving options in ammonia plants have exclusively focused on steam reforming plants. The main steam reforming process steps are explained below in detail (see Windridge et al. 1998).

## 2.5.1   Reforming reaction

After the natural gas has been desulphurised, it is mixed with air and steam to form a gas feed which is heated up to 500-600°C and then fed into the primary reformer. The primary reformer contains the

process tubes the gas is fed in and that are heated externally by fuel combustion. The resulting flue gas has a temperature of around 1000°C and is used for heat recovery. In the primary reformer only 50-60% of the feed gas is converted to hydrogen and carbon monoxide. To complete the conversion until 99% of the feed gas is converted to hydrogen, nitrogen and carbon monoxide, part of the feed gas is internally combusted with process air and the remaining feed gas is passed over a catalyst. The converted gas has a temperature of 1000°C and its heat is recovered.

### 2.5.2 Shift conversion and $CO_2$ removal

The converted gas contains around 15% CO which is converted to $CO_2$ with the help of steam and a catalyst. The $CO_2$ is then removed from the gas. The resulting synthesis gas consists of hydrogen and nitrogen.

### 2.5.3 Ammonia synthesis

The synthesis gas is compressed to 100-250 bar and passed over a catalyst to form ammonia. The compressors are driven by steam turbines. The steam is usually supplied by waste heat recovery boilers which utilise the high temperature gas from the reforming reaction and shift conversion.

Table 17 shows the typical energy consumption of the process steps of an ammonia plant based on steam reforming built in the mid-1990s and a typical modern plant of the same type. It can be seen that electricity consumption has a minor share in the total energy consumption. For the modern ammonia plant electricity consumption and steam data is not given.

Table 17: Comparison of the energy balance of a US ammonia plant in 1996 and a modern ammonia plant in GJ (NCV)/t

| Unit operation | US ammonia manufacturing | | | Low energyammonia plant[1] |
|---|---|---|---|---|
| | Natural gas | Steam | Electricity | Natural gas |
| Reformer feed | 20.4 | | | 22.3 |
| Reformer fuel | 9.9 | | | 6.8 |
| Primary reformer | | 4.8 | | |
| Secondary reformer | | 0.0 | | |
| Waste heat boiler | | -5.6 | | |
| Shift + $CO_2$ removal | | 1.2 | 0.2 | |
| Synthesis loop | | -2.0 | 0.2 | |
| Auxiliary boilers | 4.5 | -3.9 | | 0.3 |
| Turbines/compressors | | 5.5 | | |
| Micellaneous | | | 0.1 | |
| Total | 35.0 | 0.0 | 0.5 | 29.3 |
| [1] Steam and electricity consumption data not available | | | | |

Source: see Rafiqul et al. 2005

# 3. Analysis of demand side energy efficiency potential using large-scale technology options

This section identifies the most promising energy efficiency options based on large-scale technology options for each sector. For each technology typical energy efficiency potential as found in the literature is identified. As the energy efficiency potential was mostly given in fuel savings or electricity savings per t of product output, we calculated annual achievable $CO_2$ emission reductions for each technology by assuming annual production figures for typical large plants. Production volumes have been selected rather conservatively in order not to overestimate emission reductions. Table 18 gives the annual plant production chosen per type of industry.

Table 18: Assumptions for annual production capacity of heavy industry plants

| Industry | Plant production/consumption (million t/a) |
|---|---|
| Iron and steel | Pig iron: 2 |
| | Steel[6]: 2 |
| Cement | Cement: 1 |
| | Clinker: 1 |
| | Raw material: 1.5 |
| Aluminium | Aluminium: 0.17 |
| Ammonia | Ammonia: 0.5 |
| Pulp and paper | Paper: 0.1 |
| | Pulp: 0.1 |

If not otherwise mentioned, $CO_2$ emission reductions from fuel savings have been calculated assuming that coal is the fuel currently used. Coal is the most commonly used fuel in the heavy industry – except for the ammonia industry[7] - in almost all the countries surveyed – except for Brazil. Due to the unavailability of high quality coal in Brazil heavy industry uses other fuels. The Brazilian iron and steel industry mainly consumes biomass (almost 50% of the sectors' energy consumption), natural gas and oil. The Brazilian cement industry mainly uses fuel oil and the Brazilian pulp and paper industry mainly biomass. The $CO_2$ emission factors per fuel type are given in Table 19.

It has been assumed that once electricity is generated from a technology or a technology leads to increased electricity generation the electricity would have been by/to the grid respectively. According to the decisions of the CDM Executive Board, the grid emission factor (EF) for electricity generation projects should be calculated as combined margin (CM) emission factor of the grid they are connected to with a 50-50 weighting of operating margin (OM) and build margin (BM) respectively (for the reasons to choose the 50-50 weighting see Biewald 2005)[8]. However, for energy-efficiency projects that reduce electricity consumption and in circumstances where the electricity was previously supplied by the grid an ex-post calculated OM would more accurately reflect

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[6] Pig iron/steel ratio is usually 1.07

[7] Since 10-20 years almost exclusively ammonia plants running on natural gas have been built – except for China.

[8] See latest version of the "Consolidated baseline methodology for grid-connected electricity generation from renewable sources" (ACM0002) for a more detailed account of how to calculate grid EFs (see CDM EB 2005)

emission reductions achieved[9]. In fact, this is the case for the majority of project types covered in this chapter as only two project types in the iron and steel industry involve electricity generation. OM EFs we have either taken from CDM Project Design Documents in the validation stage, other publicly available sources or have calculated them on our own. BM EFs have only been available for Brazil, China (Northern grid) and on the level of some Indian states. In India, there are four regional grids with limited interconnection: the Northern, Eastern, Western and Southern Grid[10]. However, Indian project developers have preferred state level calculations. For South Africa (that has not had significant new power plants built in the last 20 years) and Indonesia we assumed that OM equals CM. In Indonesia, the three main regional grids in Java/Bali (JB), North Sumatra (NS) and South Sumatra (SS) are not connected. We have calculated the OM for all three grids.

Table 20 gives the grid EFs for the selected countries.

The emission reduction calculation results are illustrated and discussed at the end of each industries' section.

We have grouped the attractiveness of each technology option under CDM in terms of emission reduction volume as shown in taking into account transaction costs Table 21.

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[9] The same rationale holds for energy efficiency projects that increase electricity consumption (but reduce fuel consumption).
[10] There also exists a North-Eastern grid but as the North East has no heavy industry, we ignore it here.

Table 19: $CO_2$ emission factors of coal, gas and oil

| Fuel | Coal | Gas | Oil |
|---|---|---|---|
| $EFCO_2$ (t$CO_2$/TJ) | 94.6 | 56.1 | 77.37 |

Source: IPCC (1996): Revised 1996 Guidelines for National Greenhouse Gas Inventories.


Table 20: Grid $CO_2$ emission factors in selected countries (g $CO_2$/kWh)

| EF type | China Northern | India | Brazil | Indonesia (JB) | South Africa |
|---|---|---|---|---|---|
| OM | 949[1] | 870[2] (658 for Northern Grid[3] and for 1068 Rajasthan[4]) | 118[6] | Java-Bali: 770[7] North Sumatra: 310[7] South Sumatra: 270 [7] | 961[8] |
| CM | 915[1] | 870[2] (832 for Karnataka[5] and 1107 for Rajasthan[4]) | 72[6] | As OM | As OM |

[1] Project Design Document "Huitengxile Windfarm Project", China (2004)

[2] Generation weighted average of all Indian power plants, see MNES (2003): Baseline for renewable energy projects under clean development mechanism.

[3] Project Design Document "5 MW Dehar Grid-connected SHP in Himachal Pradesh, India" (2004)

[4] Project Design Document "Bundled Wind power project in Jaisalmer (Rajasthan in India) managed by Enercon (India )Ltd." (2005)

[5] Project Design Document "125 MW wind power project in Karnataka, India" (2005)

[6] Project Design Document "Northeast Caeté Mills Bagasse Cogeneration Project (NECMBCP)", Brazil (2005)

[7] Generation weighted average of the all PLN power plants connected to the grid, forthcoming paper, see Restuti et al.(2006)

[8] Average of all South African Power Plants, calculated based on Eskom (2005): Eskom Holdings Annual Report 2005


Table 21: Level of attractiveness of energy-efficiency project types according to emission reduction volume

| Emission reductions (t $CO_2$e/a) | Level of attractiveness |
|---|---|
| >100,000 | Very attractive |
| >50,000 – 100,000 | Medium attractive |
| >20,000 – 50,000 | Marginally attractive |

Source: Michaelowa et al. (2003)

## 3.1 Iron and steel industry

### 3.1.1 Coke dry quenching (CDQ) in coke production

Coke leaving the coke oven has to be cooled from around 1,100°C to 200°C. Traditionally, this has been done by spraying water on it. Coke dry quenching (CDQ) uses inert gas for heat recovery. CDQ is the equipment which quenches red-hot coke by means of circulating the inert gas heated in the coke oven in a quenching chamber. The moderate cooling rate of the red-hot coke in the CDQ equipment also improves coke quality and stabilizes blast furnace operation. Heat energy is recovered by producing steam, which can be used for electricity generation or as process steam (see Errera and Milanez 2001, p.112).Fuel savings achievable are estimated to be 0.37 GJ per tonne of crude steel (see Worrell et al. 1999).

### 3.1.2 Pulverised coal injection (PCI) in pig iron making

If pulverized coal is injected into the furnace it replaces coke. This means that coke production can be reduced and energy formerly consumed in coke making can be saved. However, fuel injection requires energy for oxygen injection, coal, and electricity and equipment to grind the coal. Coke is still required as support material in the blast furnace. The maximum fuel injection rate depends on the characteristics of the blast furnace and impact on the iron quality. Maximum theoretical coal injection rates are around 280-300 kg/t hot metal. Farla et al. (1998) estimate fuel savings of 0.77 GJ/t hot metal with a PCI of 130 kg/t hot metal.

### 3.1.3 Natural gas injection (NGI) in iron making

Instead of coal, natural gas can also be injected in the furnace. Worrell et al. (1999) assume that at a replacement rate of 1kg natural gas/kg coke leads to energy savings of 0.9 GJ/t hot metal.

### 3.1.4 Top pressure recovery turbine (TRT) in iron making

The flue gas from the blast furnace (blast furnace gas, BFG) has a very high pressure. The pressure can be utilized to produce additional electricity with a top pressure recovery turbine (TRT). A TRT can produce 15-40 kWh/t of pig iron (see Stelco 1993). For emission reduction calculation we have assumed 30 kWh/t of pig iron.

### 3.1.5 Utilisation of BFG/BOF gas for heat and/or power generation in steel production

Due to its high temperature and reasonably high net calorific value, BFG from pig iron production as well as BOF gas from steel production is very suitable for both heat recovery and combustion in a gas turbine. Worrell et al. (1999) give a general energy recovery rate of a maximum of 916 MJ/t for BFG. For emission reduction calculation we assume fuel savings of 0.5 GJ/t when BFG is used for heat recovery. If used for combustion in a combined cycle gas turbine system we assume an electricity generation of 13 kWh/t of steel[11]. The heat and gas recovery of BOF gas can yield at least 0.9 GJ per t of crude steel (see Worrell 2005).

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[11] In 1997, the Baoshan Cold Rolled Steel Plant in China installed a 150 MW combined cycle gas turbine system running on BFG. The plant has a capacity of 40 million t steel/a. When assuming a load factor of 80% the plant generates 0.26 MWh/t steel. We divided this number by 20 to match it with our model plant capacity.

### 3.1.6  Near net shape casting (thin slab casting)

Near net shape casting is direct casting of the steel into (or near to) the final shape, replacing hot rolling. In 1997, units were available up to a capacity of 1.5 million t casted steel. Hence, we calculated emission reduction based on this production capacity instead of 2 million t assumed for other project types. The energy savings of thin slab casting compared to continuous casting with hot rolling amount to 0.7 GJ/t steel of primary energy saved (see EC 1997). We assume savings of 0.35GJ/t steel and 97 kWh/t steel.

The following two figures present the calculation results for the iron and steel industry. Figure 5 shows the project potential for the project types where electricity is saved or generated as part of the project activity. Figure 6 shows the project potential for the project types where only fuel is saved. For Brazil we have assumed that 50% of fuel consumption would be charcoal for pig iron production and 50% would be fuel oil.

**Figure 5: $CO_2$ emission reduction volumes per plant in the iron and steel sector of selected large-scale technology options with an electricity saving/generation component in selected countries (kt $CO_2$e/a)**
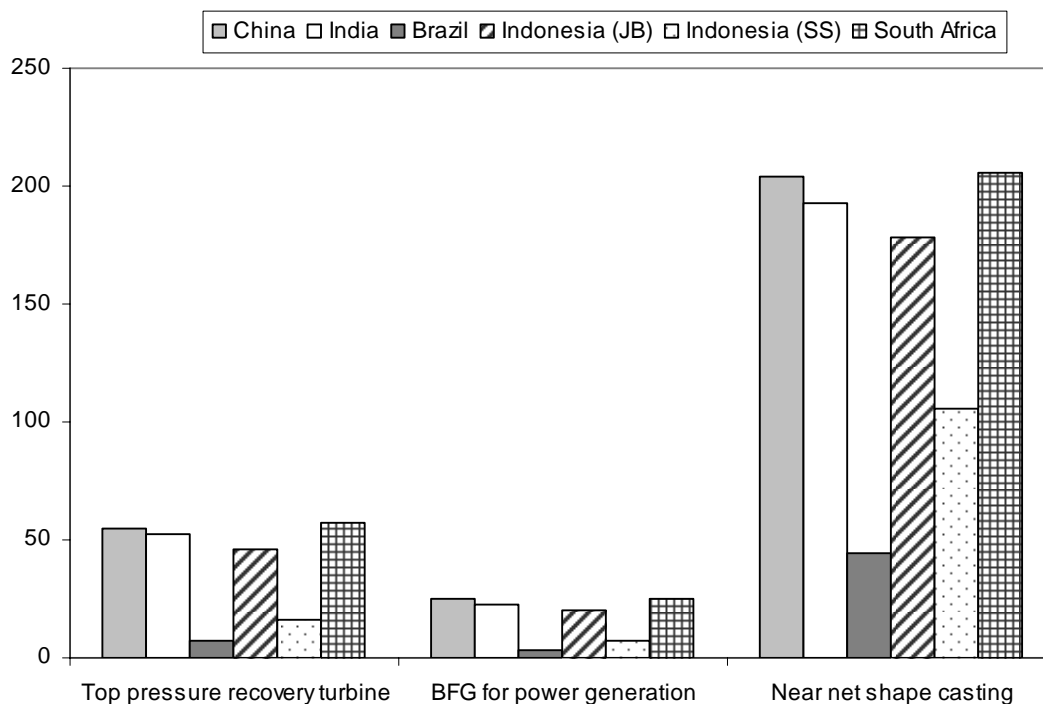
**Figure 6: CO₂ emission reduction volumes per plant in the iron and steel sector of selected large-scale technology options (fuel savings) in selected countries (kt CO₂e/a)**
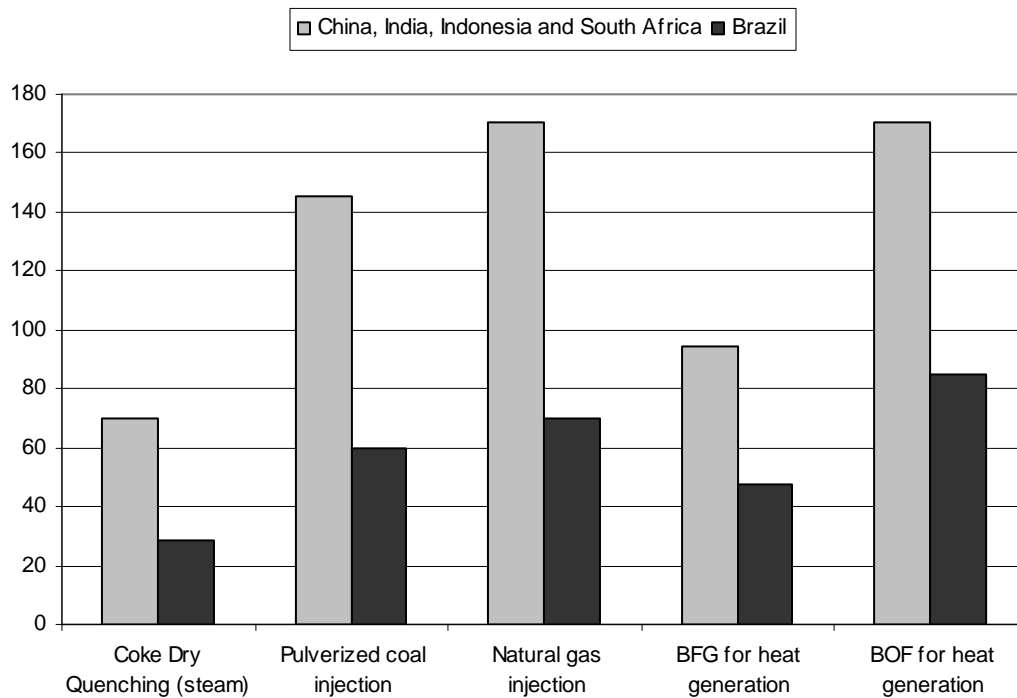


For countries with a relatively low grid CM, the potential of TRT and BFG for power generation is marginal. But also for countries with a high grid EF those project types are not very attractive. Only near net shape casting is very attractive, except in Brazil.

Concerning emission reductions from technology use that leads to fuel savings China, India, Indonesia and South Africa have the same potential as the $CO_2$ emission factor used for coal is the same for all countries. Among the fuel savings projects it can be observed that BOF gas, PCI and NGI are with more 100,000 t $CO_2$ emission savings in terms of volume very attractive project types. Also BFG and CDQ for steam generation seem to be medium attractive. Brazil has significantly lower emission reduction potential due to the different fuel mix assumed. Also PCI and NGI might not be feasible in Brazil if charcoal is used for pig iron production.

## 3.2    Cement industry
### 3.2.1    Blended cement in clinker production

A C/C ratio has an influence on the SEC of cement production.  Production and use of "blended cement" with a C/C ratio less than 0.95 (0.95: Portland cement) can significantly reduce hear energy consumption in pyro-processing and lead to emission reductions. Even though blended cement can have higher electricity demand for the final cement grinding process, this additional electricity consumption is too small to make up the savings from the reduced heat demand (see Ruth et al. 2000). Additives like fly ash and blast furnace slag are waste materials and can therefore be looked at as having no energy demand for production apart from the energy needed for shipping. So the replacement of clinker by one of these additives leads to a directly proportional reduction in heat demand for pyro-processing. Blending cement also reduces the alkali-silica-reactivity and thus lowers the need for alkali-dust removal from the kiln exhaust gases (see Worrell et al. 2004). The

decrease of the clinker-cement (C/C) ratio is a particularly attractive energy efficiency option under the CDM as the intergrinding of clinker with other additives does not only lead to a reduction in the energy consumption in clinker production, but also corresponds to a reduction in carbon dioxide emissions in calcination as well. However, if blast furnace slag is used, energy is required for drying and grinding of the blast furnace slag in a grinding mill. For emission reduction calculation we assume that clinker production consumes 3.2 GJ of fuel/t clinker and 30 kWh of electricity/t clinker (see Worrell et al. 2004) and that the emission factor from calcination is 0.785 t $CO_2$/t clinker. In the project case any additive but blast furnace slag is used and the C/C ration is increased by 5%.

### 3.2.2    Kiln replacement in pryo-processing

For calculation of emission reductions by kiln replacement we have made the following assumptions. A process change from dry process with pre-heaters to a five stage preheater and a pre-calciner, combined with a reciprocating grate cooler and adjusted speed drivers (ASD) is undertaken. This retrofit measure is assumed to reduce fuel consumption by 0.3 GJ/t clinker (see Ruth et al. 2000).

### 3.2.3    Replacement of raw material grinding equipment

We assumed that a tube mill is replaced by a roller press with static V-separator for raw material preparation. This retrofit measure can save 20 kWh of electricity/t cement (see Ruth et al. 2000).

The Figure 7 gives the calculation results for the cement industry in China, India, Brail, Indonesia and South Africa. The figure shows a considerable difference in project potential for the project types where considerable amounts of electricity are saved (kiln replacement and raw material grinding) due to the considerable difference in OM among the countries. Kiln replacement and raw material grinding only offer marginal potential – except for Brazil where the potential is lower because fuel oil has been assumed to be the fuel used in the cement industry. Blended cement projects only seem to be medium attractive. However, the decrease in C/C ratio chosen is with 5% very conservative. A decrease by more than 10% would make blended cement projects very attractive.

Figure 7: $CO_2$ emission reduction volumes per cement plant of selected large-scale technology options in five selected countries (kt $CO_2$e/a)
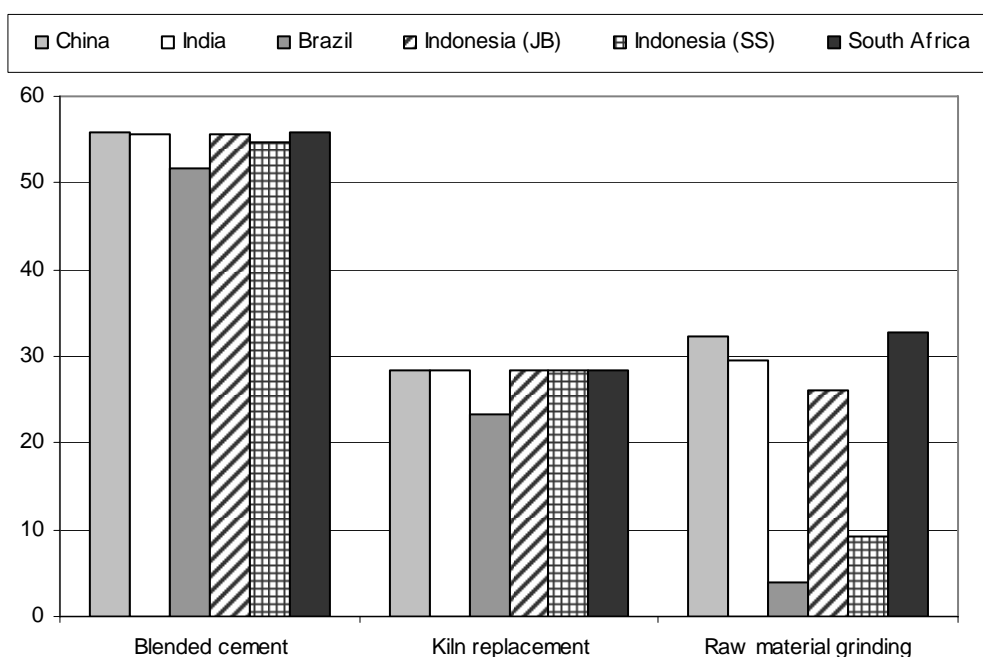


## 3.3 Aluminium industry

The replacement of the primary smelter by a PFPB smelter with inert anode/wetted cathode technology is the most obvious candidate for energy efficiency. First, the electrolysis process consumes the large bulk of energy in aluminium production. Second, a shift from older smelter technologies to newer technologies besides improvements in energy efficiency also yields a huge reduction in PFC emissions as shown in Table 22.

Table 22: PFC emission reductions from smelter technology change to PFPB and use of inert anodes/wetted cathodes in China, India, Brazil, Indonesia and South Africa depending on new technology used

| Process change to PFPB and inert anodes/wetted cathodes from | Improvement in emission factor for $CF_4$ and $C_2F_6$ (t $CO_2$e/t Al) | Reduction in $CO_2$ emissions from anode consumption (t $CO_2$e/t Al) | Direct GHG emission reduction (million t $CO_2$e/a) |
|---|---|---|---|
| CWPB | 0.77 | 1.65 | 1.78 |
| SWPB | 7.05 | 1.65 | 8.70 |
| HSS | 2.94 | 1.65 | 4.59 |
| VSS | 1.65 | 1.65 | 3.30 |

Whereas the PFC emission reductions are independent of the location the plant is operated, the emission reductions from electricity savings are not (see Figure 8).

Figure 8: CO$_2$ emission reductions per plant from smelter technology change to PFPB and use of inert anodes/wetted cathodes due to electricity savings in selected countries depending on new technology used (kt CO$_2$e/a)
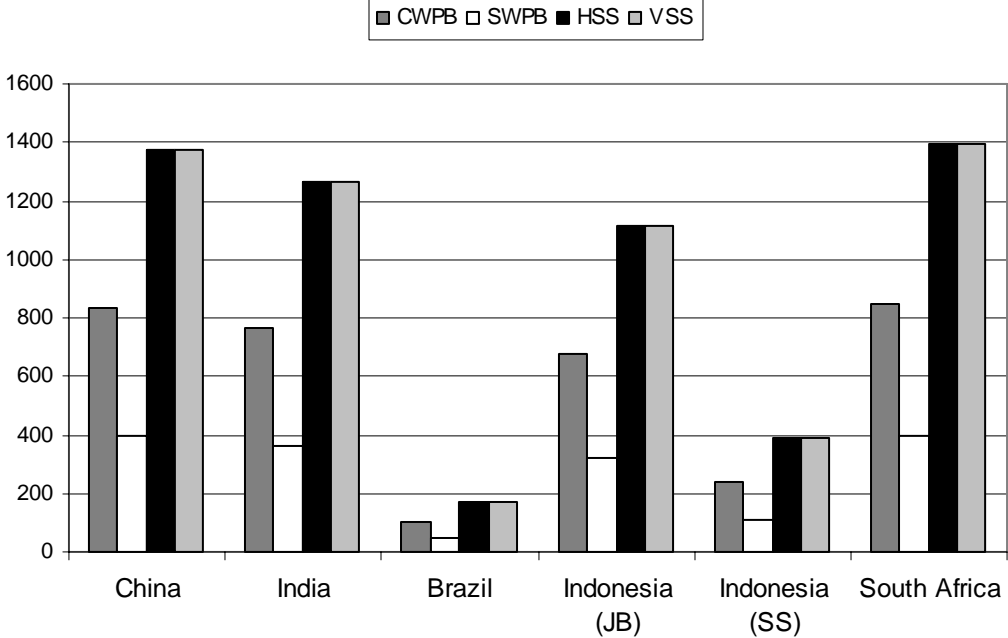


Apart from Brazil all types of smelter change types are very attractive - even in terms of electricity savings only. It can be seen that the most attractive smelter change in terms of electricity savings is the switch from HSS and VSS to PFPB. However, as a smelter change to PFPB and use of inert anodes/wetted cathodes does always come with considerable direct GHG emission reductions as shown in Table 22 above, smelter change is an even more attractive project type as shown in Figure 9 below.

Figure 9: Total GHG emission reductions by smelter technology change to PFPB and use of inert anodes/wetted cathodes in selected countries depending on new technology used (kt CO$_2$e/a)
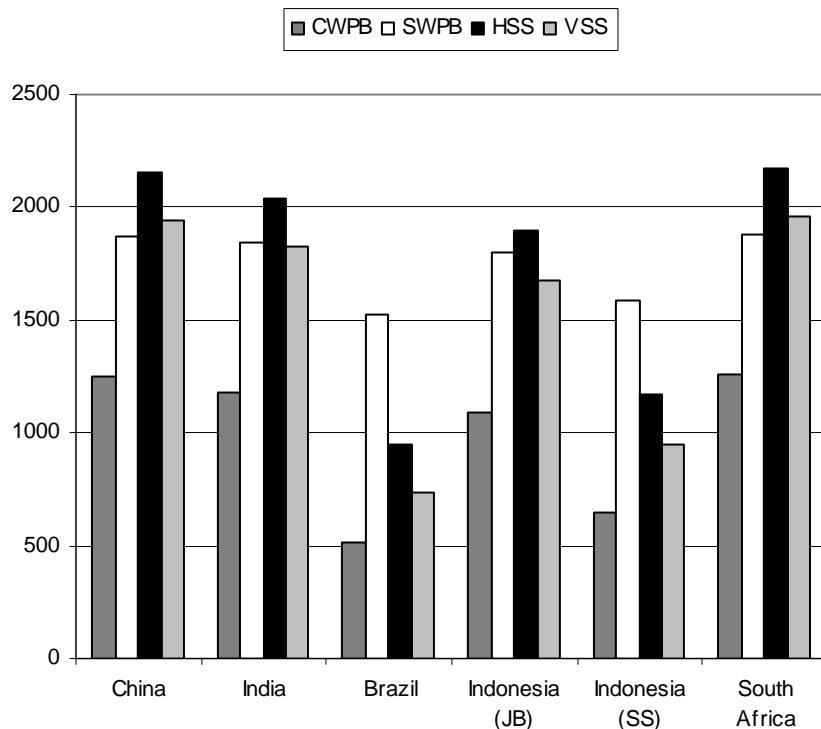


It can be observed that the process change from HSS to PFPB delivers the most CO$_2$ emission reductions compared to other technology changes apart from Brazil and South Sumatra. In those countries the low OM EF does result the change from SWPB being the most attractive change.

## 3.4    Pulp and paper industry

### 3.4.1    Continuous digesters in Kraft pulping

Continuous digesters are more energy efficient than conventional batch digesters (see Hein 2002). Using a continuous digester instead of a batch digester for pulping saves approximately 40% steam consumption (see Mohanty 1997b). In a continuous digester the wood chips are pre-steamed and cooked in the pulping liquor at 160°C. As compared to the batch digester the continuous digester continuously produces pulp and therefore is better suited for heat recovery from one part of the process to the other (see Martin et al. 2000). It is estimated that the continuous digester requires 6.3 GJ steam/t[12] pulp less than the batch digester but consumes 75 kWh electricity/ t pulp more (see Martin et al. 2000).

### 3.4.2    Batch digester modification in Kraft pulping

Martin et al. (2000) estimate that the use of indirect heating and cold blow can improve the specific steam consumption of a batch digester by 3.2 GJ/ t pulp.

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[12] For calculation of emission reductions steam consumption has been converted to fuel consumption by assuming a steam boiler efficiency of 85%.

### 3.4.3 Tampella recovery system in Sulfite pulping

The Tampella recovery system enables recausticization of the sulfite liquor for reuse in the pulping operation. Sulfite recovery saves energy in the amount of 2.9 GJ steam/t pulp (see Martin et al. 2000).

### 3.4.4 Condebelt drying

In Condebelt drying the paper is dried by contact with a hot steel band heated by steam. Although condebelt drying offers only slightly less energy improvements as the conventional contact drying, condebelt drying is much more suitable for heat recovery (see Hein 2002). Martin et al. (2000) estimate a reduction in steam consumption by 1.88 GJ/t paper and a reduction in electricity consumption by 20 kWh/t paper.

### 3.4.5 Drysheet forming

Dry sheet forming means the production of paper without the addition of water. For fiber dispersion either mechanical disbursement or air laying techniques are used. De Beer (1998) estimates energy savings of 5 GJ steam/t paper and an increase in electricity consumption by 208 kWh/t paper.

### 3.4.6 Infrared drying

Infrared drying enables better heat transfer by improving the moisture evaporation rate. Infrared dryers run on electricity and require about 1.13 MWh of electricity/t paper but reduce steam consumption by 8.16 GJ of steam/t paper compared to conventional steam dryers (see Martin et al. 2000).

Figure 10: CO$_2$ emission reduction volumes per plant in the pulp and paper sector of selected large-scale technology options in China, India, Indonesia and South Africa (kt CO$_2$e/a)
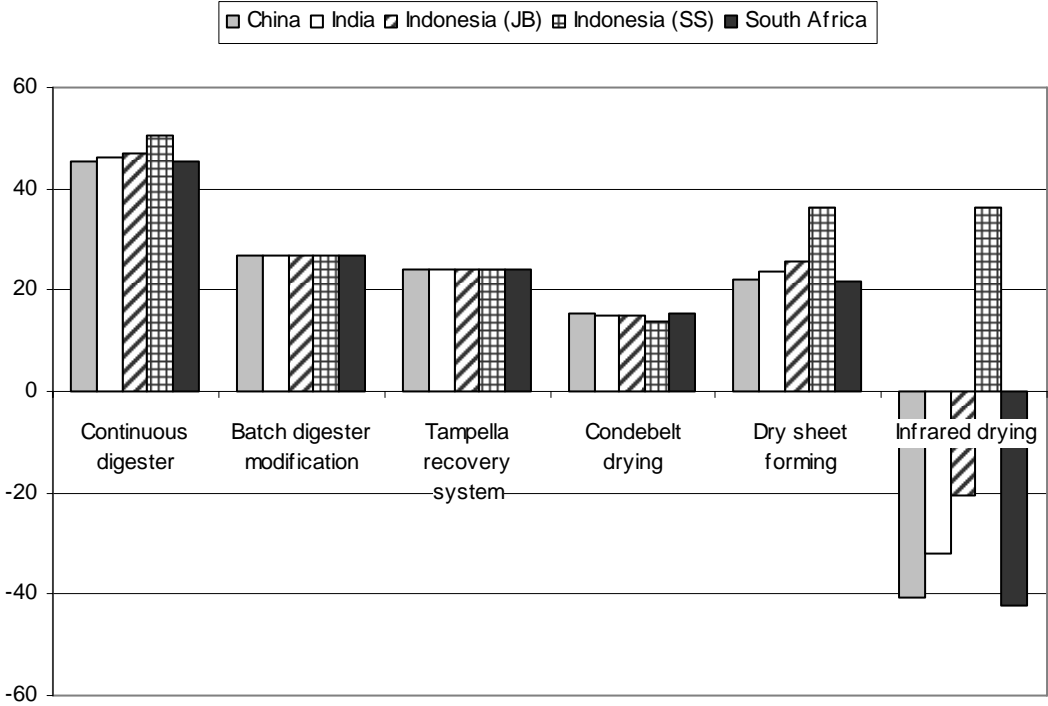


Figure 10 shows the same emission reductions from a technology change that only leads to fuel savings for all countries as the same CO$_2$ emission factor for coal is used. As thermal energy generation from biomass is widespread in the pulp and paper industry we have assumed that 25% of thermal energy for steam generation is supplied by biomass energy. We have excluded Brazil from the analysis as the biomass share in thermal energy in Brazil is above 50%. A peculiarity of the results is that infrared drying has a negative emission reduction in countries with relatively high OM EFs.

Figure 11 clearly shows that for all technology options the emission reduction volumes are at best marginally attractive – at least for the plant size that we have conservatively assumed. At very large pulp and paper plants with a production above 300,000 t/a continuous digester use might be a very attractive CDM project.

## 3.5    Ammonia industry

Based on a survey of technologies currently in use among the ammonia industry and potential process improvements Rafiqul et al. (2005) identify the following options for energy-efficiency improvement in reforming and CO$_2$ removal in already operating plants.

Reforming improvements :
-    Modification of coils
-    Waste heat recovery
-    Lowering of steam to carbon ration

Improvement of $CO_2$ removal:
- New solvents and processes like BASF aMDEA or Benfield LoHeat
- Pressure swing absorption
- Membranes for efficient removal of $CO_2$ from synthesis gas

Table 23 gives the estimated reduction in SEC ordered by retrofit measure in reforming and $CO_2$ removal as well as other measures identified by Rafiqul et al. (2005).

**Table 23: Achievable improvement in energy intensity by selected retrofit measures in a steam reforming ammonia plant**

| Retrofit measure | Average improvement in energy intensity (GJ/t ammonia) |
|---|---|
| Reforming improvements | 1.4 |
| Improvement $CO_2$ removal | 0.9 |
| Low ammonia synthesis pressure | 0.5 |
| Hydrogen recovery | 0.8 |
| Improved process control | 0.72 |
| Process integration | 3.0 |

Source: Rafiqul et al. (2005)

We calculated potential emission reductions based on the above values which are presented in Figure 12.

Figure 12: $CO_2$ emission reduction volumes per plant in the ammonia industry of selected large-scale technology options in selected countries (kt $CO_2$e/a)
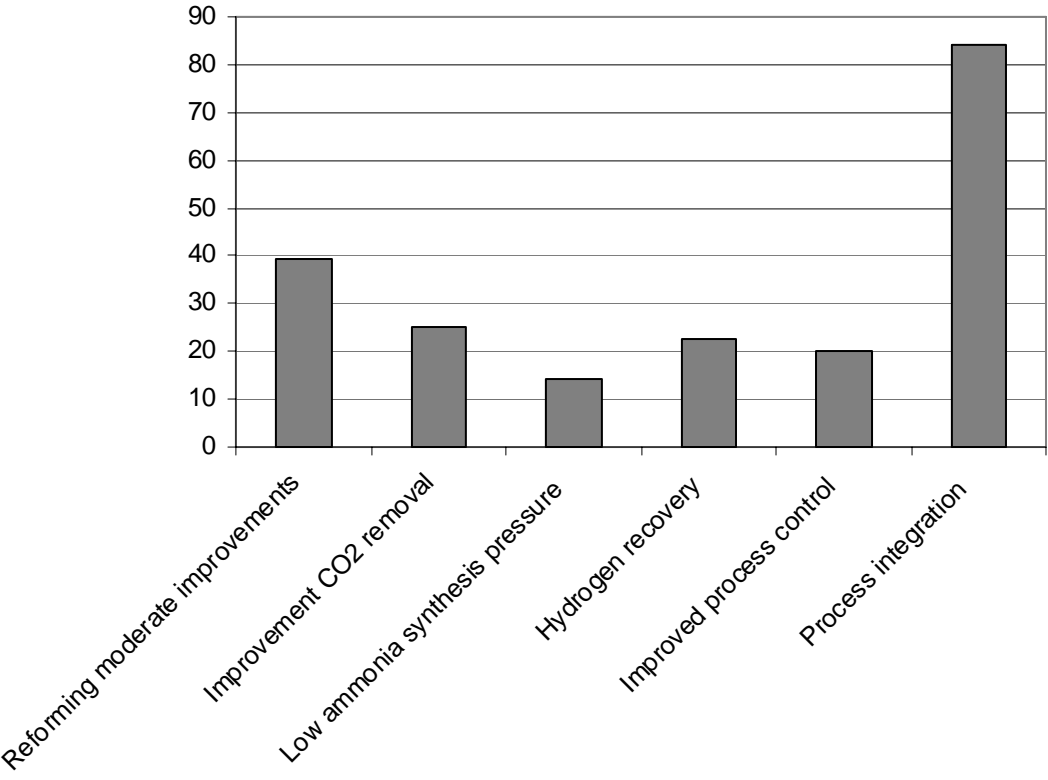


Emission reductions from are the same for China, India, Brazil, Indonesia and South Africa as the $CO_2$ emission factor of natural gas used is the same for all countries. It can be seen that only process integration has a medium potential. The other technology options only offer a marginal potential.

# 4. Analysis of greenfield energy efficiency potential

This section analyses potential of greenfield energy efficiency projects in each industry. Our methodology first identifies country-specific average SEC ($SEC_{average}$) in each industry. Next, the best available SEC ($SEC_{BAT}$) is estimated based on various global best available technologies. Energy saving potential is calculated by multiplying the difference between $SEC_{average}$ and $SEC_{BAT}$ by the model plant production figures in Table 18. It should be noted that SEC of recently built plants must be used for greenfield projects in CDM context, which yields much more conservative estimates of CER potential by greenfield CDM projects. However, this is not a practical approach here due to the data constraint. Therefore the results should be interpreted as energy savings potential compared to an average-performer plant in each country. The results are likely to be overestimated in CDM context, hence should be handled carefully.

## 4.1 Iron and steel industry

Based on various statistics and literature, $SEC_{average}$ in every country except Indonesia are calculated. Because reliable data does not exist for Indonesia, $SEC_{average}$ is not quantifiable. Ideally, $SEC_{average}$ of BOF in each country should be calculated since this study assumes installation of the state-of-art BOF plant (explained below). But it is not a practical solution, again, because of the data constraint.

This analysis focuses on a greenfield BOF plant installation project since there are more opportunities for energy efficiency improvement in BOF process compared to others. SECBAT are estimated based on the aforementioned energy efficient technologies. The technologies chosen for a combination of "pig iron – BOF – near net shape casting" processes are CDQ, TRT, and PCI for iron making, BOF gas recovery for steel making, and near net shape casting for casting and rolling.

Technologies for a combination of "smelting reduction – BOF – near net shape casting" processes are BOF gas recovery and near net shape casting. This study assumes a smelting reduction process for iron making for South Africa because there is an abundant supply of hard coal in the country, which is suitable for the smelting reduction technique. Traditional pig iron making is assumed for other countries.

Table 24: $SEC_{average}$ and crude steel production share by electric arc furnaces (EAFs) in the iron and steel industry

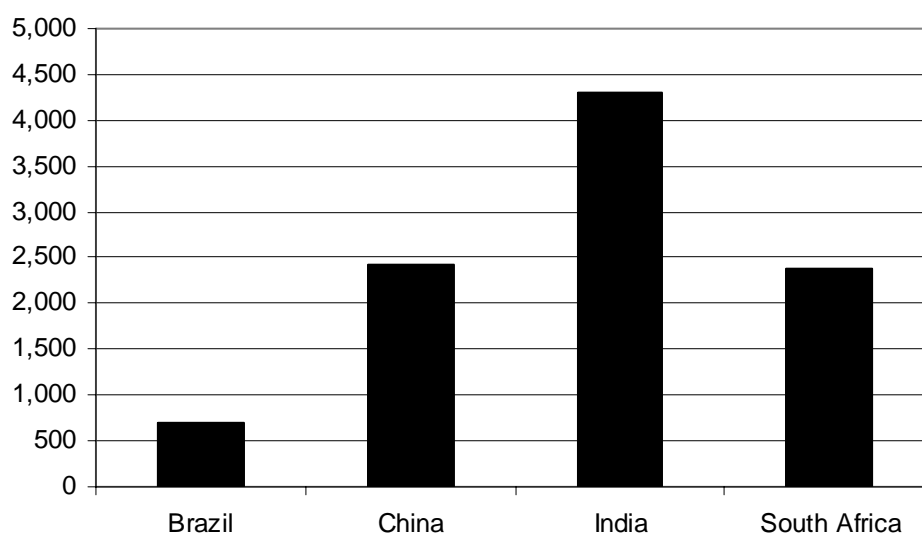| Country | $SEC_{average}$ (GJ/t) | $SEC_{average}$ data vintage | EAF share (%) | EAF share data vintage |
|---|---|---|---|---|
| Brazil | 18.0[1] | 2003 | 23.2[4] | 2004 |
| China | 23.4[2] | 2003 | 18.4[4] | 2004 |
| India | 32.5[3] | TERI 2005 (year not specified) | 38.9[4] | 2004 |
| South Africa | 22.5[1] | 2003 | 47.9[4] | 2004 |

Sources: Own calculation based on IEA (2005)[1], own calculation based on Kurushima (2005) and EDMC (2005)[2], TERI (2005) for India[3], and IISI (2005)[4]

Table 25: $SEC_{BAT}$ of BOF processes

| Process combination | $SEC_{BAT}$ (GJ/t) |
|---|---|
| Pig iron – BOF – Near net shape casting | 12.6 |
| Smelting reduction – BOF – Near net shape casting | 13.4 |

Emission reduction volumes are calculated assuming a model plant with production of 2 million t of crude steel per annum and the estimated $SEC_{BAT}$. Results are shown below. As fuel we have assumed 100% coal for all countries except for Brazil. For Brazilian plants we have estimated a fuel share of 50% biomass and 50% natural gas.

Figure 13: $CO_2$ emission reduction volumes of a greenfield project in the iron and steel sector (kt $CO_2$e/a)



## 4.2    Cement industry

$SEC_{average}$ are calculated for all the countries except Indonesia. $SEC_{average}$ data for Indonesia is only available for the year 1994, which does not likely represent the current situation. Therefore, emission reduction volume in Indonesia is not quantified here. It should be noted that C/C ratios are only available in 1994/1995 values. Even though the data is very old, we decided to use the values since

C/C ratios are essential in determining SEC in the cement industry. The data vintage gap requires careful interpretation of emission reduction results.

$SEC_{BAT}$ are also estimated for all the countries based on the technologies described above and assumed C/C ratios (5% decrease from the 1994/1995 level). Technologies chosen are a roller press with static V-separator for raw material grinding, a rotary kiln with a five-stage preheater and a precalciner, combined with a reciprocating grate cooler and ASD for pyro-processing, and a roller press with a high-efficiency separator for cement grinding/mixing. Results are shown in Table 26. Lower C/C ratio yields lower $SEC_{BAT}$.

Table 26: $SEC_{average}$ and C/C ratios in the cement industry

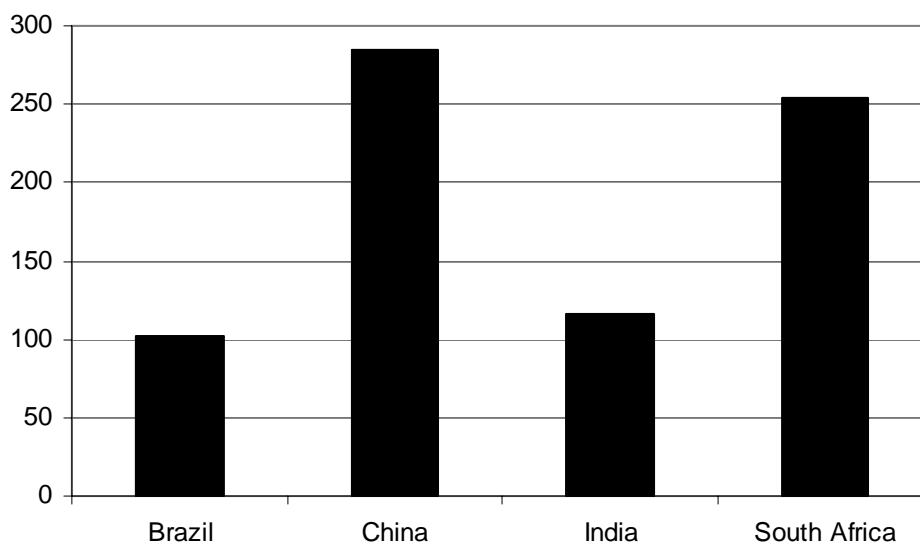| Country | $SEC_{average}$ (GJ/t) | $SEC_{average}$ data vintage | C/C ratio (%) | C/C ratio data vintage |
|---|---|---|---|---|
| Brazil | 3.44[1] | 2003 | 77[4] | 1994 |
| China | 4.89[2] | 2001 | 82[2] | 1995 |
| India | 3.36[3] | TERI 2005 (year not specified) | 89[4] | 1994 |
| South Africa | 4.59[5] | 2000 | 90[4] | 1994 |

Sources: Own calculation based on Ministério de Minas e Energia (2004)[1], own calculation based on Soule et al. (2002)[2], TERI (2005)[3], Worrell et al. (2001)[4], and own calculation based on Baumert et al. (2005), Worrell et al. (2001) and Soule et al. (2002)[5]

Table 27: $SEC_{BAT}$ in the cement industry

| Country | $SEC_{BAT}$(GJ/t) | AssumedC/C ratio (%) |
|---|---|---|
| Brazil | 2.39 | 72 |
| China | 2.54 | 77 |
| India | 2.77 | 84 |
| South Africa | 2.80 | 85 |

Emission reduction volumes are calculated assuming a model plant with production of 1 million t of cement per annum, the estimated $SEC_{BAT}$, and the assumed C/C ratios. Results are shown in Figure 14. As fuel we have assumed 100% coal for all countries except for Brazil. For Brazilian plants we have estimated 100% fuel oil.

Figure 14: CO$_2$ emission reduction volumes of a greenfield project in the cement sector (kt CO$_2$e/a)



## 4.3 Aluminium industry

SEC$_{average}$ are calculated for all the countries except Indonesia (data not available). It should be noted that SEC$_{average}$ for South Africa is a SEC$_{average}$ value for Africa average given by IAI (2004). The Africa average value is the only data available but can be a substitute for one of South Africa because a considerable amount of primary aluminium production of the Africa region is from South Africa[13].

A PFPB smelter combined with inert anode and wetted cathode is defined as BAT smelter technology. The combination reaches a SEC$_{BAT}$ of 10.25 MWh/t.

Table 28: SEC$_{average}$ in the aluminium industry (electrolysis process only)

| Country | SEC$_{average}$ (MWh/t) | SEC$_{average}$ data vintage |
|---|---|---|
| Brazil | 15.1[1] | 2004 |
| China | 14.4[2] | 2004 |
| India | 15.5[3] | TERI 2005 (year not specified) |
| South Africa (Africa average) | 14.3[4] | 2003 |

Sources: see ABAL (2005)[1], Own calculation based on Schwartz et al. (2000)[2], TERI (2005)[3], and IAI (2004)[4]

Table 29: SEC$_{BAT}$ in the aluminium industry

| Technology | SEC$_{BAT}$ (MWh/t) |
|---|---|
| PFPB combined with inert anode/wetted cathode | 10.25 |

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[13] In 2004, 1,711,300 t of primary aluminium was produced in the Africa region (see IAI 2005), of which 863,600 t in South Africa (see World Bureau of Metal Statistics 2005).

PFC emission reductions are not possible to quantify with the methodology taken in this section because country-level specific PFC emissions are not available. Therefore PFC emission reduction volumes are calculated based on the annual CER potential by PFC emission reductions in the aluminium sector given by Michaelowa et al. (2005). It should be noted that the values given by Michaelowa (2005) are based on conservative estimation.

Table 30: Annual PFC emission reductions for a model plant with production of 170,000 t of primary aluminium

| Country | Annual PFC emission reduction (kt $CO_2$e/a) |
|---|---|
| Brazil | 255.0 |
| China | 129.2 |
| India | 340.0 |
| South Africa | 283.3 |

Source: Own calculation based on Michaelowa et al. (2005)

Then total emission reduction volumes are calculated assuming a model plant with production of 170,000 t of primary aluminium per annum and the estimated $SEC_{BAT}$. Results are shown below. Because the electrolysis process is highly electricity-intensive, grid emission factors have strong effects on the emission reduction volumes.

Figure 15: $CO_2$ emission reduction volumes of a greenfield project in the aluminium sector (kt $CO_2$e/a)
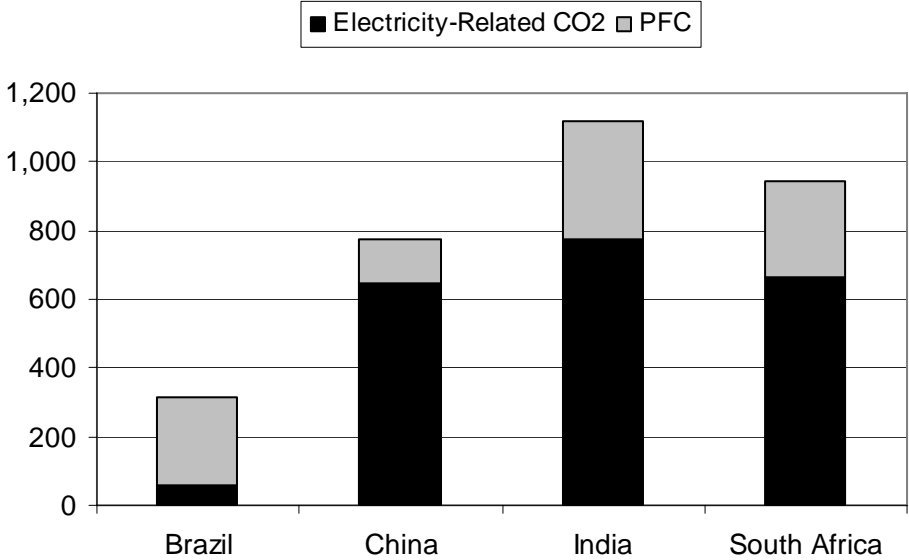


## 4.4 Pulp and paper industry

Data is not available to identify recent $SEC_{average}$ in the five countries. Hence it is not possible to quantify emission reduction volumes with the methodology taken here. IEA (2005) sums up energy consumption from publishing and printing (ISIC 22) and pulp and paper production (ISIC 21). Consequently, the energy consumption data given by IEA (2005) would not lead to representative results for SEC.

## 4.5    Ammonia industry

Data is not available to identify recent $SEC_{average}$ in the five countries. Most of the existing studies deal with SEC including feedstock, which is not an essential element of energy efficiency projects. Also, information for differentiation between fuel and electricity is hard to find, especially in the five countries of interest. Therefore emission reduction volumes cannot be quantified.

# 5. Preliminary estimate of the emission reduction potential in the iron and steel, cement and aluminium industry in selected countries

For those countries and sectors for which SEC$_{average}$ and SEC$_{BAT}$ are available in chapter four we made a rough calculation based on the difference in SEC and production forecasts until 2020. Table 31 shows the results of total production forecasts modelled by Lin-log regression[14] of real GDP growth and production per country per sector.

Table 31: Lin-log regression results of total production forecasts of cement, aluminium and steel in Brazil, China, India and South Africa from 2005 until 2020

| Cement | Estimation period | Cement production until 2020 (million t) |
|---|---|---|
| Brazil | 1980-2004 | 778.6 |
| China | 1995-2004 | 25,163.8 |
| India | 1980-2004 | 2,684.3 |
| South Africa | 1992-2001 | 203.9 |
| Aluminium | Estimation period | Aluminium production until 2020 (million t) |
| Brazil | 1970-2004 | 31.3 |
| China | 1995-2004 | 184.6 |
| India | 1970-2004 | 15.6 |
| South Africa | 1980-2004 | 22.5 |
| Iron & Steel | Estimation period | Steel production until 2020 (million t) |
| Brazil | 1970-2004 | 629.7 |
| China | 1995-2004 | 7,846.7 |
| India | 1970-2004 | 585.9 |
| South Africa | 1970-2004 | 165.4 |

Source: see Hayashi (2006)

We have multiplied the total production until 2020 with the SEC improvement potential for based on SEC$_{average}$ and SEC$_{BAT}$ and calculated resulting emission reductions. As this can only be a very rough calculation of potential emission reductions we assumed that 1% and 5% of these emission reductions would materialise under CDM. For the iron and steel sector we assumed that for China,

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[14] Production = + *log(GDP)

India, Brazil and South Africa 70%, 50%, 60% and 40% respectively of steel production would be produced in a BOF. The results are displayed in Figure 16.

Figure 16: Rough estimate of potential emission reductions in the iron and steel, cement and aluminium industry when assuming that 1% and 5% of production from 2005-2020 would be produced from plants using best available technology (million t CO₂e)
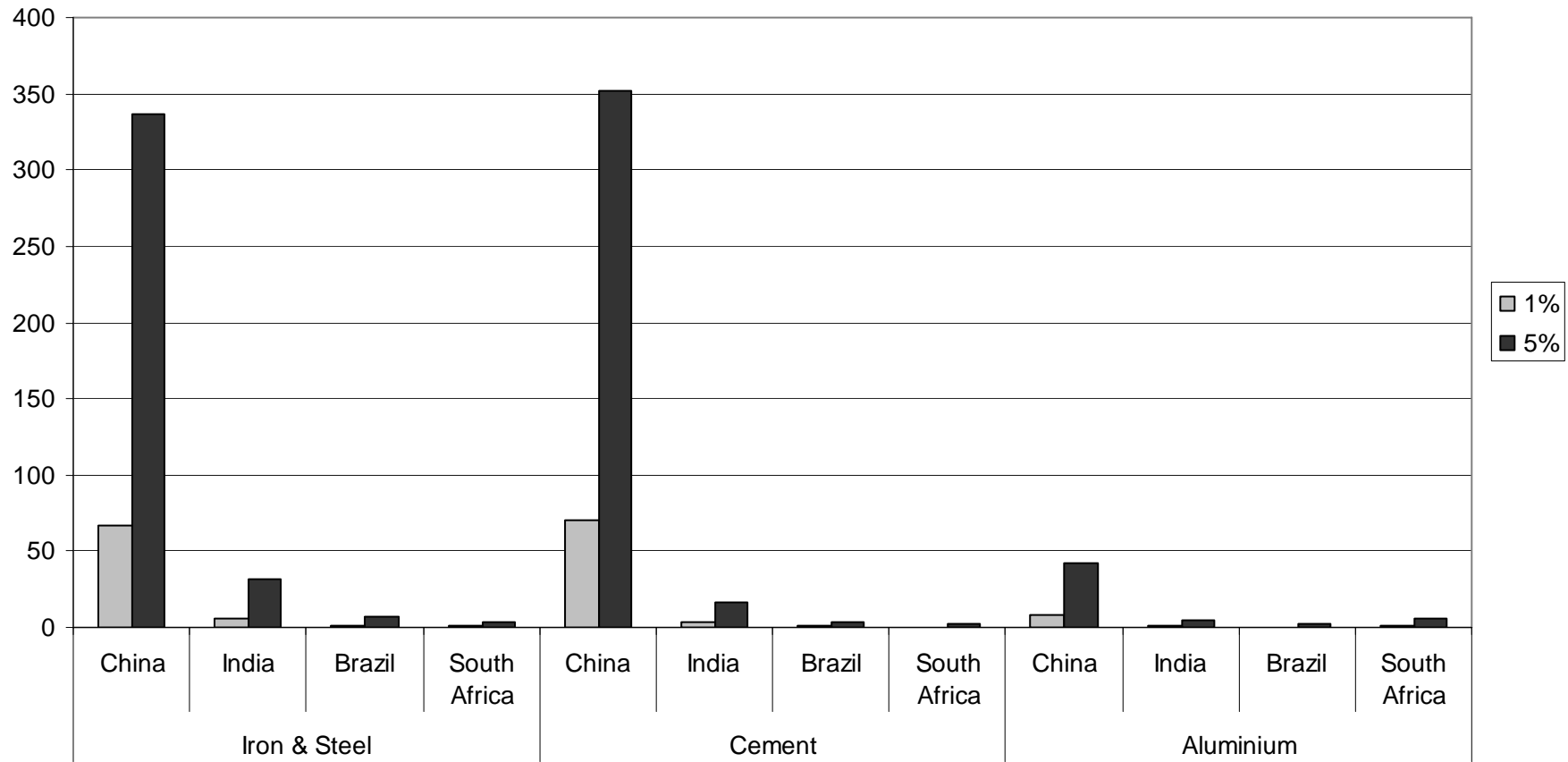
It can be seen that the potential emission reductions are vast. When assuming that 5% of the forecasted production for all four countries would come from plants having improved their SEC from $SEC_{average}$ and $SEC_{BAT}$, this would mean a total emission reduction of 810 million t $CO_2e$. The figures show that the majority of emission reductions with would come from the iron and steel (46.7%) and cement industry (46.3%). China offers by far the biggest potential (90.3%) due to its high forecasted growth in production of the respective goods.

It goes without saying that these figures should be handled with caution as they are very sensitive to the production forecasts and the SEC averages (which are relatively outdated) and only to a very limited extent take into account the real plant types and process techniques actually in use in the countries.

# 6.     Analysis of steam boiler energy efficiency improvement CDM potential

Almost all continuous industrial process plants (e.g. in the pulp and paper, chemical, textile, food processing and sugar industry) require an uninterrupted input of energy in the form of electric power and/or steam to sustain their industrial processes. This energy is usually supplied by steam boilers that generate steam for electricity generation or process steam. Combined heat-and-power (CHP) units are also common among the energy-intensive industry.

If the steam boilers only run for the purpose of electricity production only (utility boilers) they are commonly referred to as captive power plants. Especially in India, due to chronic unreliability of public power supply and high industrial electricity prices, captive power generation is very common. In 1998, 4.9 GW of diesel-based captive power generation was installed in India (see TERI 1999). However, captive power generation is not covered in this section as its emission reduction potential (except fuel switch) compared to refurbishment or replacement of boilers providing only process steam and/or electricity is minor.

Industrial steam boiler sizes vary between below 1 MW to around 100 MW. Steam boilers can be fired by coal, oil, naphtha, natural gas or biomass. In the section we focus on the boilers with capacities from 5 – 50 MW as industrial steam boilers with higher capacities are not very common.

In China, India, Indonesia and South Africa the most commonly used fuel in industrial steam boilers is coal. However, industry that uses or processes large amounts of natural gas or oil (e.g. ammonia industry or oil refineries) will usually use the respective fuel. In Brazil, the most common fuel used is natural gas which limits the potential for significant emission reductions from boiler refurbishment/replacement. In all countries an exemption is the sugar industry which usually fires bagasse.

Comprehensive studies on boiler numbers, sizes and efficiencies have not been undertaken in the countries covered in this report. Anecdotal evidence tells that the emission reduction potential is vast. The number of medium- to large sized boilers installed in those countries is enormous. A study estimates a number of 430,000 industrial boilers to exist in China with an average size of 2.3 t of steam per hour which would approximately translate into 1.7 MW average installed capacity[15] (see Wu et al. 1998). In 1993, the number of large boilers with a capacity higher than 10 t/h (~8.5 MW) was estimated to be ~140,000. Moreover, there are large efficiency gaps of the boilers when compared to western standards (see table 32 below). Lu (2005) reports that coal-fired industrial boilers in China on average only operate with 65% efficiency.

Given these low boiler efficiencies steam boiler refurbishment or replacement projects are obvious candidates for improving the efficiency of steam generation in China, India, Indonesia and South Africa. The following table shows typical technical characteristics of state-of-the-art industrial steam

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[15] When assuming · enthalpy of 2666 kJ/kg.

boilers. Besides, the boiler type, fuel used, and capacity range it shows the maximum efficiencies achievable.

Table 32: Technical characteristics of BAT industrial steam boilers

| Type | Typical fuel | Capacity (t steam/h) of single boiler | Thermal Efficiency (%) |
|---|---|---|---|
| Large water-tube-boiler (multiple fire-tubes) | Natural gas, fuel oil, coal | 1-15 | 94-95 (with economizer) |
| Water-tube-boiler | Natural gas, fuel oil, coal | > 50 | 94-95 |

Source: see Schmid et al. (2003)

Fuel type has a significant effect on boiler efficiency. The thermal efficiency hierarchy in descending order is coal, heavy fuel oil and natural gas due to the high hydrogen to carbon ratio in the natural gas (see Bessette 2002). The hydrogen which burns to form water removes a significant amount of heat from the combustion process. Hence, it has to be borne in mind that 95% is the maximum achievable efficiency if coal is used. For other fuels the efficiency can be assumed to be a few percentage points lower.

Boiler replacement projects will not necessarily involve replacement of an inefficient steam-only boiler with a more efficient steam-only boiler (of the same type) but might involve fuel switching (e.g. to natural gas), installation of a CHP unit or both. Table 33 shows typical technical characteristics of state-of-the-art industrial CHP systems. We have selected those CHP systems that are especially useful for the industries covered in this paper. For the ammonia industry this is the gas turbine (combined cycle) with heat-recovery steam generator as ammonia plants require large amounts of mechanical energy to compress gas to high pressure. The gas turbine can be used to drive the compressors directly in a very efficient manner compared to the use of electric motors (see Bessette 2002). Gas turbine systems (single cycle) are favourable in industries where very large amounts of high temperature steam is required because of the high exhaust gas temperatures. A steam boiler and back-pressure steam turbine system is very beneficial in industries with a very high steam demand in the low to demand heat or pressure range such as the pulp and paper industry. Steam boiler systems are also useful for the pulp and paper industry as they can be fired by coal which allows co-firing of biomass residues from the production process.

Table 33: Technical characteristics of typical CHP system designs

| Type | Typical fuel | Efficiency (%) | | Grade of heat or pressure |
| --- | --- | --- | --- | --- |
| | | Thermal | Electric | |
| Gas turbine (combined cycle) with heat- recovery steam generator | Natural gas | 31 | 42 | Medium |
| Gas turbine (single cycle) with heat-recovery steam generator | Natural gas | 47 | 33 | High |
| Steam boiler and back-pressure steam turbine | Coal, oil | 76 | 8 | Low - Medium |

Source: see Bessette (2002), Krushch et al. (1999), TSU (1999) and own assumptions

The efficiencies given for the above CHP systems are somewhat arbitrary as in a real project context the optimal system configuration, and hence the efficiency, will depend on the plant's exact steam and electric power needs (Krushch et al. 1999). However, figures given represent typical orders of magnitude for thermal and electric efficiencies for the respective CHP systems.

Boiler refurbishments can also deliver significant efficiency improvements. Apart from "good housekeeping" (e.g. proper boiler maintenance) typical investment measures can achieve energy efficiency improvements as illustrated in Table 34 below.

Table 34: Efficiency gains of boilers due to refurbishment

| Measure | Energy efficiency improvement |
| --- | --- |
| Improved process control (optimisation of fuel/air mixture) | 1.5% boiler efficiency improvement per 10% reduction in excess oxygen |
| Economizer (pre-heating of air, water or steam with flue gas) | 1% of fuel use saved per 20-25 °C reduction in exhaust temperature |
| Condensate return | ~10% fuel use saved |

Source: see Galitsky et al. (2003)

Meaningful data for quantification of overall CER generation potential in the five selected countries could not be obtained as current and meaningful figures for boiler numbers according to capacity, fuel and efficiency classes was not available. For China, Wei (2002) assumes an $CO_2$ emission reduction potential of 16.2 million/a. However, the study lacks transparency and detailed data.

In the following we have calculated emission reductions for six main model boiler project types.
- Project 1: Refurbishment of the boiler and a resulting improvement of the operational efficiency to 75%
- Project 2: Replacement of the boiler by a BAT coal-fired steam boiler with an operational efficiency of 93%
- Project 3: Refurbishment of the boiler and fuel switch to natural gas and a resulting improvement of the operational efficiency to 73%
- Project 4: Replacement of the boiler by a BAT natural gas-fired steam boiler with an operational efficiency of 91%

- Project 5: Replacement of the boiler by a system with a BAT coal-fired steam boiler and a back-pressure turbine with efficiencies as given in table 33
- Project 6: Replacement of the boiler by a system with a BAT gas turbine (combined cycle) with heat-recovery steam generator with efficiencies as given in table 33

For all six project types the "baseline scenario" is the continued operation of an old and inefficient coal-fired steam boiler with 55% operational efficiency for 7000h/a.

For project types 5 and 6 we have used the following approach for calculation of emission reductions:
- Calculation of the coal consumption of the old boiler (GJ/a)
- Calculation of steam generation of the old boiler (GJ/a)
- Calculation of the steam generation of the new CHP system using coal consumption of the old boiler and thermal efficiency of the new CHP system and the resulting difference in steam output
- Calculation of the "additional fuel consumption" required to deliver the steam output of the old boiler with the CHP system based on the resulting difference in steam output
- Calculation of the $CO_2$ emission reductions due to the "additional fuel consumption"
- Calculation of the electricity generation of the CHP system based on coal consumption of the old boiler and the electrical efficiency of the CHP system
- Calculation of the $CO_2$ emission reductions due to electricity generation from the CHP unit assuming that electricity generation from the grid is offset because either all electricity is exported to the grid or (partly) offsets electricity formerly imported from the grid

The calculation results for capacities of 30 MW and 50 MW are presented in Figures 16 – 19 below. It can be seen that in general installed capacities of 30MW do not allow to reach very attractive volumes. Also refurbishment or replacement projects of 30 MW and 50 MW capacity without a fuel switch or CHP component cannot result in very attractive emission reduction volumes. 50 MW boiler refurbishment or replacement projects involving fuel switch to natural gas offer very attractive projects with 120-140,000 t $CO_2$ reduction/a. Similar volumes can only be achieved by coal-fired back-pressure CHP systems in countries where the grid EF is very high. Replacement with a CHP system with gas turbine (combined cycle) with heat-recovery steam generator can lead to negative emission reductions in countries where the grid EF is very low due to the low thermal efficiency and the high electrical efficiency of this particular CHP system. However, our calculation reveal that in countries such as China, India and South Africa this project type can be very attractive.

Figure 16: CO$_2$ emission reductions from refurbishment or replacement of a coal-fired steam boiler (kt CO$_2$e/a)
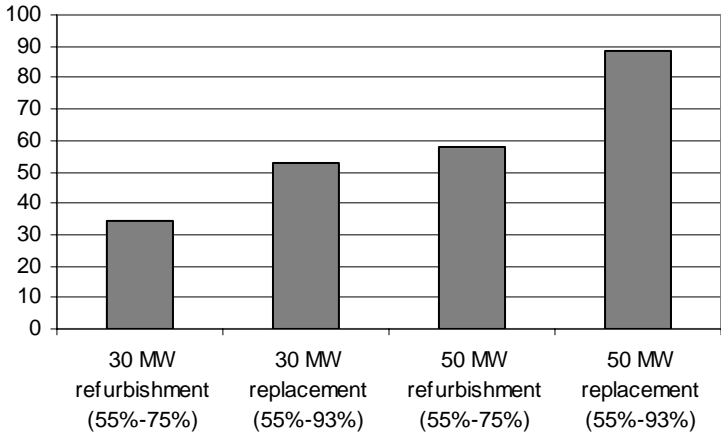


Figure 17: CO$_2$ emission reductions from refurbishment or replacement of a coal-fired steam boiler including a fuel switch to natural gas (kt CO$_2$e/a)
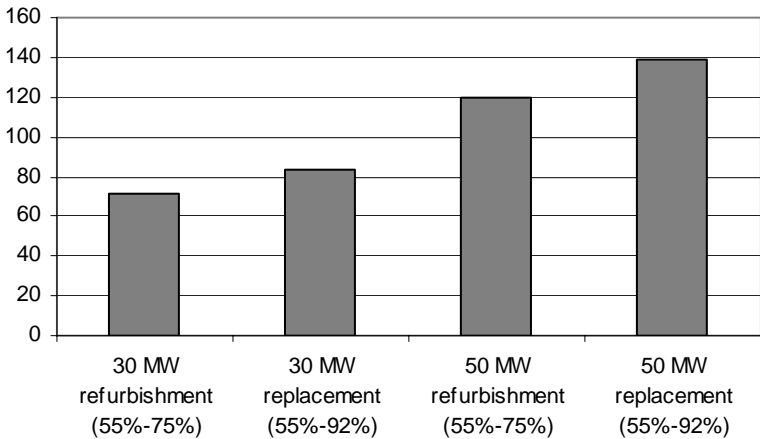
Figure 18: CO$_2$ emission reductions from replacement of a coal-fired boiler by a system with a BAT coal-fired steam boiler and a back-pressure turbine in selected countries (kt CO$_2$e/a)
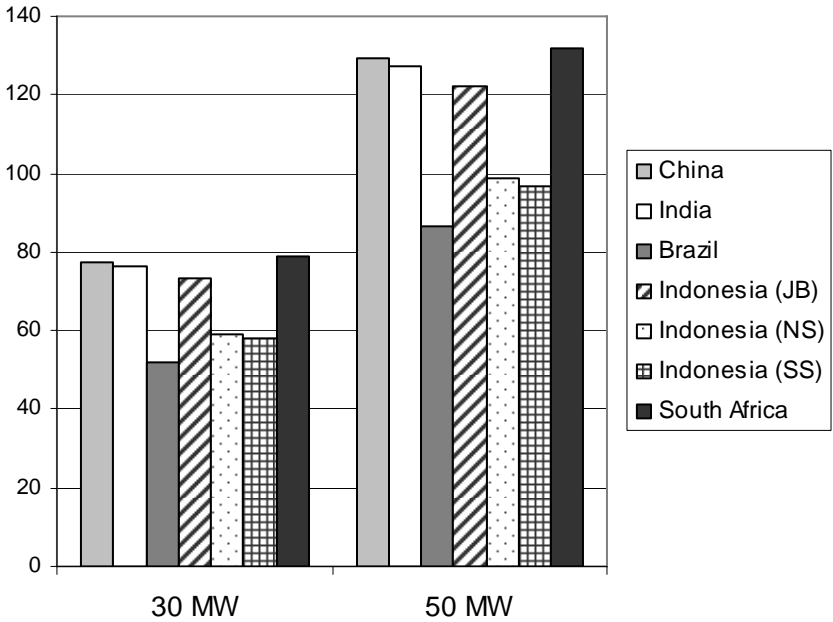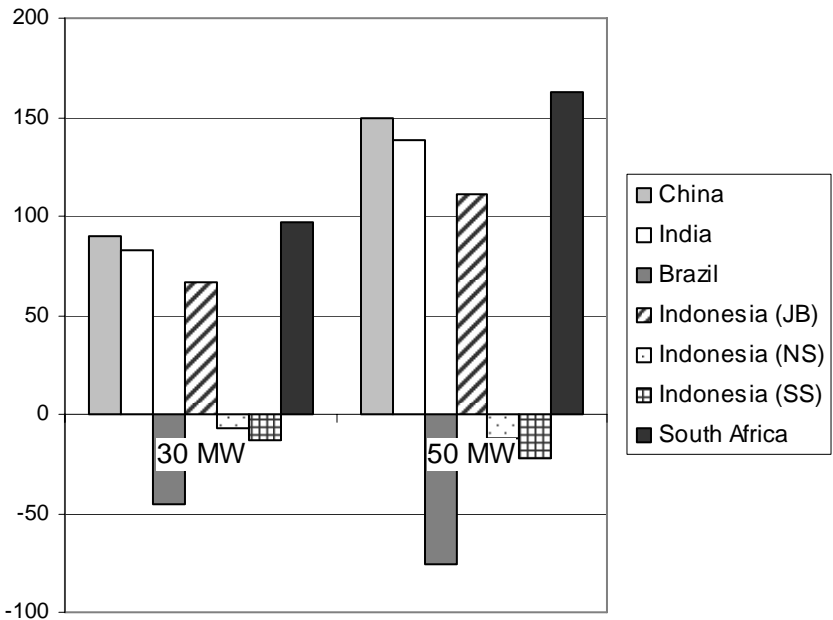


Figure 19: CO$_2$ emission reductions from replacement of a coal-fired boiler by a system with a BAT gas turbine (combined cycle) with heat-recovery steam generator in selected countries (kt CO$_2$e/a)

# 7.    Preliminary additionality screening of the most promising project types

We have identified technology options as attractive under the CDM in terms of achievable $CO_2$ emission reduction volumes in chapters 3, 4 and 5. To really judge on their attractiveness, we also have to assess the likelihood whether the technology passes the additionality test under the CDM.

The CDM Executive Board has published an official tool to harmonise additionality testing of proposed project activities (see CDM EB 2004). This consolidated additionality test involves five steps:
1.    Identification of alternatives to the project activity.
2.    Investment analysis to determine that the proposed project activity is not the most economically or financially attractive.
3.    Barrier analysis.
4.    Common practice analysis, and
5.    Impact of registration of the proposed project activity as a CDM project activity.

The investment analysis and/or barrier analysis is the core element of the additionality test. Project developers can choose whether they want to do the investment or barrier analysis. The barrier analysis mentions three main barriers: investment barriers, technological barriers and barriers due to prevailing practice. It is clearly stated what the result of the barrier analysis has to be: "Provide transparent and documented evidence, and offer conservative interpretations of this documented evidence, as to how it demonstrates the existence and significance of the identified barriers." However, guidance is very vague and information is lacking on how to proceed in detail, just providing "inter alia" recommendations.

We discuss the implications of what this means for the chances of the identified most promising project types to qualify under CDM in practice.

Investment analysis for retrofit:
Aim of the test would be to prove that the continued operation of the old technology is more economically attractive than the refurbishment. It could also be the case that a refurbishment leading to less energy efficiency improvement would be more attractive than the refurbishment undertaken under the project. This case would however imply lower baseline emissions than in the continued operation case. Often, the investment analysis would probably not be passed, given that many companies implement a payback criterion for investments of less than two years implying an IRR of over 40%.

Barrier analysis for retrofit:
In many cases, there are investment barriers with respect to availability of budget or bank loans for implementation of the technology. The payback criterion mentioned above could as well seen as an investment barrier. In terms of technology, limited experience of the company and its staff with an advanced technology will often be a barrier.

A key approach should be to compare the project technology with all combinations of technology that are possible. In the iron and steel case the options could be as follows:

      a. Plant without near net shape casting
      b. Plant with near net shape casting
      c. Plant with PCI
      d. Plant with near net shape casting and PCI

The plant with the highest IRR would constitute the baseline case. Barrier assessment would be done as in the case discussed above. Generally, technologies that would be first-of-their kind in a host country are likely to pass the barrier test as it would be easy to show that there are technological barriers. Concerning the iron and steel sector, this applies to net shape casting. For pulverized coal/natural gas injection as well as top pressure recovery turbines the same argument could apply, but to a smaller extent. Pulverized coal injection and top pressure recovery turbines are common practice in many European countries (see Worrell et al. 1999). Coke dry quenching is already happening in China and Brazil (see Yamaguchi 2005) so may face problems in passing the additionality test whereas in India, it has not yet been used. As BFG /BOF gas is routinely being used in Europe, Japan (Worrell et al. 1999) and many developing countries, these project types will likely have difficulty in passing the additionality test.

In the cement sector, blending is currently becoming a fashionable CDM project as the EB made the consolidated methodology ACM 5 available. Whether these projects pass the additionality test remains to be seen. As the technology is quite simple and does not entail substantial costs, the investment is likely to be attractive even without CDM.

Concerning aluminium, the process change from HSS to PFPB (for countries with a high OM EF) or SWPB to PFPB (for countries with a low OM EF) and the use of inert anode/wetted cathode deliver the most $CO_2$ emission reductions compared to other technology changes. Due to the lumpiness of smelter investment, replacement of a process before the end of its technical lifetime would likely be additional.

In the context of pulp and paper production, continuous digesters are a more energy efficient than conventional batch digesters and have become common practice in Europe (see Hein 2002).

Steam boiler refurbishment or replacement projects can also be very attractive project types if the installed capacity is higher than around 30 MW.

Given these rough information about the degree of use of technologies as a proxy for passing the barrier test (which is reflected in the common practice test), we evaluate additionality in Table 35.

Table 35: Additionality and attractiveness of project types in terms of CER volume

| Sector | Project type | Attractiveness in terms of CER volume | Additionality |
|---|---|---|---|
| Iron and steel | Near net shape casting | +++ | +++ |
| | Pulverized Coal Injection | +++ | ++ |
| | Natural Gas Injection | +++ | ++ |
| | BFG/BOF gas for heat generation | +++ | + |
| | Coke Dry Quenching | ++ | ++ |
| | TRT | ++ | ++ |
| Cement | Blended cement | ++ | + |
| Aluminium | Smelter change and use of inert anode/wetted cathode | +++ | +++ |
| Ammonia | Process integration | ++ | ++ |
| +++ likely to be generally additional<br>++ neutral, case-by-case<br>+ unlikely to be additional | | | |

# 8.    Conclusions

Our assessment of a number of energy efficiency improvement technologies in heavy industry shows that only some of those technologies are likely to become attractive CDM projects with more than 50,000 CERs per year and plant. In the iron and steel sector, near net shape casting promises high reductions and is likely to be additional. Pulverized coal and natural gas injection projects generate somewhat smaller emission reductions and their additionality depends on case-specific factors. In the cement sector, blending is quite attractive which is corroborated by the large number of CDM projects already submitted. However, additionality remains questionable. Other technologies are not relevant. In aluminium production, changes in smelter technology are made attractive by the large PFC reduction which is achieved as a "side effect". For pulp and paper, only the continuous digestion process achieves sizeable reductions; in ammonia production this is the case for complete process integration. Steam boiler refurbishment or replacement projects can only be attractive if installed capacity is sufficiently high. The total preliminary estimation of total emission reduction potential of selected sectors has shown that iron and steel and cement industry could offer emission reductions of several hundred million tons $CO_2e$, with the overwhelming majority of emission reductions coming from China.

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