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**Environmental Energy
Technologies Division**

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Energy Use and Carbon Dioxide Emissions in Energy-Intensive Industries in Key Developing Countries

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Introduction

The industrial sector is the most important end-use sector in developing countries in terms of energy use and was responsible for 50% of primary energy use and 53% of associated carbon dioxide emissions in 1995 (Price et al., 1999). The industrial sector is extremely diverse, encompassing the extraction of natural resources, conversion of these resources into raw materials, and manufacture of finished products. Five energy-intensive industrial subsectors account for the bulk of industrial energy use and related carbon dioxide emissions: iron and steel, chemicals, petroleum refining, pulp and paper, and cement.

In this paper, we focus on the steel and cement sectors in Brazil, China, India, and Mexico.[1] We review historical trends, noting that China became the world's largest producer of cement in 1985 and of steel in 1996. We discuss trends that influence energy consumption, such as the amount of additives in cement (illustrated through the clinker/cement ratio), the share of electric arc furnaces, and the level of adoption of continuous casting.

To gauge the potential for improvement in production of steel and cement in these countries, we calculate a "best practice" intensity based on use of international best practice technology to produce the mix of products manufactured in each country in 1995. We show that Brazil has the lowest potential for improvement in both sectors. In contrast, there is significant potential for improvement in Mexico, India, and especially China, where adoption of best practice technologies could reduce energy use and carbon dioxide emissions from steel production by 50% and cement production by 37%.

We conclude by comparing the identified potential for energy efficiency improvement and carbon dioxide emissions reduction in these key developing countries to that of the U.S. This comparison raises interesting questions related to efforts to improve energy efficiency in developing countries, such as: what is the appropriate role of industrialized countries in promoting the adoption of low carbon technologies, how do international steel and cement companies influence the situation, and how can such information be used in the context of Clean Development Mechanism in the Kyoto Protocol?

Methodology[2]

We begin our analysis by assessing the key processes and technologies used within each specific industrial sector. We then review historical production trends of the major commodities produced by that sector as well as trends in key structural indicators in a given country. At a sectoral level, we define sector structure as the product mix within a sector, accounting for differences in product quality (e.g. primary vs. secondary steel) and factors that affect product mix. Feedstock and process type are not considered to be indicators of sector structure, unless they influence the product mix (or product quality) (Phylipsen et al., 1998). After accounting for differences in production processes and product mix, the remaining difference in energy use between countries is due to the specific technologies used and how efficiently individual plants are managed and operated.

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[1] The top 10 steel producing developing countries in 1998 were China, South Korea, Brazil, India, Taiwan, Mexico, South Africa, Iran, Argentina, and Venezuela. The top 10 cement producing developing countries in 1995 were China, India, South Korea, Thailand, Brazil, Mexico, Indonesia, Taiwan, Egypt, and Iran.

[2] The methodologies described here were developed through collaboration with international energy efficiency experts (Martin et al. 1994; Phylipsen et al., 1996) and described in the Handbook on International Comparisons of Energy Efficiency in the Manufacturing Industry (Phylipsen et al., 1998). The methodologies are currently being used within the International Network on Energy Demand analysis in the Industrial Sector (LBNL, 1999).

In order to account for the structural differences, we calculate a best practice benchmark energy intensity using best practice energy intensities for the actual product mix and feedstocks used in each country. The best practice benchmark energy intensity is calculated to reflect the sector structure for each year for each country, based on that country's product mix and feedstock. These best practice benchmark energy intensities are then compared to actual energy intensities. To make this comparison, we use an energy efficiency index, which is the ratio of the actual energy intensity to the best practice energy intensity, where the best practice equals 100.

Carbon intensity trends are closely related to energy intensity trends but are also dependent upon the fuel mix used by the iron and steel industry in each country.[3] As with energy intensity, the structural differences between countries can be taken into account by calculating a carbon intensity index, which compares the actual level of emissions per tonne of product to a best practice benchmark level of emissions. The best practice benchmark carbon intensity for each of the processes and products is calculated by multiplying the actual carbon intensities with the best practice carbon intensities and the carbon emission factor for each process. The sectoral best practice benchmark carbon intensity is calculated as a weighted average based on the shares of the processes and products in each country. The carbon intensity index is the ratio of the actual carbon intensity to the best practice benchmark carbon intensity, where a carbon intensity of 100 represents best practice and the higher the carbon intensity index the higher the emission reduction potential for a given sector structure.

Compared to the energy efficiency index there is one complicating factor in calculating the carbon intensity index. In addition to sector structure and energy efficiency, fuel mix also influences CO_2 emissions per tonne of product. Using the fuel mix associated with the best practice technology in the carbon intensity index calculation implies a fuel switch from actual fuel mix to this best practice fuel mix. Because of constraints on the availability of indigenous resources this is not always economically feasible. Therefore, we have excluded the influence of fuel mix in our calculations of the carbon intensity index. This is done by using a national average fuel mix, instead of the best practice fuel mix, to calculate the benchmark carbon intensity[4]. This means that the index is an indication of the emission reduction potential by efficiency improvements only. Additional emissions reductions can be accomplished through fuel switching.

Steel Production

Greenhouse gas emissions in the steel sector are primarily the result of burning fossil fuels during the production of iron and steel. Currently there are two main routes for the production of steel: production of primary steel using iron ores and scrap and production of secondary steel using scrap only. A wide variety of steel products are produced by the industry, ranging from slabs and ingots to thin sheets, which are used in turn by a large number of other manufacturing industries.

Ironmaking. During the ironmaking process, sintered or pelletized iron ore is reduced using coke (produced in coke ovens) in combination with injected coal or oil to produce pig iron in a blast furnace. Limestone is added as a fluxing agent. Reduction of the iron ore is the largest energy-consuming process in the production of primary steel. In 1994, this process was responsible for over 45% of the CO2 emissions from U.S. integrated steelmaking and had a primary energy intensity of 18.6 GJ/tonne of steel produced (including the energy used for ore preparation and cokemaking) (Worrell et al., 1999).

Primary steel is produced by two processes: open hearth furnace (OHF) and basic oxygen furnace (BOF). Steelmaking using a basic oxygen furnace (BOF) has a relatively low energy intensity (0.7 GJ/tonne) compared to the 3.9 GJ/tonne energy intensity of open hearth furnaces (OHFs), which are much more common in developing countries (WEC, 1995). The OHF is still used in Eastern Europe, China, India and other developing countries. While OHF uses more energy, this process can also use more scrap than the BOF process. However, the BOF process is rapidly replacing the OHF worldwide, because of its greater productivity and lower capital costs (IISI, 1990). In addition, this process needs no net input of energy and can even be a net energy exporter in the form of BOF-gas and steam. The process operates through the injection of oxygen, oxidizing the carbon in the hot metal. Several configurations exist depending on the way the oxygen is injected. The steel quality can be improved further by ladle refining processes used in the steel mill. The scrap input is rather small for the BOF-route, typically about 10-25%.

Secondary steel is produced in an electric arc furnace (EAF) using scrap. In this process, the coke production, pig iron production, and steel production steps are omitted, resulting in much lower energy consumption and a primary energy

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[3] Carbon emissions factors are from the Intergovernmental Panel on Climate Change (IPCC, 1996).

[4] This assumes that the efficiency of the best practice technology does not change with changing fuel mix.

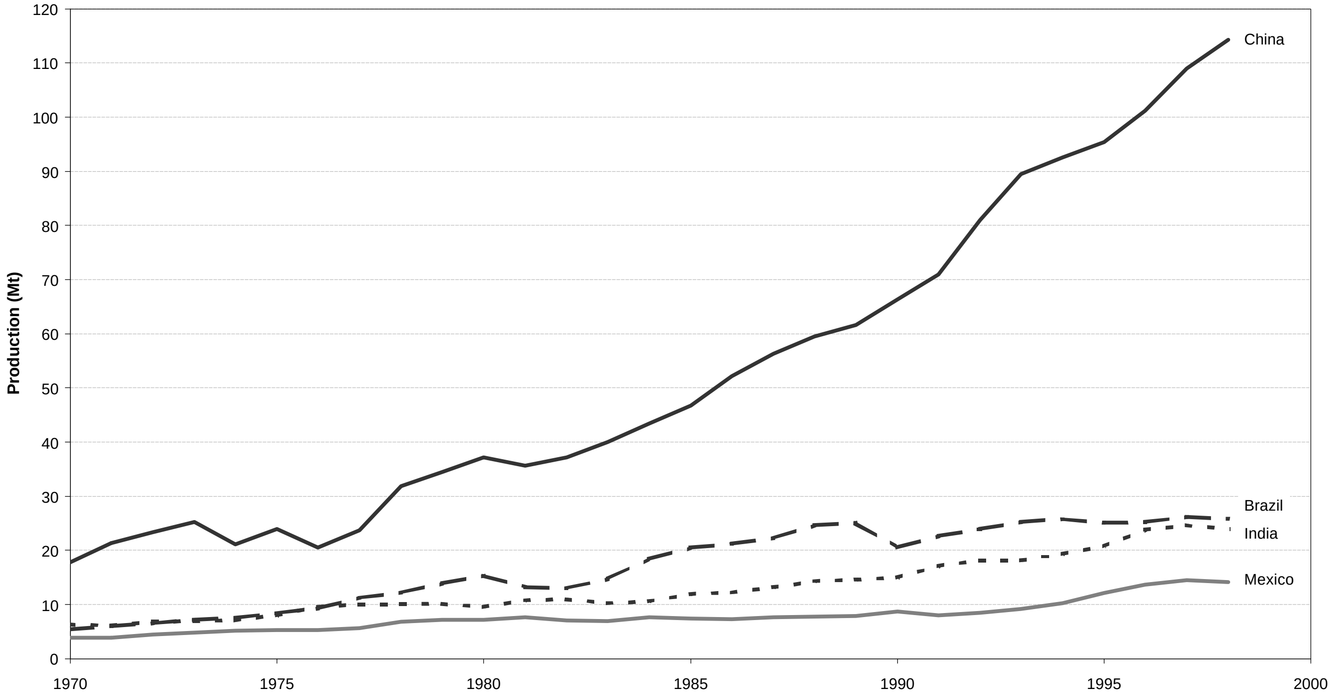
intensity of 5.5 GJ/tonne (Worrell et al., 1999). To produce secondary steel, scrap is melted and refined, using a strong electric current. The EAF can also be fed with iron from the direct reduced iron (DRI) route, but energy consumption increases due to the added carbon, resulting in an EAF primary energy intensity of 6.7 GJ/tonne. DRI is used to enhance steel quality or if high quality scrap is scarce or expensive. Several process variations exist, using either AC or DC currents, and fuels can be injected to reduce electricity use. Energy optimizing furnaces (EOFs) can also be used to produce steel from scrap. This process is essentially an oxygen steelmaking process using combined side blowing. The heat from the carbon-oxygen reaction is used to preheat scrap (Chatterjee, 1996).

Casting can be a batch (ingots) or a continuous process (slabs, blooms, billets). Ingot casting is the classical process and is rapidly being replaced by continuous casting machines (CCM). In 1998, 83% of global crude steel production was cast continuously (IISI, 1999). Continuous casting is a significantly more energy-efficient process for casting steel than the older ingot casting process. In the U.S., continuous casting uses 0.15 GJ/tonne of steel on average, 1.85 GJ/tonne less than ingot casting (Brown et al., 1985; Energetics, 1988; Worrell, 1994). Rolling of the cast steel begins in the hot rolling mill where the steel is heated and passed through heavy roller sections reducing the thickness of the steel. Hot rolling typically consumes 5.4 GJ/tonne of steel (Worrell et al., 1999). The sheets may be further reduced in thickness by cold rolling. Finishing is the final production step, and may include different processes such as annealing, pickling, and surface treatment. Cold rolling and finishing add 1.8 GJ/tonne to the rolling energy use (Worrell et al., 1999). Thin slab or near net shape casting are more advanced casting techniques which reduce the need for hot rolling because products are intially cast closer to their final shape. Primary energy used for casting and rolling using thin slab casting is 0.6 GJ/tonne (Worrell and Moore, 1997).

Steel Production Trends

Historical trends in steel production from 1970 to 1998 for four key developing countries are presented in Figure 1. China clearly dominates in steel production among these developing countries. In 1996, China became the world's largest steel producer, passing Japan and the U.S. (IISI, 1999). The highest average annual growth in steel production over the 1970 to 1998 period was seen in China, followed by Brazil, India, and Mexico, respectively. Steel production grew between 4.7% and 6.4% per year on average in these countries.

Figure 1. Historical Steel Production in Key Developing Countries



Structural Factors Affecting Energy Use and Carbon Dioxide Emissions in Steel Production

Country-specific structural factors that must be accounted for when making international comparisons include the products produced as well as the processes used when these processes are influenced by the product mix (Phylipsen, Blok and Worrell 1998). For the steel industry, the processes used are important because different feedstocks (e.g. scrap, iron ore) can influence product quality and the amount of scrap available to a steel plant may be a limiting factor in choosing between iron and scrap. Thus, even though EAF steelmaking may be more efficient than OHF and BOF steelmaking, demand for products of a certain quality or lack of available scrap can influence how much steel is made using this process in a given country at a given time. The mix of products produced in a country also influences total energy use for steelmaking. In the iron and steel industry product mix is defined as the share of iron, slabs, hot rolled steel, cold rolled steel and wire.

Table 1 provides information on the steelmaking processes used in each of the key developing countries in 1998. The OHF process typically uses 3.2 GJ/tonne crude steel more energy than the BOF process. The less efficient OHFs were phased out in Brazil by 1989 and in Mexico by in 1992. In both countries a sharp decline in the share of OHFs started in the mid-1970s when stronger growth in new steel capacity was accompanied with a gradual shutdown of old OHF capacity. The share of OHF in total production is also declining over time in China and India. The share of EAF steelmaking grew steadily in India and Mexico, but declined slightly in Brazil and China around 1995 only to grow again by 1997/98.

Table 1. Share of OHF, BOF, and EAF Steelmaking in Key Developing Countries in 1998.

Country	Share of OHF	Share of BOF	Share of EAF	Share of Other[5]
Brazil	0%	79%	20%	1%
China	5%	75%	20%	0%
India	14%	54%	32%	0%
Mexico	0%	35%	65%	0%

Source: IISI, 1999.

An indication of the energy intensity of the product mix is given by the share of more energy-intensive cold rolled products that are produced in a country. Additional energy is used to produce cold rolled steel which is a thinner and smoother product typically used in the manufacture of commodities such as refrigerators. The share of cold rolled steel has hovered around 10% in China since 1970. There was a downward trend in the share of cold rolled steel in Mexico from 1970 to 1995, dropping from nearly 30% to about 14%, but this trend reversed and now the share is over 20%. The share of cold rolled steel has grown continuously in India and Brazil, where this more energy-intensive commodity was responsible for 17% and 36% of rolled steel in 1995 in these countries, respectively.

One steelmaking technology that is clearly energy-efficient is continuous casting, which typically uses 1.85 GJ/tonne crude steel less than ingot casting. The level of adoption of this technology is one indication of the energy efficiency of steelmaking in a given country. Figure 2 shows that the share of continuous casting has increased significantly in all four countries since 1970. The share of continuous casting grew to 80% and 86% by 1998 in Brazil and Mexico, respectively. In China 68% of the steel was continuously cast in 1998, while India's share of continuous casting was 50% that year (IISI, 1999).

Energy and Carbon Dioxide Intensity Benchmarking for Steel Production

In order to compare energy use across countries while accounting for differences in processes used to produce steel as well as steel products produced, we calculated an energy efficiency index (EEI), which is the ratio of the actual energy intensity to the best practice energy intensity, where the best practice equals 100. The best practice benchmark for primary steel production is equivalent to the 1988 energy intensity of an integrated steel plant in The Netherlands, assuming 10% scrap addition in the BOF (Worrell et al., 1993). The best practice benchmark for secondary steel production is equivalent to the 1988 energy intensity of an EAF plant in Germany (Teoh, 1989). Best practice benchmarks for continuous casting, the hot strip mill, and the cold rolling mill are also based on the 1988 actual energy intensity at an integrated steel plant in The Netherlands (Worrell et al., 1993). These best practice benchmark energy intensities are then compared to actual energy

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[5] The category of "other" in Brazil consists of Energy Optimizing Furnaces (EOF).

intensities. Figure 3 shows that all of the countries experienced a downward trend towards the best practice benchmark value of 100. By the mid-1990s, the steel industry in Brazil was the closest to best practice, followed by Mexico, India, and China, respectively. Similar trends are seen when the carbon dioxide intensity index is plotted.

Figure 2. Share of Continuously Cast Steel in Total Crude Steel Production: 1970-1998

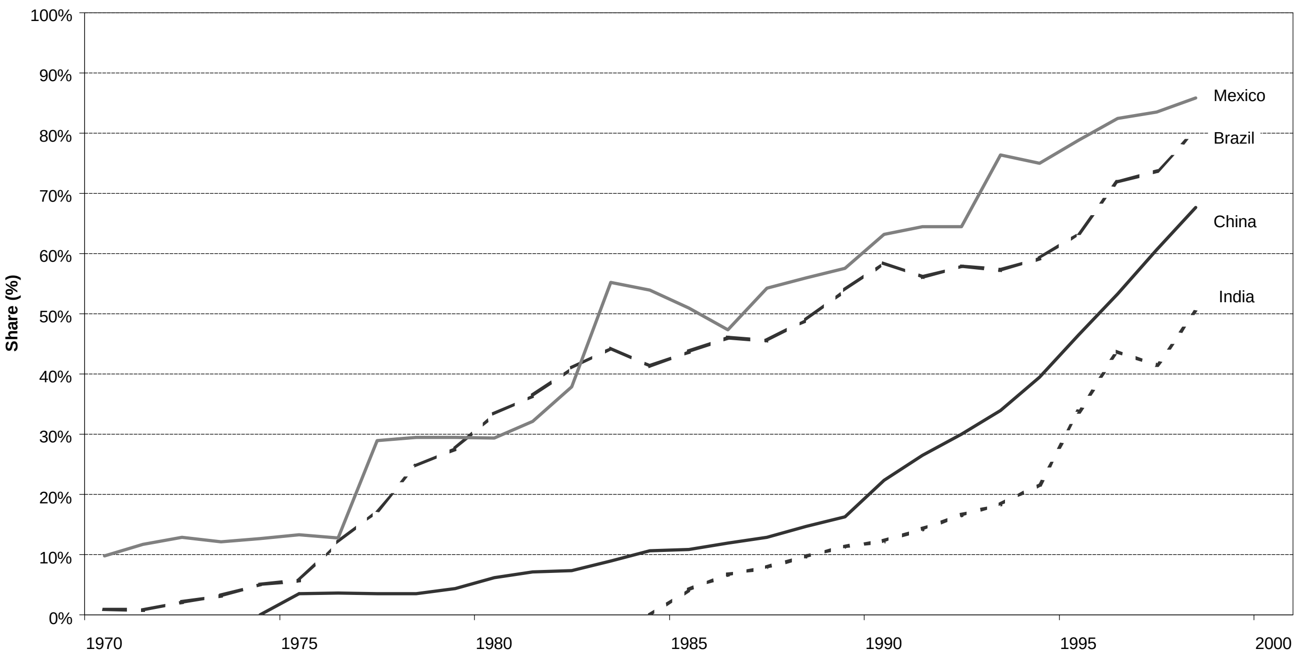


Figure 3. Best Practice Benchmarking for Steel Production

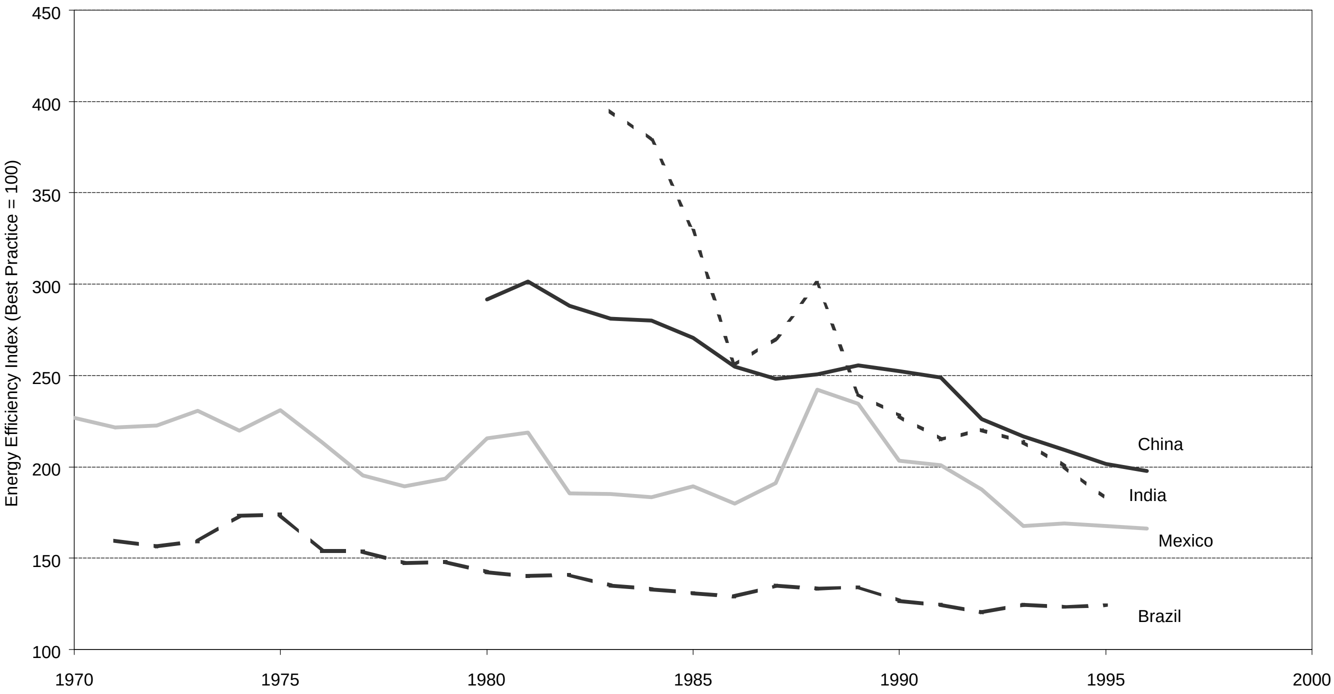


Table 2 provides the 1995 actual and best practice benchmark primary energy intensity values for Brazil, China, India, and Mexico, as well as the technical potential primary energy savings which is the difference between actual and best practice primary energy use. China and India have the highest technical potential for reducing primary energy use in steelmaking; energy consumption of 20 and 17 GJ/tonne of steel produced in those countries, respectively, is used because of outdated technology or inefficient practices. Potential savings in Mexico and Brazil are significantly lower. Carbon dioxide emissions from steelmaking would be almost 0.5 tC less per tonne of steel produced if best practice technologies were used in China and India. Similarly, carbon dioxide emissions would be reduced 0.1 tC and 0.2 tC per tonne of steel in Brazil and Mexico, respectively, if those countries implemented best practice technologies for steelmaking.

Table 2. Best Practice Benchmarking: Identification of Technical Potential Primary Energy Savings and Carbon Dioxide Savings for Steelmaking in 1995.

Country	Actual Primary Energy Intensity (GJ/tonne)	Best Practice Primary Energy Intensity (GJ/tonne)	Technical Potential Primary Energy Savings (GJ/tonne)
Brazil	23.1	18.6	4.5
China	40.7	20.2	20.5
India	37.3	20.5	16.8
Mexico	22.6	13.5	9.1
Country	**Actual Carbon Dioxide Intensity (tC/tonne)**	**Best Practice Carbon Dioxide Intensity (tC/tonne)**	**Technical Potential Carbon Dioxide Savings (tC/tonne)**
Brazil	0.36	0.27	0.09
China	0.96	0.48	0.48
India	0.98	0.53	0.45
Mexico	0.42	0.24	0.18

Technical Potential for Carbon Dioxide Emissions Reduction in Steelmaking in Key Developing Countries

If best practice technologies and practices were used by the key developing countries for production of steel, energy use and associated carbon dioxide emissions could be significantly reduced. Table 3 provides the technical potential carbon dioxide emissions reductions for Brazil, China, Mexico, and India. If best practice technologies had been used in 1995 in China, India and Mexico, carbon dioxide emissions from steel production would have been about 40-50% lower than actual emissions. Carbon dioxide emissions would have been 26% less in Brazil if best practices had been used in 1995.

Table 3. Technical Potential for Carbon Dioxide Emissions Reduction Using Best Practice Technologies in 1995.

	Annual Steel Production (Mt)	Actual Carbon Dioxide Emissions (MtC)	Technical Potential Carbon Dioxide Emissions (MtC)	Difference (Share of Actual Carbon Dioxide Emissions)
Brazil	25.1	9.1	6.8	26%
China	96.3	91.6	46.2	50%
India	20.8	20.4	11.0	46%
Mexico	12.1	5.1	2.9	42%

Cement Production

Greenhouse gas emissions in the cement industry are the result of burning fossil fuels during the production process and of the chemical reactions taking place in the formation of clinker, an intermediate in cement production. The production of clinker is the most energy-intensive step in cement production, accounting for 70-80% of total energy consumed (WEC, 1995). The clinker is mixed with a number of additives to produce different types of cement. The most important use of cement is the production of concrete. In addition, cement is used as a binder in masonry.

Clinker is produced out of a mixture of raw materials, most importantly limestone ($CaCO_3$), silicon dioxide, aluminium oxide and iron oxides (out of clay and coal shale). These materials are fed to a kiln and slowly heated to a temperature of 1450°C. During the process, water is released and a chemical reaction takes place in which the limestone is converted to calcium oxide (CaO) and carbon dioxide. The calcium oxide subsequently reacts to alite (tricalcium silicate) which is mainly responsible for the hardening properties of cement. The materials in the melt stick together to forms nodules, which are called clinker. The melt needs to be cooled rapidly to prevent unwanted side reactions to take place.

Clinker production can take place in a wet process, a dry process or intermediate forms. In the wet process, the kiln is fed by a slurry of the raw materials mixed with water to obtain better homogenization. The semi-wet, or Lepol, process was introduced later, using materials with a lower moisture content, which reduces fuel consumption. In the dry process the kiln is fed with raw meal, further decreasing fuel consumption.

In industrialized countries the predominant type of kiln used is the rotary kiln, which basically consists of a tube with a diameter of up to 6 meters. The tube is installed at an angle of 3-4°, and rotates about twice a minute to improve homogenization. Raw materials are fed to the top and move towards the flame at the bottom of the kiln. The length of short kilns can be up to 65-120m. Long kilns can get as large as 200m (Hendriks et al., 1998). The kiln can be equipped with a preheater, in which the raw meal is preheated with waste heat from the kiln. A type of preheater that is especially suitable for the dry kiln is the suspension preheater, consisting of multiple preheating stages. The higher the number of stages is, the larger the energy savings compared to a kiln without preheater. An option to further reduce energy consumption is the application of a precalciner in between the kiln and the preheater. The precalciner basically consists of a separate burner chamber, in which 80-90% of the $CaCO_3$ is dissociated before it enters the kiln (Hendriks et al., 1998).

Shaft kilns are mainly used in small cement plants, and they can mostly be found in China and India. The shaft kiln is positioned vertically and the material travels from top to bottom. Shaft kilns can obtain reasonably high efficiencies, because of the good interaction between material and exhaust gases. The biggest problem in shaft kilns is caused by incomplete combustion (Hendriks et al., 1998).

The cooled clinker is ground together with additives to produce cement. Grinding can be done using ball mills, roller mills or roller presses. Often combinations of these milling techniques are used (Hendriks et al., 1998). Coarse material can be separated and returned for additional grinding. Power consumption for grinding depends on the desired fineness of the material and the amount and type of additives used. Also, some of the additives used, such as blast furnace slag, may require drying (Worrell et al., 1995). Both material fineness and additives determine the cement properties to some extent. In general, the quality of blended cements is comparable to Portland cement. The main differences are a lower early strength but higher final strength and an improved resistance to sulfate and seawater for blended cements (Cangiano et al., 1992).

Cement Production Trends

Historical trends in cement production for the four key developing countries are presented in Figure 4 (note that China's production is presented on the right axis in the figure). China dominates in cement production among these four countries as well as the whole world. Since the mid-1980s, China has been the largest cement producer in the world, with production in 1995 five to six times as high as the second and third largest countries (Japan and the U.S., respectively). China has also experienced the highest average annual growth in cement production, averaging over 12% per year between 1970 and 1995. While growth in Brazil and Mexico averaged just over 4.5% per year during this period, growth was highest in the period up to 1980 in Brazil and 1985 in Mexico, when slower overall economic growth resulted in slower cement production rates. Growth in cement production in India fluctuated over the 1970 to 1995 time period, averaging 6.6% per year overall.

Figure 4. Historical Cement Production in Key Developing Countries (note: China on right axis)

Structural Factors Affecting Energy Use and Carbon Dioxide Emissions in Cement Production

A structural indicator in the cement industry is the clinker content of cement because of its influence on product quality as well as the availability of alternative additives (e.g. blast furnace slag). Also, imports and exports of the intermediate product (i.e. clinker) are a part of sector structure, although not very important yet in the countries included in this analysis. Both aspects, clinker content and import/export streams, can be incorporated into one single structural indicator: the clinker production to cement production ratio. Table 4 presents the clinker production to cement production ratio for 1970, 1980, 1990, and 1995 for the key developing countries, showing great variability in this ratio in almost all countries.

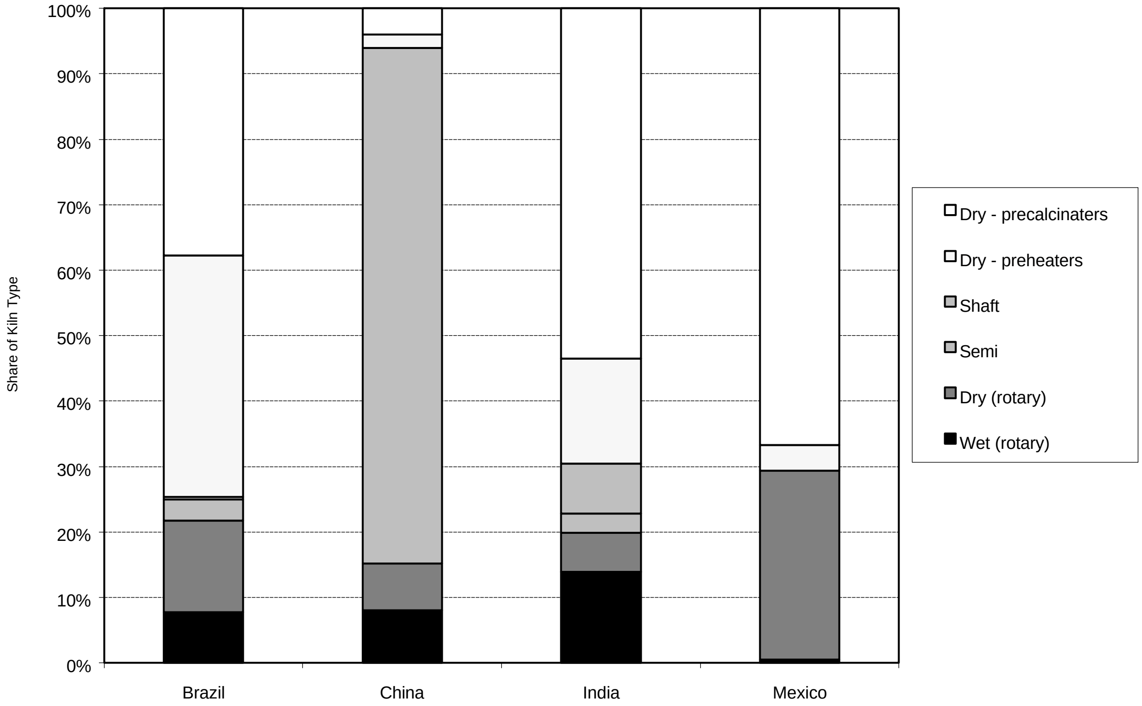
Table 4. Clinker to Cement Ratio in Key Developing Countries, 1970, 1980, 1990, and 1995.

	1970	1980	1990	1995
Brazil	0.9	0.81	0.74	0.80
China		0.73	0.74	0.70
India		0.85	0.84	0.90
Mexico		0.86*	0.92	0.88

*1981

There are a number of types of kilns used for cement production, ranging from inefficient wet process kilns to highly efficient dry process kilns with multi-stage preheaters and precalciners. All four developing countries have been phasing out the inefficient wet kiln technology, with India dropping from a 62% share of wet kilns in the mid-1970s to 14% in 1994, followed by Brazil which dropped from 40% to 8% over the same period. The share of wet kilns in China dropped from 18% in 1980 to 8% in 1994. Mexico, which had only 9% wet kilns in the mid-1970s has virtually phased out this technology today. Figure 5 shows the kiln types used in the four countries in 1994 (Cembureau, 1998). Remarkable is the large share of shaft kilns in China and the large share of dry kiln with multistage preheaters and/or precalciners in Mexico, Brazil, and India.

Figure 5. Share of Kiln Types in Key Developing Countries, 1994



Energy and Carbon Dioxide Intensity Benchmarking for Cement Production

In order to compare energy use for cement production across countries while accounting for the structural differences, we calculate an energy efficiency index (EEI) which is the ratio of the actual energy intensity to the best practice energy intensity, where the best practice equals 100. The best practice benchmark for cement production is based on the actual energy intensity of the Ash Grove's Seattle plant that began production in 1993 (Steuch and Riley, 1993). The best practice benchmark energy intensity is calculated to reflect the sector structure for each year for each country, based on that country's product mix and feedstock. In the cement industry product mix is defined as the clinker content in cement, while taking into account the import/export streams of clinker. Feedstock (e.g. blast furnace slags, fly ash) is important because the product quality can be influenced by the additives (i.e. product mix is influenced) (Phylipsen et al., 1998). These best practice benchmark energy intensities are then compared to actual energy intensities. Figure 6 shows that all of the countries experienced a downward trend towards the best practice benchmark value of 100, with especially a large decline for India between 1976 and 1991. By the mid-1990s, the cement industry in Brazil was the closest to best practice, followed by Mexico, India, and China, respectively.

Table 5 provides the 1995 actual and best practice benchmark primary energy intensity values for Brazil, China, India and Mexico, as well as the technical potential primary energy savings which is the difference between actual and best practice primary energy use. China and India have the highest technical potential for reducing primary energy use in cement production; per tonne of cement produced in those countries 0.5 to 1.5 GJ is used because of outdated technology or inefficient practices. Potential savings in Mexico and Brazil are around 0.3 GJ/tonne cement produced. Note that the best practice used here is base on plants that have been built a number of years ago. There are indications that recently built plants in Japan and South Korea are more efficient (about 0.2 GJ/t clinker). Adjusting our best practice values to reflect these developments would result in a somewhat larger distance between actual intensities and the best practice benchmark and, therefore, somewhat larger energy savings.

Figure 6. Best Practice Benchmarking for Cement Production

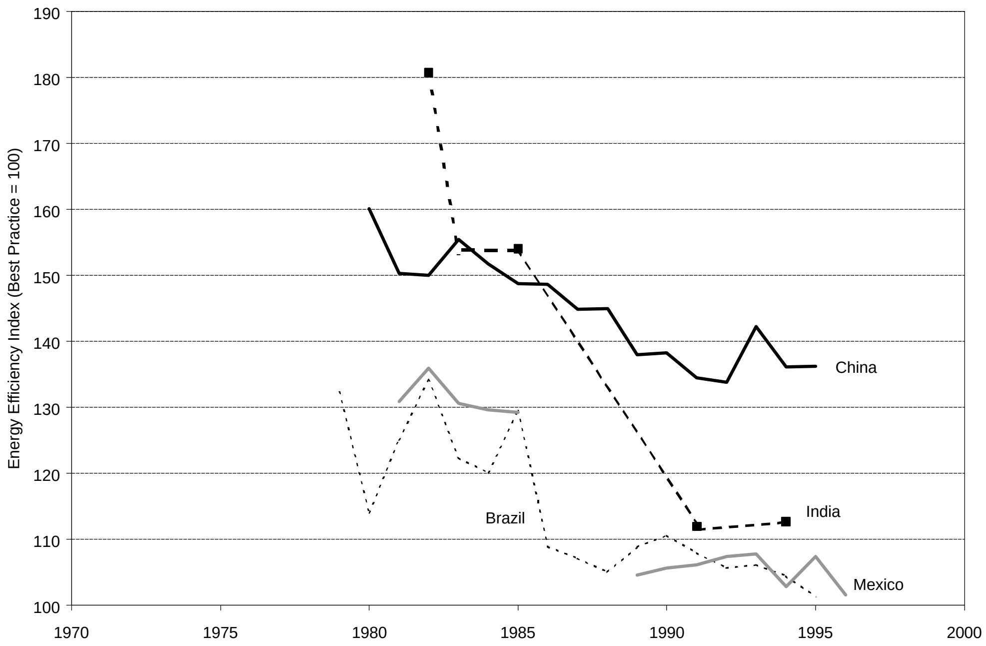


Table 5. Best Practice Benchmarking: Identification of Technical Potential Primary Energy Savings for the Production of Cement in 1995.

Country	Actual Primary Energy Intensity (GJ/tonne)	Best Practice Primary Energy Intensity (GJ/tonne)	Technical Potential Primary Energy Savings[2] (GJ/tonne)
Brazil	4.0	4.0	0.0
China	5.8	3.8	2.0
India*	5.0	4.6	0.4
Mexico	4.7	4.5	0.2

* 1994

Technical Potential for Carbon Dioxide Emissions Reduction in Cement Production in Key Developing Countries

If best practice technologies and practices were used by the key developing countries for production of cement, energy use and associated carbon dioxide emissions could be significantly reduced. Table 6 provides the technical potential carbon dioxide emissions reductions for Brazil, China, Mexico, and India. If best practice technologies had been used in 1995 in China, India and Mexico, carbon dioxide emissions from cement production would have been about 25-35% lower than actual emissions. Carbon dioxide emissions would have been 19% less in Brazil if best practices had been used in 1995.

Table 6. Technical Potential for Carbon Dioxide Emissions Reduction Using Best Practice Technologies in 1995.

	Annual Cement Production (Mt)	Actual Carbon Dioxide Emissions (MtC)	Technical Potential Carbon Dioxide Emissions (MtC)	Difference (Share of Actual Carbon Dioxide Emissions)
Brazil	28.3	1.4	1.13	19%
China	475.9	70.8	44.54	37%
India*	62.4	8.1	5.8	28%
Mexico	24.0	2.0	1.5	24%

*****1994

Comparison to U.S. Steel and Cement Production Trends

In 1998, the U.S. was the world's second largest producer of steel, manufacturing 98 Mt. Approximately 60% of U.S. production is of primary steel using BOF technology while the remaining 40% is produced using EAFs. Primary steel production using inefficient OHF technology in the U.S. dropped from 37% in 1970 to 8% in 1982 and was completely phased out by 1992. While China and India still use this technology, Brazil and Mexico phased out OHFs in 1989 and 1992, respectively. The adoption of continuous casting technology in the U.S. was much more gradual than in Mexico and Brazil from 1970 to 1985 at which time the U.S. began to adopt this technology more rapidly. Using the same international benchmarks to measure the efficiency of U.S. steel production, we find that in 1994 the EEI for the U.S. was 167, higher than that of Brazil (123), comparable to Mexico (169), and lower than China (209) and India (200). We found that based on technical potential alone, in 1994 the U.S. could have reduced carbon dioxide emissions from steel production by over 40% if best practice technologies had been used.

The U.S. is the world's third largest producer of cement and produced 77 Mt in 1995. The U.S. has a high clinker to cement ratio, averaging around 90% during the 1980s and 1990s and in 1994 had a higher clinker to cement ratio than Brazil or China and had a comparable ratio to that in Mexico. The U.S. also used inefficient wet kiln technology to produce 26% of the cement manufactured in 1995. The U.S. has a higher share of cement produced by wet kilns than any of the four developing countries analyzed in this paper. Using the international best practice benchmark, we found that the U.S. EEI for 1994 for cement production was 125, higher than that of India (112), Brazil (101), and Mexico (107). Only China (136) had a higher EEI that year. We also found that based on technical potential alone, the U.S. could have reduced carbon dioxide emissions from cement production by over 20% if best practice technologies had been used in 1994.

Data Quality and Comparability Issues

Data quality and comparability are a key issue in this research. For most of the countries analyzed here, the required data are available and gathered in the INEDIS database.[6] Within INEDIS these data are checked for consistency, such as system boundaries, conversion factors used (e.g. LHV or HHV), etc. For a number of smaller developing countries, however, no data on energy consumption, product mix and technologies used are available within the country itself. For other countries, such as China and India, data quality may be a problem. For India the results found in this paper for the cement industry are comparable to those found by Bode et al. (1999) or Schumacher and Sathaye (1998). It appears that for the Indian cement industry only medium size and small plants are included in both energy and production data. The excluded small plants are estimated to account for 5% of production and 10% of energy consumption (CMA 1998). Including these small plants in our analysis will result in an increase in average specific energy consumption and a decrease in estimated energy efficiency. Roughly, this will result in an increase in SEC of 5% and in the energy efficiency index of 11 points. For the Chinese cement industry other sources list somewhat lower primary energy intensities (about 10% lower) (Zhiping and Sinton 1994; Sinton and Yang 1997). It is not clear whether small cement plants are included in those studies, as they are for China in our analysis. Generally speaking, however, the findings presented in this paper regarding the ranking of countries in terms of energy efficiency corresponds with the technologies in those countries. The least efficient countries (China and India) in steel production have the highest share of OHF capacity and the lowest share of continuous casting, while the most efficient country (South Korea) has the lowest share of OHF capacity and the highest share of continuous casting. In the cement industry, the most efficient countries are the countries with the lowest share of wet process capacity. Only China is less efficient than what would be expected based on the share of wet process capacity.

Conclusions

Identification of the technical potential primary energy savings and carbon dioxide emissions reductions provides a rough estimate of the savings potential available in various countries. While the technical potential is based on actual energy use and carbon dioxide emissions from plants in commercial operation, country and plant-specific conditions will determine what portion of the technical potential can be realized in any given country. Using an international best practice benchmark for two energy-intensive industries, we found that there is great potential for improving energy efficiency and reducing associated greenhouse gas emissions in both steel and cement production in four key developing countries. The largest

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[6] The International Network for Energy Demand Analysis in the Industrial Sector (INEDIS) is comprised of analysts from a variety of research institutions and organizations that focus on analysis of the industrial sector. LBNL is an organizing member of this network and maintains the INEDIS database.

potential was seen in China and India, where the use of outdated technology is a key factor in the high level of energy used per tonne of product produced.

This analysis has also shown that a number of key developing countries are equally or more energy efficient than the U.S. industry. In the steel industry, we found that Brazil is more efficient than the U.S. while Mexico has achieved a comparable level of energy efficiency. For cement production, we found that Mexico and Brazil are more efficient than the U.S., while India appears to have become more efficient in recent years. China is the least efficient country in our analysis. The data for India and China, however, must be interpreted with care, and a further analysis of these countries is needed.

The key developing countries analyzed in this paper are important in the context of climate change, since they are experiencing rapid growth in production and emissions. Our analysis indicates, however, that many of these countries are producing steel and cement equally or more efficiently than the U.S. More information on the relative efficiency of other industrial sectors is essential for U.S. policy makers in light of on-going climate negotiations and potential decision-making on investments projects under the Clean Development Mechanism of the Kyoto Protocol.

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