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Energy Analysis Department
Environmental Energy Technologies Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

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Abstract.
This paper reports on an in-depth analysis of the U.S. cement industry, identifying cost-effective energy efficiency measures and potentials. We assess this industry at the aggregate level (Standard Industrial Classification 324), which includes establishments engaged in manufacturing hydraulic cements, including portland, natural, masonry, and pozzolana when reviewing industry trends and when making international comparisons. Coal and coke are currently the primary fuels for the sector, supplanting the dominance of natural gas in the 1970s. Between 1970 and 1997, primary physical energy intensity for cement production (SIC 324) dropped 30%, from 7.9 GJ/t to 5.6 GJ/t, while carbon dioxide intensity due to fuel consumption (carbon dioxide emissions expressed in tonnes of carbon per tonne cement) dropped 25%, from 0.16 tC/tonne to 0.12 tC/tonne. Carbon dioxide intensity due to fuel consumption and clinker calcination dropped 17%, from 0.29 tC/tonne to 0.24 tC/tonne. We examined 30 energy efficient technologies and measures and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for each of the measures. We constructed an energy conservation supply curve for U.S. cement industry which found a total cost-effective reduction of 0.6 GJ/tonne of cement, consisting of measures having a simple payback period of 3 years or less. This is equivalent to potential energy savings of 11% of 1994 energy use for cement making and a savings of 5% of total 1994 carbon dioxide emissions by the U.S. cement industry. Assuming the increased production of blended cement in the U.S., as is common in many parts of the world, the technical potential for energy efficiency improvement would not change considerably. However, the cost-effective potential, would increase to 1.1 GJ/tonne cement or 18% of total energy use, and carbon dioxide emissions would be reduced by 16% (due to the reduced clinker production). This demonstrates that blended cement production could be key to a cost-effective strategy for energy efficiency improvement and carbon dioxide emission reductions in the U.S. cement industry.

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I. Introduction

In 1994 the manufacturing sector consumed 23 EJ of primary energy in the United States, almost one-quarter of all energy consumed that year (U.S. DOE, EIA 1997).[1] Within manufacturing, a subset of raw materials transformation industries (cement, primary metals, pulp and paper, chemicals, petroleum refining) require significantly more energy to produce than other manufactured products.

This report reflects an in-depth analysis of one of these energy-intensive industries – cement, the binding agent in concrete and mortar -- identifying energy savings and carbon dioxide emissions reduction potentials. We analyze the cement industry at the aggregate level (Standard Industrial Classification 324 (3241)), which includes establishments engaged in manufacturing hydraulic cements, including portland, natural, masonry, and pozzolana cements.

The production of cement is an energy-intensive process that results in the emission of carbon dioxide from both the consumption of fuels (primarily for the kiln) and from the calcination of limestone. In this report, we briefly describe the various stages in the cement production process. We then provide details on energy consumption in the U.S. cement industry in 1994, followed by an assessment of various energy efficiency measures applicable to the U.S. cement industry, and estimate the cost-effective potential for energy efficiency improvement.

II. Overview of U.S. Cement Industry

Cement is an inorganic, non-metallic substance with hydraulic binding properties, and is used as a bonding agent in building materials. It is a fine powder, usually gray in color, that consists of a mixture of the hydraulic cement minerals to which one or more forms of calcium sulfate have been added (Greer *et al.*, 1992, ASTM specification C-150). Mixed with water it forms a paste, which hardens due to formation of cement mineral hydrates. Cement is the binding agent in concrete, which is a combination of cement, mineral aggregates and water. Concrete is a key building material for a variety of applications.

The U.S. cement industry is made up of clinker plants, which produce clinker, cement plants that grind clinker obtained elsewhere, or a combination of the two, an integrated plant. Clinker is produced through a controlled high-temperature burn in a kiln of a measured blend of calcareous rocks (usually limestone) and lesser quantities of siliceous, aluminous, and ferrous materials. The kiln feed blend (also called raw meal or raw mix) is adjusted depending on the chemical composition of the raw materials and the type of cement desired. Cement plants grind clinker and add a variety of additives to produce cement, while integrated plants both manufacture clinker and grind it to make cement.

Portland and Masonry cements are the chief types produced in the United States. More than 90% of the cement produced in the U.S. in 1997 was Portland cement, while Masonry cement accounted for 4.4% of U.S. cement output in 1997 (USGS, 1998).

There were 119 operating cement plants in the U.S. in 1997, spread across 37 states and in Puerto Rico, owned by 42 companies. Portland cement was produced at 118 plants in 1997, while

[1] To convert from EJ to Quads, from PJ to TBtu, and from GJ to MBtu, multiply by 0.95; to convert from metric tons to short tons, multiply by 1.1; to convert from GJ/metric ton to MBtu/short ton, multiply by 0.86.

Masonry cement was produced at 82 plants (81 of which also produced Portland cement). Clinker was produced at 108 plants (110 including Puerto Rico) in the U.S. in 1997. Clinker kiln capacity varies between 75 and 1550 kilotonnes per year (RTI, 1996). Production rates per plant vary between 0.5 and 3.1 million metric tons (Mt) per year. Total production of U.S. cement plants in 1997 was slightly over 82.5 Mt (USGS, 1998). Clinker is produced with either the "wet" or "dry" process. These processes are discussed in detail in section III.

Clinker production, cement production, and materials consumption trends are quite similar. All three categories experienced gradual growth between 1970 and 1997, with prominent dips in the late 1970s and early 1980s. Clinker production increased from 67 Mt in 1970 to 74 Mt in 1997, at an average rate of 0.4% per year, hitting a low of 55 Mt in 1982, and its current high in 1997. Within this slow production increase, the composition of clinker production changed significantly between 1970 and 1997. Clinker produced with the wet process decreased at an average of –2.7% per year, falling from a 60% share of total clinker production in 1970 to a 26% share in 1997. Clinker produced with the dry process increased at an average of 2.6% per year, increasing from a 40% share of total clinker production in 1970 to a 72% share in 1997. Cement production increased at 0.7% per year between 1970 and 1997, rising from 69 Mt in 1970 to 84 Mt in 1997. Portland cement remained the dominant cement type during that time span, maintaining a share between 94% and 96%. Materials consumption increased at an average of 0.5% per year between 1970 and 1997, rising from 115 Mt in 1970 to 133 Mt in 1997.

Cement production (0.7% average per year) grew more rapidly than clinker production (0.4% average per year) between 1970 and 1997, which may be due increased use of additives and changes in clinker imports. Between 1970 and 1997, the clinker to cement ratio (expressed as clinker production divided by cement production) decreased from 0.97 to 0.88 t cement/t clinker. The number of clinker plants has decreased from 169 in 1970 to 110 in 1997, while the number of cement plants has fallen from 181 in 1970 to 118 in 1997. Thus, average plant capacity has increased.

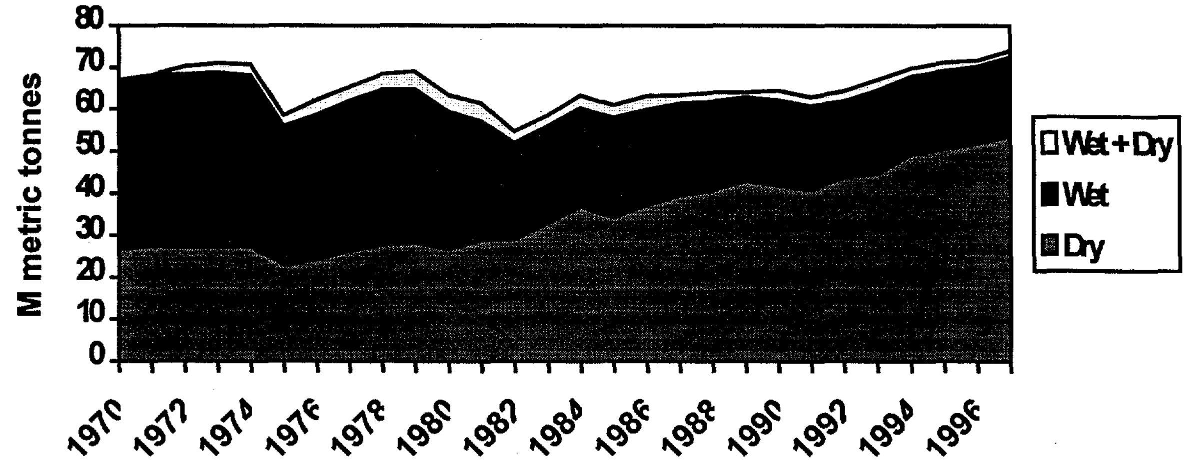


Figure 1. U.S. Clinker Production by Process, 1970 to 1997 (expressed in Million metric tons/year). Source: USGS, various years.

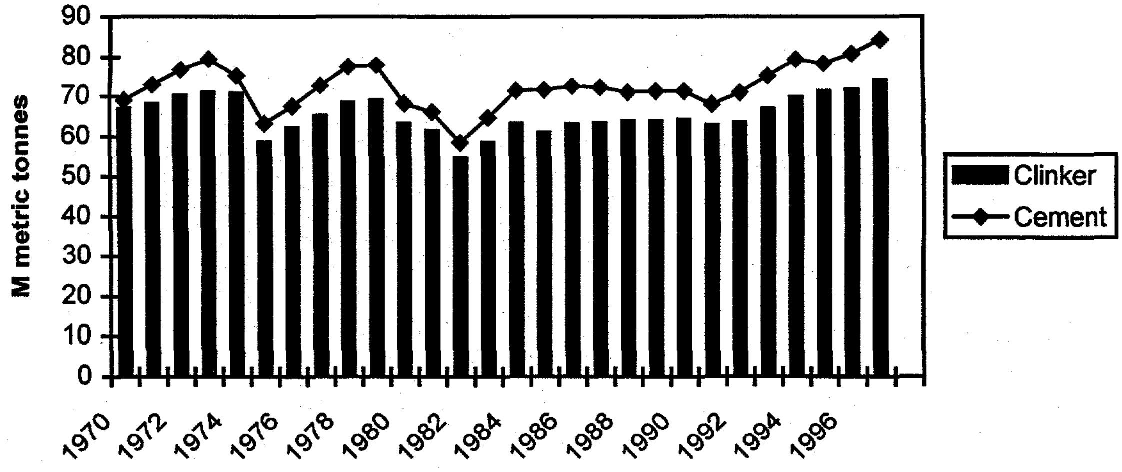


Figure 2. U.S. Cement and Clinker Production, 1970 to 1997 (expressed in Million metric tons/year). Source: USGS, various years.

III. Process Description

Mining and Quarrying

The most common raw materials used for cement production are limestone, chalk and clay (Greer et al, 1992). Most commonly the main raw material, the limestone or chalk, is extracted from a quarry adjacent to or very close to the plant (Limestone and chalk provide the required calcium oxide and clay provides much of the silicon, aluminum and iron oxides required for portland cement). The limestone and chalk are most often extracted from open-face quarries but underground mining can be employed (Greer et al., 1992). The collected raw materials are selected, crushed, ground, and proportioned so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyro-processing systems (Greer et al, 1992). It is often necessary to raise the content of silicon oxides and iron oxides by adding quartz sand and iron ore. The excavated material is transported to a crusher. Normally first a jaw or gyratory crusher, followed by a roller or hammer mill is used to crush the limestone. The crushed material is screened, and stones are returned. At least 1.5-1.75 tonnes of raw material are required to produce one tonne of portland cement (Greer *et al.*, 1992; Alsop and Post, 1995).

Kiln Feed Preparation

Raw material preparation is an electricity-intensive production step requiring about 25-35 kWh/tonne raw material (23-32 kWh/short ton). The raw materials are further processed and ground. The grinding differs with the pyro-processing process used. The raw materials are prepared for clinker production into a 'raw meal' either by dry or wet processing. In dry processing, the materials are ground into a flowable powder in ball mills or in roller mills. In a ball (or tube) mill, steel balls in are responsible for decreasing the size of the raw material pieces in a rotating tube. Rollers on a round table fulfil this task of comminution in a roller mill. The raw materials may be further dried from waste heat from the kiln exhaust before pyroprocessing. The moisture content in the (dried) feed of the dry kiln is typically around 0.5% (0 - 0.7%).

When raw materials contain more than 20% water, wet processing can be preferable[2]. In the wet process raw materials are ground with the addition of water in a ball mill to produce a slurry typically containing 36% water (range of 24-48%). Various degrees of wet processing exist, e.g. semi-wet (moisture content of 17-22%) to reduce the fuels consumption in the kiln.

Clinker Production (Pyro-Processing)

Clinker production is the most energy-intensive stage in cement production, accounting for over 90% of total industry energy use. Clinker is produced by pyro-processing in large kilns. These kiln systems evaporate the free water in the meal, calcine the carbonate constituents (calcination), and form portland cement minerals (clinkerization) (Greer *et al.*, 1992).

The kiln type used in the U.S. is the large capacity rotary kiln. In these kilns a tube with a diameter up to 8 meters (25 feet) is installed at a 3-4 degree angle that rotates 1-3 times per minute. The ground raw material, fed into the top of the kiln, moves down the tube toward the flame. In the sintering (or clinkering) zone, the combustion gas reaches a temperature of 1800-2000°C (3300 –3600 °F). While many different fuels can be used in the kiln, coal has been the primary fuel in the U.S. since the 1970s.

In a wet rotary kiln, the raw meal typically contains approximately 36% moisture. These kilns were developed as an upgrade of the original long dry kiln to improve the fineness control in the raw meal. The water is first evaporated in the kiln in the low temperature zone. The evaporation step makes a long kiln necessary. The length to diameter ratio may be up to 38, with lengths up to 230 meters (252 yards). The capacity of large units may be up to 3600 tonnes (3970 short tons) of clinker per day. Fuel use in a wet kiln can vary between 5.3 and 7.1 GJ/tonne clinker (4.6 and 6.1 MBtu/short ton clinker, LHV) (COWIconsult *et al.*,1993; Vleuten,1994). The variation is due to the energy requirement for the evaporation, and hence the moisture content of the raw meal.

In a dry kiln, feed material with much lower moisture content (0.5%) is used, thereby reducing the need for evaporation and reducing kiln length. The first development of the dry process took place in the U.S. and was a long dry kiln without preheating, or with one stage suspension preheating. Later developments have added multi-stage suspension preheaters (i.e. a cyclone) or shaft preheater. Additionally, pre-calciner technology was more recently developed in which a second combustion chamber has been added to a conventional pre-heater that allows for further reduction of kiln energy requirements. The typical fuel consumption of a dry kiln with 4/5-stage preheating can vary between 3.2 and 3.5 GJ/tonne clinker (2.7 and 3.0 MBtu/short ton clinker) (COWIconsult *et al.*,1993). A six stage preheater kiln can theoretically use as low as 2.9-3.0 GJ/tonne clinker (2.5-2.6 Mbtu/short ton clinker) (Vleuten,1994). The most efficient pre-heater, pre-calciner kilns use approximately 2.9 GJ/tonne clinker (2.5 MBtu/short ton clinker) (Anon (a),1994; Somani *et al.*, 1997; Su,1997; Steuch and Riley, 1993). Kiln dust (KD) bypass systems may be required in kilns in order to remove alkalis, sulfates, and chlorides. Such systems lead to additional energy losses since you are removing the sensible heat from the dust.

Once the clinker is formed it is cooled rapidly in order to ensure the maximum yield of alite (tricalcium silicate), an important component for the hardening properties of cement. The main cooling technologies are either the grate cooler or the tube or planetary cooler. In the grate cooler, the clinker is transported over a reciprocating grate passed through by a flow of air. In the tube or

[2] Originally, the wet process was the preferred process, as it was easier to grind and control the size distribution of the particles in a slurry form. The need for the wet process was reduced by the development of improved grinding processes.

planetary cooler, the clinker is cooled in a counter-current air stream. The cooling air is used as combustion air for the kiln.

Finish Grinding

After cooling, the clinker is stored in the clinker dome or silo. The material handling equipment used to transport clinker from the clinker coolers to storage and then to the finish mill is similar to that used to transport raw materials (e.g. belt conveyors, deep bucket conveyors, and bucket elevators) (Greer *et al.*, 1992). To produce powdered cement, the nodules of cement clinker are ground. Grinding of cement clinker, together with additives (3-5%) to control the properties of the cement (gypsum and anhydrite) can be done in ball mills, roller mills, or roller presses (Alsop and Post, 1995). Combinations of these milling techniques are often applied. Coarse material is separated in a classifier to be returned for additional grinding.

Power consumption for grinding depends on the fineness required for the final product and the additives used (in intergrinding). Electricity use for raw meal and finish grinding depends strongly on the hardness of the material (limestone, clinker, pozzolan extenders) and the desired fineness of the cement as well as the amount of additives. Blast furnace slags are harder to grind and hence use more grinding power, between 50 and 70 kWh/tonne (45 and 64 kWh/short ton) for a Blaine[3] of 3,500 cm^2/g. (COWIconsult *et al.,* 1993). Traditionally, ball or tube mills are used in finish grinding, while many plants use vertical roller mills. In ball and tube mills, the clinker and gypsum are fed into one end of a horizontal cylinder and partially ground cement exits from the other end. Modern ball mills may use between 32 and 37 kWh/tonne (29 and 34 kWh/short ton) (Seebach *et al.*,1996, Cembureau, 1997) for cements with a Blaine of 3,500 .

Modern state-of-the-art concepts are the high pressure roller mill and the horizontal roller mill (Horomill®) (Seebach *et al.*,1996) which can use 20-50% less energy than a ball mill. The roller press is a relatively new technology, and is more common in Western Europe than in other regions, e.g. North America (Holderbank,1993). Various new grinding mill concepts are under development or have been demonstrated (Seebach *et al.*,1996), e.g. the Horomill® (Buzzi,1997), Cemax (Folsberg,1997), the IHI mill, and the air-swept ring roller mill (Folsberg, 1997).

Finished cement is stored in silos, tested and filled into bags, or shipped in bulk on bulk cement trucks or railcars. Additional power is consumed for conveyor belts and packing of cement. The total consumption for these purposes is generally low and not more than 5% of total power use (Vleuten,1994). Total power use for auxiliaries is estimated at roughly 10 kWh/tonne clinker (9 kWh/short ton clinker) (Heijningen *et al.*,1992). The power use for conveyor belts is estimated at 1-2 kWh/tonne cement (0.8-1.8 kWh/short ton cement) (COWIconsult *et al.*,1993). The power consumption for packing depends on the share of cement packed in bags.

[3] Blaine is a measure of the total surface of the particles in a given quantity of cement, or an indicator of the fineness of cement. It is defined in terms of square centimeters per gram. The higher the Blaine, the more energy required to grind the clinker and additives to the desired fineness (Holderbank, 1993).

IV. Energy Use and Carbon Dioxide Emissions[4] in the U.S. Cement Industry (SIC 324)

Historical Energy Use and Carbon Dioxide Emissions Trends

Energy consumption in the U.S. cement industry declined between 1970 and 1997. Primary energy intensity decreased at an average of –0.6% per year, from 550 PJ in 1970 to 470 PJ in 1997, although production increased over that time span. The overall energy consumption trend in the U.S. cement industry between 1970 and 1997 shows a gradual decline, though energy consumption started to increase in the early 1990s and increased between 1992 and 1997 at an average of 4% per year. The share of the two main clinker-making processes in energy consumption changed significantly between 1970 and 1997. While the wet process consumed 62% of total cement energy consumption in 1970, it used only 31% in 1997, while energy consumption of the dry process increased from 38% of total cement energy consumption in 1970 to 67% in 1997 (see Figure 3).

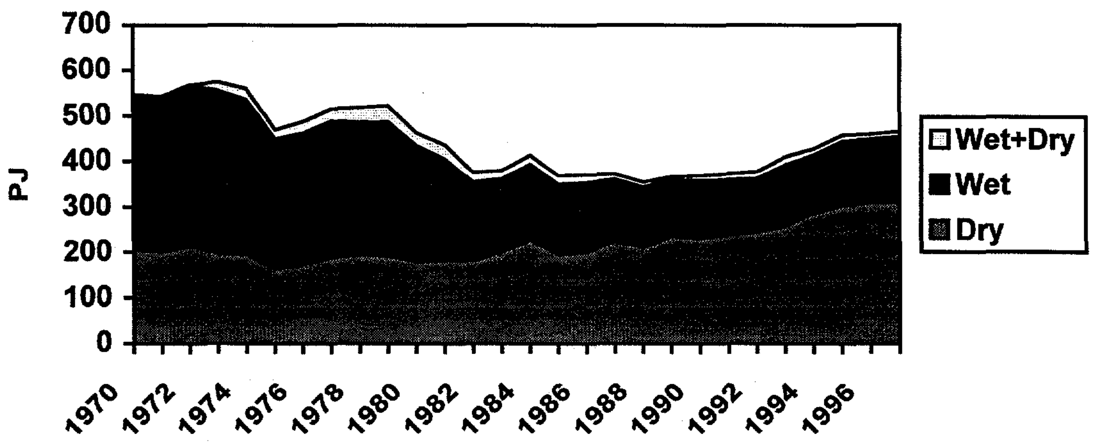


Figure 3. Primary Energy Consumption in U.S. Cement Production by Process, 1970 to 1997 (expressed in PJ). Source: USGS, various years.

Carbon dioxide emissions from fuel consumption in the cement industry decreased from 11.0 MtC in 1970 to 10.2 MtC in 1997, falling at an average rate of –0.3% per year. Carbon dioxide emissions from clinker calcination increased from 9.3 MtC in 1970 to 10.2 MtC in 1997, at an average rate of 0.4% per year, resulting in total carbon dioxide emission increase of 0.03% per year, on average (see Figure 5). Carbon dioxide emissions from fuel consumption have decreased with energy consumption, and shifting fuel use patterns have affected carbon emissions significantly as well. The largest change occurred in natural gas use, which decreased from a 44% fuel share in 1970 to a 6% fuel share in 1997, due to natural gas price increases and fuel diversification policies after the oil price shocks. Natural gas was commonly substituted by coal and coke, which increased fuel share from 36% in 1970 to 71% in 1997 (see Figure 6). Oil's share fell from 13% in 1970 (17% in 1973) to 1% in 1997. Electricity's share increased from 7% in 1970 to 11% in 1997, while the remainder of 1997's fuel share is composed of liquid waste fuel (8%) and tires and solid waste (a combined 2%).

[4] Carbon dioxide emissions are commonly expressed in metric tons carbon. To convert to carbon dioxide multiply by 44/12.

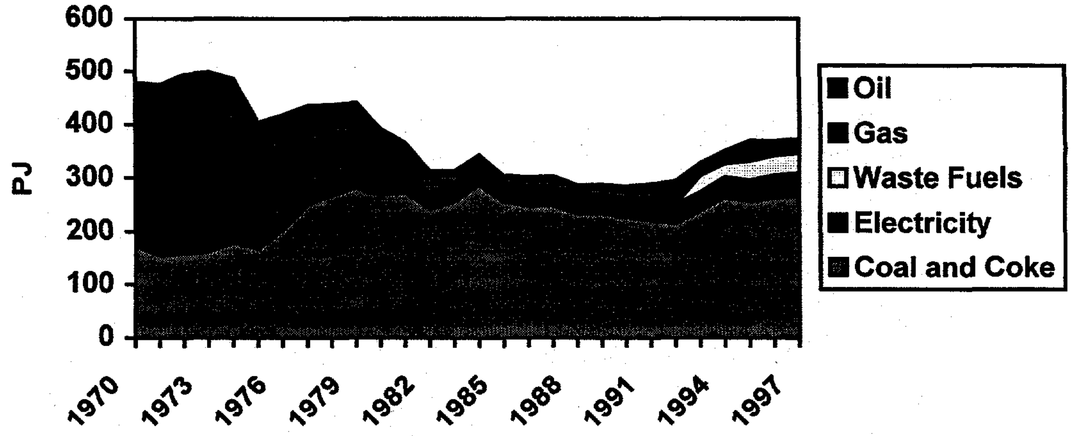


Figure 4. Energy Consumption in U.S. Cement Production by Fuel, 1970 to 1997 (expressed in PJ). Source: USGS, various years.

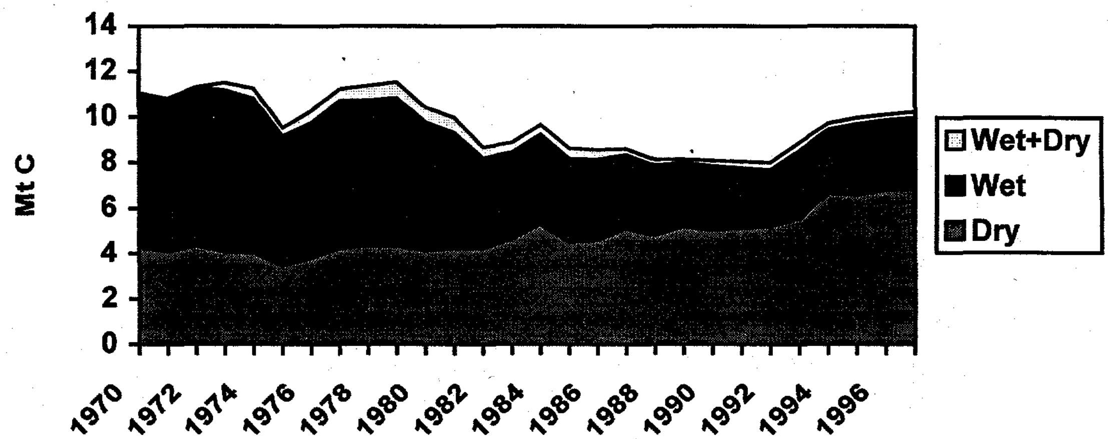


Figure 5. Carbon Emissions from the U.S. Cement Industry by Clinker Production Process, 1970 to 1997 (expressed in Mt C/year). Source: USGS, various years.

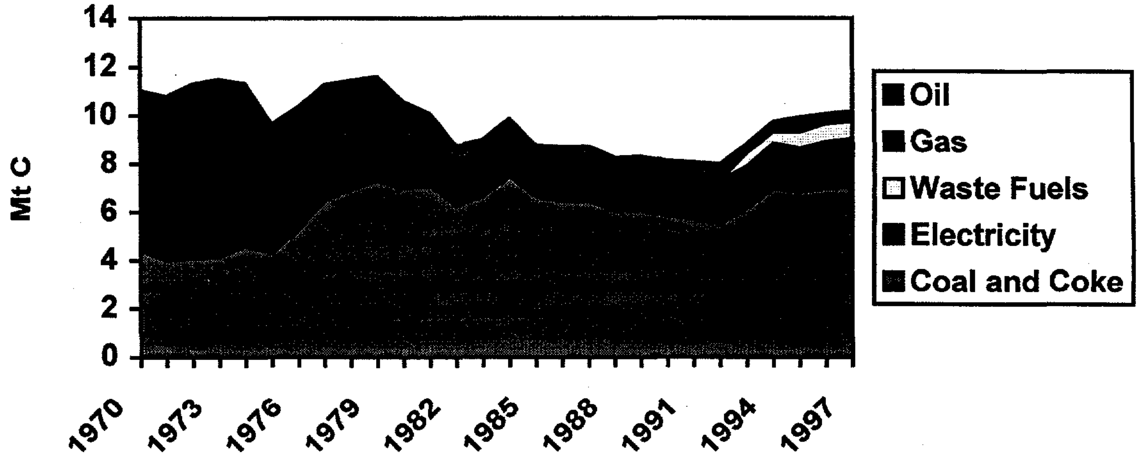


Figure 6. Carbon Dioxide Emissions from the U.S. Cement Industry by Fuel, 1970 to 1997 (expressed in Mt C/year). Source: USGS, various years.

Historical Energy Intensity and Specific Carbon Dioxide Emission Trends

Primary energy intensity in the U.S. cement industry decreased between 1970 and 1997. Primary energy intensity of cement production decreased at an average rate of –1.3% per year, from 7.9 GJ/tonne in 1970 to 5.6 GJ/tonne in 1997. While intensity slowly decreased overall between 1970 and 1997, intensity started to climb in the early 1990s, rising 0.9% per year, on average, between 1992 and 1997 (see Figure 7). Both the wet and dry processes decreased in energy intensity. The energy intensity of the wet process decreased at an average of 0.4% per year between 1970 and 1997 while the energy intensity of the dry process decreased by more than double of that of the wet process, i.e. average of –1.0% per year. Energy intensity of cement production decreased due to increased capacity of the more energy efficient dry process for clinker-making (see Figure 1), energy efficiency improvements (see Figure 7) and reduced clinker production per ton of cement produced (see Figure 2).

Specific carbon dioxide emission from fuel consumption declined from 160 kg C per tonne of cement in 1970 to 120 kg C/t cement in 1997, decreasing at an average of 1.0% per year. Total carbon dioxide emissions (including emissions from limestone calcination for clinker-making) decreased at 0.7% per year, on average, from 290 kg C/t cement in 1970 to 240 kg C/t cement in 1997. Like the energy intensity trend, specific carbon dioxide emissions decreased overall between 1970 and 1997, then grew between 1990 and 1997. Carbon intensity increased from 114 kg C/t cement in 1990 to 121 kg C/t cement in 1997 (see Figure 8). The specific carbon dioxide emissions from both the wet and dry processes decreased between 1970 and 1997, the wet process at an average of 0.05% per year and the dry process at an average rate of 0.8% per year. The increased dry process clinker production capacity, improved energy efficiency, and decreasing clinker/cement-production ratio reduced the specific carbon dioxide emissions, while the substantial fuel shifts towards more carbon intensive fuels like coal and coke contributed to an increase in specific carbon dioxide emissions (see Figure 8). Overall, fuel mix trends were more than offset by energy intensity reductions, leading to an overall decrease in specific carbon dioxide emissions.

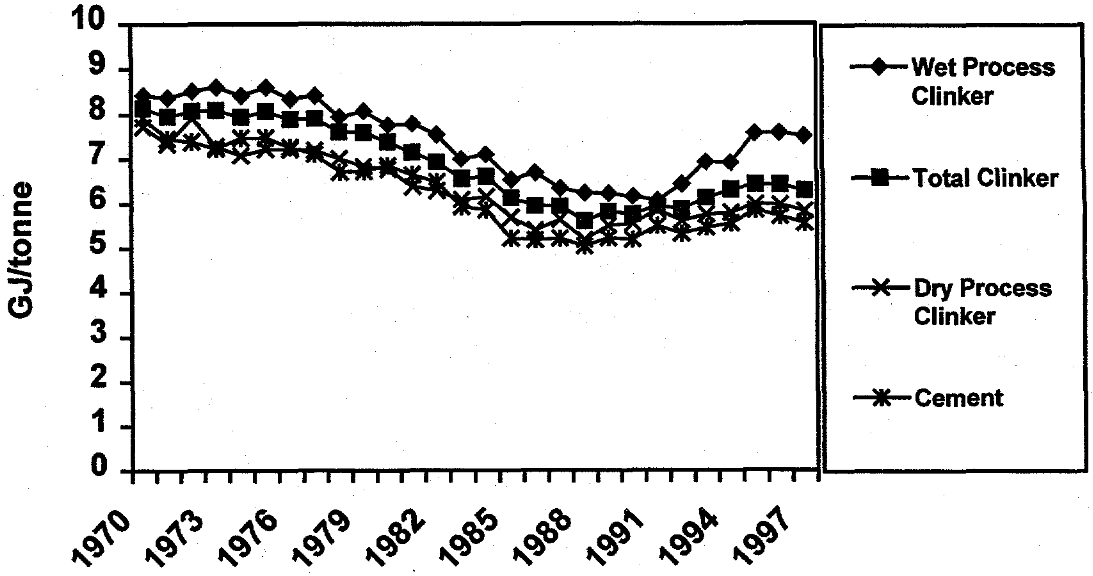
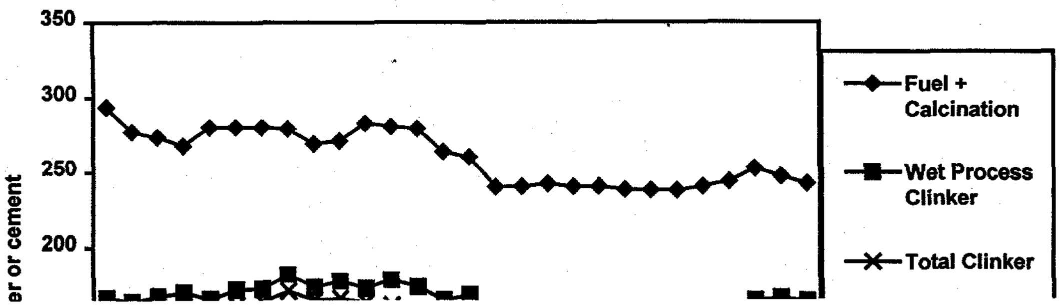


Figure 7. Primary Energy Intensity of U.S. Cement and Clinker Production, 1970 to 1997 (expressed in GJ/tonne). Source: USGS, various years.



V. 1994 Baseline Energy Use and Carbon Dioxide Emissions for Energy Use in U.S. Cement Production (SIC 324)

In 1994, the U.S. cement industry consumed 366 PJ (347 TBtu) of final energy (about 2% of total U.S. manufacturing energy use) and emitted 19 MtC of carbon dioxide[5] (about 4% of total U.S. manufacturing carbon emissions). Table 1 provides our estimate of 1994 U.S. baseline energy consumption by process.

Table 1. 1994 Energy Consumption and Specific Energy Intensity in the U.S. Cement Industry by Process.

Process Stage	Fuel (PJ)	Elec. (PJ)	Primary Energy (PJ)	Fuel SEC (GJ/t)	Elec. SEC (kWh/t)	Primary SEC (GJ/t)	Carbon Dioxide Emissions Energy Use (MtC)	Carbon Dioxide Emissions Calcination (MtC)	Carbon Dioxide Intensity (kgC/t)
Wet Process									
Kiln Feed Preparation	0	4	11	0.0	29	0.3	0.2	0.0	4.6
Clinker Production[6]	117	2	124	6.0	30	6.3	2.9	2.7	284.2
Finish Grinding	0	4	13	0.0	57	0.6	0.2	0.0	9.1
Total Wet Process	*117*	*10*	*148*	*5.5*	*133*	*7.0*	*3.2*	*2.7*	279.0
Dry Process									
Kiln Feed Preparation	0	11	33	0.0	34	0.4	0.5	0.0	5.4
Clinker Production	211	6	230	4.3	35	4.7	5.3	6.8	245.8
Finish Grinding	0	11	34	0.0	57	0.6	0.5	0.0	9.1
Total Dry Process	*211*	*28*	*296*	*4.0*	*145*	*5.6*	*6.2*	*6.8*	244.6
Total All Cement	**328**	**38**	**444**	**4.4**	**142**	**6.0**	**9.5**	**9.5**	**254.4**

Note: To convert from PJ to Trillion Btu multiply by 0.947. To convert from GJ/t to Mbtu/short ton multiply by 0.859.

Raw Materials Baseline

In 1994, 123 Mt (135 million short tons) of raw materials were used in the cement industry (van Oss, 1995). We assume that 29% of raw materials were for the wet process kilns and 71% of raw materials were used for dry process kilns. Additionally we assume an electricity use of 29 kWh/t (26 kWh/short ton) raw material preparation for wet kilns and 34 kWh/t (31 kWh/short ton) for dry kilns due to the additional processing (COWIconsult *et al.*, 1993; Jaccard and Willis, 1996).

Clinker Production Baseline

According to van Oss, (1995) Wet process clinker production was 18.6 Mt while dry process production was 49.3 Mt. Accounting for production from plants with both wet and dry processes on site, we estimate a total clinker production of 68.5 Mt (75.5 million short tons) in that year. We assume an average U.S. wet kiln fuel intensity in 1994 of 6.0 GJ/t clinker (5.7 Mbtu/short ton clinker) and an average dry kiln fuel intensity of 4.3 GJ/t (3.7 Mbtu/short ton) (Holderbank, 1993; PCA, 1996b; Jaccard and Willis,1996; van Oss, 1995). Electricity requirements of 30 kWh/t (27 kWh/short ton) are assumed for fuel preparation and for operating the kiln, fans, and coolers for wet kilns and 35 kWh/t (32 kWh/short ton) for dry kilns (COWIconsult *et al.*, 1993; Ellerbrock and Mathiak, 1994).

Finish Grinding Baseline

We assume that the amount of throughput for finish grinding is the same as the total amount of cement produced in 1994, 21.2 Mt (23.4 million short tons) for wet cement and 53.1 Mt (58.6

[5] We express carbon dioxide emissions in their metric carbon equivalent. To obtain carbon dioxide emissions expressed in full molecular weight multiply by 44/12.

[6] Imported clinker into the U.S. is not counted in clinker production, but is included in the energy consumption for finish grinding.

million short tons) for dry cement (van Oss, 1995). Based on Lowes (1990) COWIconsult (1993) we estimate average energy requirements for finish grinding to be 57 kWh/t (52 kWh/short ton) (Lowes, 1990; COWIconsult *et al.*, 1993).

Carbon Emissions Baseline

Carbon emissions in the cement industry are produced both through the combustion of fossil fuels and waste fuels, and the calcination of limestone. In the calcination process we assume that 0.14 tonnes of carbon are emitted for every tonne of clinker produced (UNEP *et al.*, 1996). This amounts to 9.5 MtC given a production of 68.5 million tonnes of clinker (75.5 million short tons) in 1994 (van Oss, 1995). We rely on the U.S. Energy Information Administration (EIA, 1996, Appendix B) for 1994 carbon coefficients for the various commercial fuels, except we use the Intergovernmental Panel on Climate Change (UNEP *et al.*, 1996) for coke and breeze. For electricity we use the 1994 average fuel mix for electricity generation in the U.S. Energy use, carbon coefficients, and carbon emissions from fossil fuel combustion are shown in Table 2.

Table 2. Energy Consumption, Carbon Emissions Coefficients, and Carbon Emissions from Energy Consumption, and Carbon Dioxide Emissions from calcination for the U.S. Cement Industry in 1994.

Energy – Related Carbon Emissions			
Fuel	**Energy Use (PJ)**	**Carbon Emissions Coefficient (MtC/PJ)**	**Carbon Emissions (MtC)**
Electricity	37.9	0.045	1.7
Residual Fuel Oil	0.2	0.020	0.0
Distillate Fuel Oil	4.0	0.019	0.1
Natural Gas	18.6	0.014	0.3
LPG	0.0	0.016	0.0
Coal	259.9	0.024	6.3
Petroleum coke	24.5	0.030	0.7
Other	20.6	0.0192	0.4
Total Energy	365.7	-n.a.-	9.5
Process – Related Carbon Emissions			
	Clinker Production (Mt)	Carbon Emissions Coefficient (tC/t clinker)	Carbon Emissions (MtC)
Clinker	68.5	0.138	9.5
Total Carbon Emissions			
Industry Total	-n.a.-	-n.a.-	18.9

Sources: (van Oss, 1995; PCA, 1996a; EIA, 1996; UNEP et al., 1996).

VI. Energy Efficiency Technologies and Measures for the U.S. Cement Industry

Several technologies and measures exist that can reduce the energy intensity (i.e. the electricity or fuel consumption per unit of output) of the various process stages of cement production. This section provides more detailed estimates on the technologies and measures, their costs, and potential for implementation in the U.S. Table 3 lists the technologies and measures that we consider in our analysis

Table 3. Energy-Efficient Practices and Technologies in Cement Production.

Raw Materials Preparation	
Efficient transport systems	
Raw meal blending systems (dry process)	
Conversion to closed circuit wash mill	
High-efficiency roller mills (dry cement)	
High-efficiency Classifiers (dry cement)	
Clinker Production (Wet)	**Clinker Production (Dry)**
Kiln combustion system improvements	Kiln combustion system improvements
Kiln shell heat loss reduction	Kiln shell heat loss reduction
Use of waste fuels	Use of waste fuels
Conversion to modern grate cooler	Conversion to modern grate cooler
Optimize grate coolers	Heat Recovery for Power Generation
Conversion to pre-heater, pre-calciner kilns	Low pressure drop cyclones for suspension pre-heaters
Conversion to semi-wet kilns	Long dry kiln conversion to multi-stage pre-heater kiln
	Optimize grate coolers
	Long dry kiln conversion to multi-stage pre-heater, pre-calciner kiln
	Addition of pre-calciner to pre-heater kiln
Finish Grinding (applies to both wet and dry cement production)	
Improved grinding media (ball mills)	
High-pressure roller press	
High efficiency classifiers	
Improve mill internals	
General Measures	
Preventative Maintenance (insulation, compressed air losses, maintenance)	
Reduced Kiln Dust Wasting	
Energy Management and Process Control	
High efficiency motors	
Efficient fans with variable speed drives	
Product Changes	
Blended Cements	
Reducing the Concentration of C_3S in cements	
Reducing fineness of cement for selected uses	

Raw Materials Preparation

Efficient Transport Systems. Transport systems are required to transport powdered materials such as raw meal, kiln dust, and cement throughout the plant. These materials are usually transported by means of either pneumatic or mechanical conveyors. While mechanical conveyors use less power than pneumatic they can have higher capital costs than pneumatic. Based on Holderbank, (1993) we assume an energy savings of 2 kWh/t raw material (1.9 kWh/short ton) with a switch to mechanical conveyor systems. Installation costs for the system are estimated at

$3/t raw material production based on the Holderbank study (1993). We currently apply this measure to all plants older than 30 years, or 23% of the industry capacity.

Raw Meal Blending (Homogenizing) Systems. In order to produce a good quality product and to maintain optimal and efficient combustion conditions in the kiln, it is crucial that the raw meal is uniform. Most plants use compressed air to agitate the powdered meal in so-called air-fluidized homogenizing silos (using 1-1.5 kWh/tonne raw meal). Older dry process plants use mechanical systems, which simultaneously withdraw material from 6-8 different silos at variable rates (Fujimoto,1993), using 2-2.6 kWh/tonne raw meal. Modern plants use gravity-type homogenizing silos, saving power use. In these silos, material funnels down one of many discharge points, where it is mixed in an inverted cone. Gravity-type silos may not give the same blending efficiency as air-fluidized systems, which can often be solved by installing on-line analyzers for raw mix control (Fujimoto,1993; Holderbank,1993). Although most older plants use mechanical or air-fluidized bed systems, more and more new plants seem to have gravity-type silos, because of the significant reduction in power consumption (Holderbank,1993). Silo retrofit options are cost effective when the silo can be partitioned with air slides and divided into compartments which are sequentially agitated, as opposed to the construction of a whole new silo system (Gerbec, 1999). The energy savings are estimated at 0.9-2.5 kWh/tonne raw meal (Fujimoto,1993; Holderbank,1993; Alsop & Post,1995, Cembureau, 1997; Gerbec, 1999). We assume savings of 1 kWh/t raw meal. Costs for the silo retrofit are estimated at $3.7/t raw material (assuming $550K per silo and an average capacity of 150,000 tonnes). We apply this to 20% of raw material preparation.

Use of Roller Mills. Traditional ball mills used for grinding certain raw materials (mainly hard limestone) can be replaced by high-efficiency roller mills, by ball mills combined with high pressure roller presses, or by horizontal roller mills. The use of these advanced mills saves energy without compromising product quality. In our measure we estimate an energy savings of 7 kWh/t raw materials (Cembureau, 1997) through the installation of a vertical or horizontal roller mill. An additional advantage of these mills is that they can combine raw material drying with the roller process by using large quantities of low grade waste heat from the kilns or clinker coolers (Venkateswaran and Lowitt, 1988). Holderbank, (1993) claims that 17.6% of installed power was for roller mills for raw grinding, most likely in dry plants, which suggests about 20% of raw grinding capacity is using roller mills. We therefore apply this measure to 72% of raw material preparation in dry process plants. We use an average cost of $5.3/t raw material production (Holderbank, 1993).

High-efficiency Classifiers. A recent development in efficient grinding technologies is the use of high-efficiency classifiers or separators. Classifiers separate the finely ground particles from the coarse particles. The large particles are then recycled back to the mill. Standard classifiers may have a low separation efficiency, which leads to the recycling of fine particles, leading to extra power use in the grinding mill. Various concepts of high-efficiency classifiers have been developed (Holderbank,1993; Süssegger,1993). In high-efficiency classifiers, the material stays longer in the separator, leading to sharper separation, thus reducing overgrinding. Electricity savings through implementing high-efficiency classifiers are estimated at 8% of the specific electricity use (Holderbank,1993). Other case studies have shown a reduction of 1.7-2.3 kWh/tonne cement (2.8-3.8 kWh/t raw material) (Salzborn and Chin-Fatt,1993; Süssegger,1993). High efficiency classifiers can be used in both the raw materials mill and in finish grinding. In our analysis for the raw mill, we assume a savings of 8% of raw material electricity consumption, or 2.3 kWh/t raw material for the wet process and 2.7 kWh/t raw material for the dry process. Replacing a conventional classifier by a high-efficiency classifier has led to 15% increases in the grinding mill capacity (Holderbank,1993) and improved product quality due to a more uniform particle size (Salzborn and Chin-Fatt,1993), both in raw meal and cement. We assume an investment cost of $2/t raw material production based on the Holderbank study (Holderbank, 1993) We apply this measure to 70% of U.S. dry kiln process raw material preparation.

Clinker Production - Wet and Dry Process Kilns

Kiln combustion system improvements. Fuel combustion systems in kilns can be contributors to kiln inefficiencies with such problems as poorly adjusted firing, incomplete fuel burn-out with high CO formation, and combustion with excess air (Venkateswaran and Lowitt, 1988). One technique developed in the U.K. of flame control resulted in fuel savings of 2-10% depending on the kiln type (Venkateswaran and Lowitt, 1988). Lowes, (1990) discusses advancements from combustion technology that improve combustion through the use of better kiln control. He also notes that fuel savings of up to 10% have been demonstrated for the use of flame design techniques to eliminate reducing conditions in the clinkering zone of the kiln in a Blue Circle plant (Lowes, 1990). A recent technology that has been demonstrated in several locations is the Gyro-therm technology that improves gas flame quality while also reducing NOx emissions. A demonstration project at an Adelaide Brighton plant in Australia found average fuel savings between 5 and 10% as well as an increase in output of 10% (CADDETT, 1997). A second demonstration project at the Ash Grove plant in the U.S. (Durkee, OR) found fuel savings between 2.7% and 5.7% with increases in output between 5 and 9% (CADDET, 1998; Vidergar and Rapson, 1997). We assume a fuel savings of 4%, and currently apply this measure on a percentage basis to all kilns using gas as their primary or secondary fuel, or about 6% of clinker production capacity. Costs for the technology vary by installation. We assume an average cost of $0.98/t clinker capacity based on reported costs in the demonstration projects.

Kiln shell heat loss reduction. There can be considerable heat losses through the shell of a cement kiln, especially in the burning zone. The use of better insulating refractories (e.g. Lytherm) can reduce heat losses (Venkateswaran and Lowitt, 1988). Estimates suggest that the development of high-temperature insulating linings for the kiln refractories can reduce fuel use by 0.1-0.4 GJ/t (Lowes, 1990; COWIconsult, 1993; Venkateswaran and Lowitt, 1988). We assume a value of 0.15 GJ/t. Costs for insulation systems are estimated to be $0.25/t clinker capacity (Lesnikoff, 1999). Structural considerations may limit the use of new insulation materials. We apply this measure to 25% of current kiln capacity.

Use of Waste Derived Fuels. Waste fuels can be substituted for traditional commercial fuels in the kiln. Waste derived fuels may replace the use of commercial fuels, and are hence accounted as energy savings. The carbon dioxide emission reduction depends on the carbon content of the waste derived fuel, as well as the alternative use of the waste and efficiency of use (e.g. incineration with or without heat recovery). Our analysis focuses on the use of tires or tire-derived fuel. The St. Lawrence Cement Factory in Joliette, Quebec completed a project in 1994 where they installed an automated tire feed system to feed whole tires into the mid-section of the kiln, which replaced about 20% of the energy (CADDET, 1995). This translates to energy savings of 0.6 GJ/t, (a savings of 3.0 GJ/t fuel input for 20% of kiln energy use). Costs for the installation of the Joliette system ran about $3.40/t clinker capacity. Costs however for less complex systems where the tires are fed as input fuel are $0.1-$1/t clinker. While operating and licensing costs at the Joliette facility increased, there was some operating cost reduction due to receiving charges collected by the cement company. We therefore do not estimate any significant change in operating costs (CADDET, 1995; Gomes, 1990, Venkateswaran and Lowitt, 1988). We assume a cost of $1/t clinker. Tires currently account for an estimated 1% of total fuel inputs in the industry and we estimate that 4% of dry process kiln capacity and 10% of wet process kiln capacity use alternative fuels (van Oss, 1995; Cembureau, 1996).

Conversion to Grate Cooler. Four main types of coolers are used in the cooling of clinker: shaft, rotary, planetary and grate cooler. The grate cooler is the modern variant and is used in almost all modern kilns. The advantages of the grate cooler are its large capacity (allowing large kiln capacities) and efficient heat recovery (the clinker leaves the cooler at 83°C, instead of 120-200°C (Vleuten,1994)). Modern grate coolers recover more heat than do the other types of coolers. For large capacity plants, grate coolers are the preferred equipment. For smaller plants the grate cooler may be too expensive (COWIconsult et al.,1993). Grate coolers are essential if a precalciner is installed, as the grate cooler produces the required tertiary air, except in the case of through the kiln calciner systems. Replacement of planetary coolers by grate coolers is not uncommon (Alsop and Post,1995). Grate coolers are standard technology for modern large-scale kilns. Planetary and rotary coolers are found in older kilns only. When compared to a planetary cooler, additional heat recovery is possible with grate coolers at an extra power consumption of approximately 3 kWh/tonne clinker (COWIconsult et al., 1993; Vleuten,1994). The savings are estimated to be up to 8% of the fuel consumption in the kiln (Vleuten,1994). In our analysis we estimate an energy savings of 0.3 GJ/t (Birch, 1990, Holderbank, 1993). Cooler conversion probably is economically attractive only when installing a precalciner, which is necessary to produce the tertiary air (see above). The cost of a cooler conversion is estimated to be $0.4 - 0.5/t clinker capacity with annual operation costs increasing to $0.1/t clinker capacity (Jaccard and Willis, 1996). Cembureau provides data on cooler types for U.S. cement plants. Plants that responded to the Cembureau survey (92% of plants) indicated that 6% of the industry still utilized planetary or rotary coolers. We therefore apply this conversion measure to this 6% of clinker capacity.

Clinker Production - Wet Process Kilns

Wet Process Conversion to Semi-Wet Process. In the wet process the slurry typically contains 36% water (range of 24-48%). A filter press can be installed in a wet process kiln in order to reduce the moisture content to about 20% of the slurry and obtain a paste ready for extrusion into pellets (COWIconsult et al., 1993, Venkateswaran and Lowitt, 1988). Additional electricity consumption is 3-5 kWh/t clinker (COWIconsult et al., 1993). In our analysis we assume increased energy use of 4 kWh/t clinker to reduce the moisture content to 20%. The corresponding fuel savings are 1.2 GJ/t (COWIconsult et al., 1993). Jaccard and Willis, 1996 estimate the conversion cost to run $1.8/t clinker capacity with increased operation costs of $0.1/t clinker (Jaccard and Willis, 1996). We assume a conversion of 10% of wet kiln capacity, a small percentage, since it is more likely that a wet kiln would be converted to a multi-stage pre-heater, pre-calciner kiln..

Wet Process Conversion to Multi-stage pre-heater, pre-calciner kiln. In some cases, it may be feasible to convert a wet process facility to a state-of-the art dry process production facility that includes both pre-heater, pre-calciner technology. Average fuel consumption in U.S. wet kilns is estimated at 6.0 GJ/t (5.7 Mbtu/short ton). Studies of several kiln conversions in the U.S. in the 1980s found fuel savings of 3.4 GJ/t, (2.9 MBtu/ton) but baseline wet kiln energy use was higher than current levels (6.8 GJ/t) (Venkateswaran and Lowitt, 1988). In Hranice, the Czech Republic, a 1050 tonne per day wet process plant was converted to a dry kiln plant with a new kiln energy consumption of 3.13 GJ/t clinker (2.7 MBtu/ton) (Anon., 1994b). This equals a savings of 2.9 GJ/t (2.5 Mbtu/ton) from the U.S. average fuel intensity for wet kilns. We assume fuel savings of 2.8 GJ/tonne (2.4 Mbtu/ton) and an increase in power use of about 10 kWh/tonne clinker (Vleuten, 1994) The cost of converting a wet plant to a dry process plant may be high, as it involves the full reconstruction of an existing facility. Costs may vary between $50/t clinker capacity and $110/t clinker capacity (van Oss, 1999; Nisbet, 1996). We assume a cost of $75/t clinker capacity. We apply this measure to all wet kilns over 30 years of age, or 42% of wet kiln capacity.

Clinker Production - Dry Process Kilns

Low Pressure Drop Cyclones for Suspension Pre-heaters. Cyclones are a basic component of plants with pre-heating systems. The installation of newer cyclones in a plant with lower pressure losses, will reduce the power consumption of the kiln smoke gas fan system. Depending on the efficiency of the fan 0.6-0.8 kWh/t clinker can be saved for each 50 mm VS the pressure loss is reduced. For most older kilns this amounts to savings of 0.6-1.1 kWh/t (Birch, 1990). Fujimoto, (1994) discussed a Lehigh Cement plant retrofit in which low pressure drop cyclones were installed in their Mason City Iowa plant and save 4.4 kWh/t (4 kWh/short ton) (Fujimoto, 1994). For our analysis, we assume savings of 4 kWh/t. Installation of the cyclones can be expensensive, however, since it may often entail the rebuilding or the modification of the pre-heater tower, and is very site specific. Also, new cyclone systems may increase overall dust loading and increase dust transport costs. We assume a cost of $3/t clinker for a low-pressure drop cyclone system. We assume that this measure can be installed in dry pre-heater and pre-calciner kilns older than 15 years of age, or 31% of total dry process kiln capacity.

Heat Recovery for Cogeneration. Waste gas discharged from the kiln exit gases, the clinker cooler system, and the kiln pre-heater system all contain useful energy that can be converted into power. Cogeneration systems can either be direct gas turbines that utilize the waste heat (top cycle), or the installation of a waste heat boiler system that runs a steam turbine system (bottom cycle). Our measure focuses on the steam turbine system since these systems have been installed in many plants world-wide and have proven to be economic (Steinbliss, 1990; Jaccard and Willis, 1996, Neto, 1990). While electrical efficiencies are still relatively low (18%), based on several case studies power generation may vary between 11-25 kWh/t clinker (Scheur & Sprung, 1990, Steinbliss, 1990; Neto, 1990). We assume electricity savings of 20 kWh/t clinker. Jaccard and Willis (1996) estimate installation costs for such a system at $2-4/t clinker capacity with operating costs of $0.2-0.3/t clinker. In 1994, U.S. plants cogenerated 574 million kWh (van Oss, 1995) Assuming that 34% of the energy introduced into long dry kilns is exhausted as waste gas (Venkateswaran and Lowitt, 1988), this suggests a potential generation of 1,200 million kWh. In our analysis we assume that long dry kilns younger than 20 years can potentially be equipped with cogeneration technology, or 4% of dry kiln capacity.

Dry Process Conversion to Multi-Stage Preheater Kiln. Older dry kilns may not have multi-stage preheating, but only one-, two- or three-stage preheating. This leads to higher heat losses. Installing multi-stage suspension preheating (i.e. four- or five-stage) may reduce the heat losses and thus increase efficiency. Modern cyclone or suspension preheaters also have a reduced pressure drop, leading to increased heat recovery efficiency and reduced power use in fans (see low pressure drop cyclones above). By installing new preheaters, the productivity of the kiln will also increase, due to a higher degree of pre-calcination (up to 30-40%) as the feed enters the kiln. Also, the kiln length may be shortened by 20-30% thereby reducing radiation losses (van Oss, 1999). As the capacity increases, the clinker cooler may also have to be adapted in order to be able to cool the large amounts of clinker. The conversion of older kilns is attractive when the old kiln needs replacement and a new kiln would be too expensive, assuming that limestone reserves are adequate. Energy savings depend strongly on the specific energy consumption of the dry process kiln to be converted as well as the number of preheaters to be installed. For example, cement kilns in the former German Democratic Republic were rebuilt by Lafarge to replace four dry process kilns originally constructed in 1973 and 1974. In 1993 and 1995 three kilns were equipped with four-stage suspension preheaters. The specific fuel consumption was reduced from

3.9 GJ/tonne to 3.4 GJ/tonne clinker, while the capacity of the individual kilns was increased from 1500 to 2300 tpd (Duplouy and Trautwein,1997). In the same project, the power consumption was reduced by 25%, due to the replacement of fans and the finish grinding mill. We assume energy savings of 0.9 GJ/t for the conversion which reflects the difference between the average dry kiln fuel intensity (4.5 GJ/t clinker) and the energy intensity of a modern preheater kiln (3.6 GJ/t clinker) based on a study of the Canadian cement industry (Holderbank, 1993). The study estimates the specific costs at 30-40 US$/tonne capacity for conversion to a multi-stage preheater kiln while Vlueten, 1994 estimates a cost of $28/t clinker capacity for the installation of suspension pre-heaters. However, Jaccard and Willis estimate a much lower cost of $5/t. We assume a value of $20/tonne in our analysis. In 1994, 30% of U.S. capacity was long dry kilns (Cembureau, 1996). We assume a conversion potential of half of this capacity.

Installation of pre-calciner on dry pre-heater kiln. An existing preheater kiln may be converted to a multi-stage preheater precalciner kiln by adding a precalciner and, when possible an extra preheater. The addition of a precalciner will generally increase the capacity of the plant, while lowering the specific fuel consumption. Using as many features of the existing plant and infrastructure as possible, special precalciners have been developed by various manufacturers to convert existing plants, e.g. Pyroclon®-RP by KHD in Germany. Generally, the kiln, foundation and towers are used in the new plant, while cooler and preheaters may be replaced. Cooler replacement may be necessary in order to increase the cooling capacity for larger production volumes. The conversion of a plant in Italy, using the existing rotary kiln, led to a capacity increase of 80-100% (from 1000 tpd to 1800-2000 tpd), while reducing energy use from 3.56 to 3.06-3.19 GJ/tonne clinker, resulting in a saving of 11-14% (Sauli,1993). Fuel savings will depend strongly on the efficiency of the existing kiln and on the new process parameters (e.g. degree of precalcination, cooler efficiency). Based on the experiences with the Italian plant, we estimate the savings at 0.4 GJ/tonne clinker (Sauli,1993). Sauli (1993) does not outline the investments made for the conversion project. Vleuten (1994) estimates the cost of adding a precalciner or suspension preheaters at 28 US$/tonne annual capacity (it is not clear what is included in this estimate) while Jaccard and Willis (1996) estimate a much lower cost of $8.5/t clinker capacity. We currently assume a cost of $10/t clinker and assume the installation in pre-heater kilns greater than 400 kt/yr capacity, or 21% of U.S. dry process capacity. We also assume an operation cost savings of $1/t clinker capacity due to expanded production capacity (Jaccard and Willis, 1996).

Conversion of long dry kilns to dry pre-heater, pre-calciner kilns. In some cases it may be feasible to upgrade a long dry kiln to the more current state of the art multi-stage pre-heater, pre-calciner kiln. In our case we assume energy savings of 1.3 GJ/t clinker for the conversion. This savings reflects the difference between the average dry kiln fuel intensity (4.5 GJ/t clinker) and the energy intensity of a modern preheater, pre-calciner kiln kiln (3.2 GJ/t clinker) based on a study of the Canadian cement industry and the retrofit of an Italian plant (Holderbank, 1993, Sauli, 1993). The Holderbank study gives a range of $23-29/t clinker for a pre-heater, pre-calciner kiln. Vleuten, 1994 estimates investment costs of $28/t clinker capacity for adding precalciner or suspension preheaters. Jaccard and Willis (1996) give a much lower value of $8.6/t clinker capacity. We assume a cost of $28/t clinker capacity and that 2/3 of long dry kilns greater than 30 years old are converted, or 8% of dry process capacity.

Optimisation of Heat Recovery in the Clinker Cooler. The clinker cooler cools clinker from 1200°C down to 100°C. The most common cooler designs are of the rotary, planetary (or satellite) and grate type. All coolers heat the secondary air for the kiln combustion process and sometimes also tertiary air for the precalciner (Alsop and Post, 1995). Grate coolers are the modern variant and are suitable for large-scale kilns (up to 10,000 tpd). Grate coolers use electric fans and excess air. The highest temperature portion of the remaining air can be used as tertiary air for the precalciner. Rotary coolers (used for approximately 5% of the world clinker capacity for plants up to 2000-4500 tpd) and planetary coolers (used for 10% of the world capacity for plants up to 3000-4000 tpd) do not need combustion air fans and use little excess air, resulting in relatively lower heat losses (Buzzi and Sassone,1993; Vleuten,1994). Grate coolers may recover between 1.2 and 1.5 GJ/tonne clinker sensible heat (Buzzi and Sassone,1993). Improving heat recovery efficiency in the cooler results in fuel savings, but may also influence product quality and emission levels. Heat recovery can be improved through reduction of excess air volume (Alsop and Post,1995), control of clinker bed depth and new grates such as ring grates (Buzzi and Sassone,1993; Lesnikoff, 1999). Control of cooling air distribution over the grate may result in lower clinker temperatures and high air temperatures. Additional heat recovery results in reduced energy use in the kiln and precalciner, due to higher combustion air temperatures. Birch, (1990) notes a savings of 10-20 kcal/kg (0.04 GJ/t) through the improved operation of the grate cooler, while Holderbank, (1993) notes savings of 0.15 GJ/t clinker for retrofitting a grate cooler. COWIconsult et al. (1993) note savings of 20 kcal/kg (0.08 GJ/t) but an increase in electricity use of 2 kWh/t. We assume thermal energy savings of 0.1 GJ/t clinker. We assume that the costs of this measure are half the costs of the replacement of the planetary to grate cooler, or $0.2t/clinker capacity. As noted earlier, 92% of coolers in the U.S. in 1994 were grate coolers. We assume that existing grate coolers can be further optimized in all kilns older than 10 years, or 63% of kiln capacity (Cembureau, 1997).

Finish Grinding

Advanced Grinding Concepts. The energy efficiency of ball mills for use in finish grinding is relatively low, consuming up to 33-45 kWh/t clinker, (30-42 kWh/short ton clinker) depending on the fineness of the cement (Marchal, 1997; Cembureau, 1997). Several new mill concepts exist that can significantly reduce power consumption in the finish mill to 22-33 kWh/t clinker (20-30 kWh/short ton clinker), including roller presses, roller mills, and roller presses used for pre-grinding in combination with ball mills (Alsop and Post, 1995; Cembureau, 1997; Seebach *et al.*, 1996). Roller mills employ a mix of compression and shearing, using 2-4 grinding rollers carried on hinged arms riding on a horizontal grinding table (Cembureau, 1997; Alsop and Post, 1995). In a high-pressure rolling mill, two rollers put the material under a pressure of up to 3500 bar (Buzzi, 1997), improving the grinding efficiency dramatically (Seebach et al., 1996).

Air swept vertical roller mills with integral classifiers are used for finish grinding, whereas a recent off-shoot technology which is not air swept is now being used as a pre-grinding system in combination with a ball mill. A variation of the roller mill is the air swept ring roller mill which has been shown to achieve an electricity consumption of 25 kWh/t with a Blaine of 3000 (Folsberg, 1997). A new mill concept is the Horomill, first demonstrated in Italy in 1993 (Buzzi, 1997). In the Horomill a horizontal roller, within a cylinder, is driven. The centrifugal forces resulting from the movement of the cylinder cause a uniformly distributed layer to be carried on the inside of the cylinder. The layer passes the roller (with a pressure of 700-1000 bar (Marchal, 1997). The finished product is collected in a dust filter. The Horomill is a compact mill that can produce a finished product in one step and hence has relatively low capital costs. Grinding portland cement with a Blaine of 3200 cm2/g consumes approximately 23 kWh/tonne (Buzzi,1997) and even for pozzolanic cement with a Blaine of 4000 power use may be as low as 28 kWh/tonne (Buzzi,1997).

Today, high-pressure roller presses are most often used to expand the capacity of existing grinding mills, and are found especially in countries with high electricity costs or with poor power supply (Seebach et al, 1996). After the first demonstration of the Horomill in Italy, this concept is now also applied in plants in Mexico (Buzzi, 1997), Germany, Czech Republic and Turkey (Duplouy and Trautwein,1997). The electricity savings of a new finish grinding mill when replacing a ball mill is estimated at 27 kWh/t. We further estimate a savings of 8 kWh/t for the addition of a pre-grinding system to a ball mill (Cembureau, 1997; Holland and Ranze, 1997; Scheur and Sprung, 1990) Capital cost estimates for installing a new roller press vary widely in the literature, ranging from low estimates like \$2.5/t cement capacity (Holderbank,1993) or \$3.6/t cement capacity (Kreisberg,1993) to high estimates of \$8/t cement capacity (COWIconsult *et al.*,1993). We estimate the costs at approximately \$4/t cement capacity. The capital costs of roller press systems are lower than those for other systems (Kreisberg,1993) or at least comparable (Patzelt,1993). Some new mill concepts may lead to a reduction in operation costs of as much as 30-40% (Sutoh *et al.*,1992). The total grinding capacity in the U.S. in 1994, including white cement and dedicated grinding facilities, was 91.23 Mt (PCA, 1996a). Of this amount, only 8% had already installed roller presses in 1994. We assume that 50% of large ball mills (>100 kt capacity) older than 25 years (22% of U.S. grinding capacity) are retrofitted with advanced mill systems, and 50% of large ball mills between 10 and 25 years old are retrofitted with roller press pre-grinding systems (19% of U.S. grinding capacity).

High Efficiency Classifiers. A recent development in efficient grinding technologies is the use of high-efficiency classifiers or separators. Classifiers separate the finely ground particles from the coarse particles. The large particles are then recycled back to the mill. Standard classifiers may have a low separation efficiency, which leads to the recycling of fine particles, leading to extra power use in the grinding mill. In high-efficiency classifiers, the material is more finely separated, thus reducing over-grinding. A study of the use of high efficiency classifiers in Great Britain found a reduction in electricity use of 6 kWh/t after the installation of the classifiers in their finishing mills and a 25% production increase (Parkes, 1990). Holderbank, (1993) estimates a reduction of 8% of electricity use (5 kwh/t) while other studies estimate 1.7-2.3 kwh/t (Salborn and Chin-Fatt, 1993; Sussegger, 1993). We assume an energy savings of 3 kWh/t. We assume an investment cost of \$2/t finish material based on the Holderbank study (Holderbank, 1993). We assume that classifiers are installed in a similar share of facilities as was high-pressure rolling mills (40% of U.S. grinding capacity).

Improved Grinding Media. Improved wear resistant materials can be installed for grinding media, especially in ball mills. Grinding media are usually selected according to the wear characteristics of the material. Increases in the specific gravity and surface hardness of grinding media and wear resistant mill linings have shown a potential for reducing wear as well as energy consumption. (Venkateswaran and Lowitt, 1988). Improved balls and liners made of high chromium steel is one such material but other materials are also possible. Other improvements included the used of improved liner designs, such as grooved classifying liners. These have the potential to reduce grinding energy use by 5-10% in some mills. We assume a savings of 2.0 kWh/t (Venkateswaran and Lowitt, 1988). We apply this measure to 25% of cement capacity.

General Measures

Preventative Maintenance. Preventative maintenance involves training personnel to be attentive to energy consumption and efficiency. Successful programs have been launched in many industries (Caffal, 1995; Nelson, 1994). While many processes in cement production are primarily automated, there still are opportunities, with minimal training, to increase energy savings. Also, preventative maintenance (e.g. to the kiln refractory) can also increase a plant's utilization ratio, since it has less down time over the long term. Birch (1990) mentions that the reduction of false air input into the kiln at the kiln hood has the potential to save 11 kcal/kg clinker (0.05 GJ/t). We use this as our estimate of fuel savings. Lang (1994) notes a reduction of up to 5 kWh for various preventative maintenance and process control measures. We assume a potential savings of 3 kWh/t (Lang, 1994). We estimate that annual costs and start up costs for implementing this training are minimal (less than $0.1 per tonne cement). We apply this to all kilns older than 10 years or 90% of the industry kiln capacity.

Process Control & Management Systems. Heat from the kiln may be lost through non-optimal process conditions or process management. Automated computer control systems may help to optimize the combustion process and conditions. Improved process control will also help to improve the product quality, e.g. reactivity and hardness of the produced clinker, which may lead to more efficient clinker grinding. In cement plants across the world, different systems are used, marketed by different manufacturers. Most modern systems use so-called 'fuzzy logic' or expert control, while some use rule-based control strategies. Expert control systems do not use a modeled process to control process conditions, but try to simulate the best controller, using information from various stages in the process. These systems are also described as 'neural networks'. One such system, called LINKman, was originally developed in the United Kingdom by Blue Circle Industries and SIRA (ETSU, 1988). The first system was installed at Blue Circle's Hope Works in 1985, which resulted in a fuel consumption reduction of nearly 8% (ETSU, 1988). The LINKman system has successfully been used in both wet and dry kilns. After their first application in 1985, modern control systems now find wider application and can be found in many European plants. Additional process control systems include the use of on-line analyzers that permit operators to instantaneously determine the chemical composition of raw materials being processed in the plant, thereby allowed for immediate changes in the blend of raw materials. A uniform feed allows for more steady kiln operation, thereby saving ultimately on fuel requirements. Energy savings from such process control systems may vary between 2.5% and 10% (ETSU, 1988; Haspel and Henderson,1993; Ruby, 1997), and the typical savings are estimated at 2.5-5%. We assume the savings of 4% of fuel intensity (0.2 GJ/tonne clinker) and power savings of 3% of electricity intensity or 4 kWh/t cement (Haspel and Henderson, 1993; Holderbank, 1993). The economics of advanced process control systems are very good and payback periods can be as short as 3 months (ETSU, 1988). The system at Blue Circle's Hope Works needed an investment of £203,000 (1987), equivalent to £0.2/tonne clinker ($0.3/t clinker). (ETSU, 1988), including measuring instruments, computer hardware and training. Holderbank (1993) notes an installation cost for on-line analyzers of $0.8-1.7/t clinker. We therefore use an installation cost of $1.5/t clinker capacity. We assume that this system can still be applied to kilns older than 20 years or 49% of industry kiln capacity.

High-Efficiency Motors and Drives. Motors and drives are used throughout the cement plant to drive fans (preheater, cooler, alkali bypass), rotate the kiln, transport materials and, most importantly, for grinding. In a typical cement plant 500-700 electric motors may be used, varying from a few kW to MW-size (Vleuten, 1994). Power use in the kiln (excluding grinding) is roughly estimated at 40-50 kWh/tonne clinker (Heijningen *et al.*, 1992). Variable speed drives, improved control strategies and high-efficiency motors can help to reduce power use in cement kilns. If the replacement does not influence the process operation, motors may be replaced at any time. However, motors are often rewired rather than being replaced by new motors. Power savings may vary considerably on a plant-by-plant basis, ranging from 3 to 8% (Fujimoto, 1994). Vleuten (1994) estimates the potential power savings at 8% of the power use. In our analysis we assume a savings of 5 kWh/t cement or 4% of total electricity use. Based on an analysis of motors in the U.S. Department of Energy MotorMaster+ software, and a breakdown of motors in a 5,000 tpd cement plant given in Bosche (1993), we assume that high-efficiency motors replace existing motors in all plant fan systems with an average cost of $0.2/t cement capacity. This measure is applied to 50% of cement production capacity.

Adjustable Speed Drives. Drives are the largest power consumers in cement-making. The energy efficiency of a drive system can be improved by reducing the energy losses or by increasing the efficiency of the motor (see above). Energy losses in the system can be reduced by reducing throttling and coupling losses through the installation of adjustable speed drives (ASD). Most motors are fixed speed AC models. However, motor systems are often operated at partial or variable load (Nadel *et al.*,1992). Also, in cement plants large variations in load occur (Bösche,1993). There are various technologies to control the motor (Worrell *et al.*,1997). The systems are offered by many suppliers and are available worldwide. Worrell *et al.* (1997) provide an overview of savings achieved with ASD in a wide array of applications. The savings depend on the flow pattern and loads. The savings may vary between 7 and 60%. ASD equipment is used more and more in cement plants (Bösche,1993; Fujimoto,1993), but the application may vary widely, depending on electricity costs. Within a plant, ASDs can mainly be applied for fans in the kiln, cooler, preheater, separator and mills, and for various drives. One case study for a modern cement plant estimated potential application for 44% of the installed motor power capacity in the plant (Bösche, 1993). Energy savings strongly depend on the application and flow pattern of the system on which the ASD is installed. Although savings are significant (Holderbank, 1993), not many quantitative studies are available for the cement industry. One hypothetical case study estimates the savings at 70%, compared to a system with a throttle valve (or 37% compared with a regulated system) for the raw mill fan (Bösche, 1993). Fujimoto, (1994) notes that Lafarge Canada's Woodstock plant replaced their kiln ID fans with ASDs and reduced electricity use by 5 kWh/t. We will estimate the potential savings at 15% for 44% of the installed power, or roughly equivalent to 9 kWh/tonne cement. The specific costs depend strongly on the size of the system. For systems over 300 kW the costs are estimated at 70 ECU/kW (75 US$/kW) or less and for the range of 30-300 kW at 115-130 ECU/kW (120-140 US$/kW) (Worrell *et al.*,1997). Using these cost estimates, the specific costs for a modern cement plant, as studied by Bösche (1993), the costs can be estimated at roughly 0.9-1.0 US$/t cement capacity. Other estimates vary between $0.4 and $3/t cement (Holland and Ranze, 1997; Holderbank, 1993). We apply this measure to all kilns older than 30 years, or 24% of the industry kiln capacity.

Product Change

Blended cements. The production of blended cements involves the intergrinding of clinker with one or more additives (fly ash, pozzolans, blast furnace slag, silica fume, volcanic ash) in various proportions. The use of blended cements is a particulary attractive efficiency option since the intergrinding of clinker with other additives not only allows for a reduction in the energy used (and carbon emissions) in clinker production, but also corresponds to a reduction in carbon dioxide emissions in calcination as well. Blended cements are very common in Europe, and blast furnace and pozzolanic cements account for about 12% of total cement production with portland composite cement accounting for an additional 44% (Cembureau, 1997). In the U.S., some of the most prevalent blending materials are fly ash and blast furnace slag. A recent analysis of the U.S. situation cited an existing potential of producing 31 Mt of blended cement in 2000 using both fly ash and blast furnace slag, or 36% of U.S. capacity (PCA, 1997). This analysis was based on estimates of the availability of intergrinding materials and then surveying ready-mix companies to estimate feasible market penetration. The blended cement produced would have, on average, a clinker/cement ratio of 65% or would result in a reduction in clinker production of 9.3 Mt. The reduction in clinker production corresponds to a specific fuel savings of 1.42 GJ/t. We assume an increase in fuel use of 0.09 GJ/t for drying of the blast furnace slags but a corresponding energy savings of 0.2 GJ/t for reducing the need to use energy to bypass kiln exit gases to remove alkali-rich dust. We assume a savings of 5 Kcal/kg per percent bypass (Alsop and Post, 1995). The bypass savings are due to the fact that blended cements offer an additional advantage in that the interground materials also lower alkali-silica reactivity (ASR) thereby allowing a reduction in energy consumption needed to remove the high alkali content kiln dusts. This measure therefore results in total fuel savings of 1.41 GJ/tonne (blended) cement. Electricity consumption however is expected to increase due to the added electricity consumption associated with grinding the blending materials. We estimate an increase in electricity consumption of 17 kWh/t (Buzzi, 1996). We assume an investment cost of $0.7/t cement capacity which reflects the cost of new delivery and storage capacity (bin and way-feeder). This measure is applied to 42% of total U.S. clinker production, based on results of the PCA-study.

Reducing the Fineness for Particular Applications. Cement is normally ground to a uniform fineness. However, the applications of cement vary widely, and so does the optimal fineness. The grinding of the cement to the desired fineness could reduce the energy demand for grinding. Holderbank (1993) suggests that cement in Canada and the U.S. is ground finer (on average) than in Western-Europe, which suggests that energy savings could be achieved. However, without a detailed assessment of the market and applications of cement, we can not estimate the potential contribution of this measure to potential energy savings in the U.S. cement industry. Therefore, we do not account this measure in the analysis of the technical and cost-effective potential for energy efficiency improvement.

Advanced Technologies

In this section we discuss several advanced technologies for cement production. As our study focuses on commercially available technologies, the advanced technologies are not included in the analysis of the cost-effective potential for energy efficiency improvement. They are discussed for completeness of the technical analysis.

Fluidized Bed Kiln. The Fluidized Bed Kiln (FBK) is a totally new concept to produce clinker. Developments in FBK technology started as early as the 1950s (Venkateswaran and Lowitt,1988). Today, developments mainly take place in Japan (Kawasaki Heavy Industries) and the U.S. (Fuller Co.) (Cohen,1995; Van Kuijk *et al.*,1997). In an FBK, the rotary kiln is replaced by a stationary kiln, in which the raw materials are calcined in a fluidized bed. An overflow at the top of the reactor regulates the transfer of clinker to the cooling zone. The (expected) advantages of FBK technology are lower capital costs because of smaller equipment, lower temperatures resulting in lower NOx-emissions and a wider variety of the fuels which can be used, as well as lower energy use. The Kawasaki design uses cyclone preheaters, a precalciner kiln and a fluidized bed kiln. Energy use is expected to be 10-15% lower compared to conventional rotary kilns (Vleuten, 1994). The Fuller Co. stood at the basis of the US development of a fluidized bed kiln for clinker making. Early developments did not prove to be commercially successful due to the high clinker recycling rate (Cohen, 1992) and were commercialized for alkali dust recycling only (Cohen,1993). The technology was also used in the development of the advanced cement furnace (CAF). CAF uses a preheated pellet feed, using primarily natural gas or liquid fuels (Cohen, 1993). A pilot plant was built and used to produce clinker. The NOx emissions were reduced to 0.86 kg/tonne clinker, compared to 2.3-2.9 kg/tonne for conventional plants due to lower combustion temperatures (Cohen, 1993). The future fuel consumption is estimated at 2.93-3.35 GJ/tonne clinker (Cohen, 1995). The fuel use of the FBK may be lower than that of conventional rotary kilns, although modern precalciner rotary kilns have shown fuel use of 2.9-3.0 GJ/tonne clinker. Cohen (1995) expects a future fuel use of 2.93-3.35 GJ/tonne clinker. No data are available on the expected power use for the FBK. The use of the FBK may result in lower alkali-content of the clinker (Cohen, 1992). FBK needs less space and also has a higher flexibility with respect to raw material feed.

Advanced Comminution Technologies. Grinding is an important power consumer in modern cement-making. However, current grinding technologies are highly inefficient. Over 95% of the energy input in the grinding process is lost as waste heat, while only 1-5% of the energy input is used to create new surface area (Venkateswaran and Lowitt, 1988). Some of the heat may be used to dry the raw materials, for example in finish grinding or the grinding of limestone. Current high-pressure processes already improve the grinding efficiency in comparison with conventional ball mills (see above). In the longer term further efficiency improvements can be expected when non-mechanical "milling" technologies become available (OTA, 1993). Non-mechanical systems may be based on ultrasound (Suzuki *et al.*, 1993), laser, thermal shock, electric shock or cryogenics. However, non-mechanical grinding technologies have not been demonstrated yet and will not be commercially available in the next decades. Although the theoretical savings of non-mechanical comminution are large, no estimate of the expected savings can be given at this stage of fundamental research.

Mineral Polymers. Clinker is made by calcining calcium carbonate (limestone), which releases CO2 into the atmosphere, leaving calcium silicates as the binding agent. Mineral polymers can be made from inorganic alumino-silicate compounds. An inorganic polycondensation reaction results in a three-dimensional structure, like that of zeolites. It can be produced by blending three elements, i.e. calcined alumino-silicates (from clay), alkali-disilicates and granulated blast furnace slag or fly-ash (Davidovits, 1994). The cement hardens at room temperatures and provides compressive strengths of 20 MPa after 4 hours and up to 70-100 MPa after 28 days (Davidovits, 1994). The zeolite-like matrix results in the immobilization of materials, e.g. wastes. Despite the high alkali content, mineral polymers do not show alkali aggregate reactions (Davidovits, 1993). Research on mineral polymers was already going on in Eastern Europe and the U.S in the early 1980s. CO_2 emissions from the production of mineral polymers are determined by the carbon content of the raw materials and the energy used in the production. The silica-alumina raw materials can be found on all continents. Calcination of the potassium or sodium may result in CO_2 emissions. Research in this area is still ongoing. The manufacturing of mineral polymers is done at relatively low temperatures. The calcining of alumino-silicates occurs at temperatures of 750°C (Davidovits, 1994). However, no energy consumption data have been found in the literature. The use of mineral polymers results in the immobilization of solid wastes in the matrix (Davidovits, 1991).

VI. Energy Efficiency and CO_2 Emission Reduction Potential in the Cement Industry

Conservation Supply Curves

Supply curves are a common tool in economics. In the 1970s, conservation supply curves were developed by energy analysts as a means of ranking energy conservation investments alongside investments in energy supply in order to assess the least cost approach to meeting energy service needs (Meier et al., 1983). Conservation supply curves rank energy efficiency measures by their "cost of conserved energy" (CCE), which accounts for both the costs associated with implementing and maintaining a particular technology or measure and the energy savings associated with that option over its lifetime. The CCE of a particular option is calculated as:

$$\text{CCE} = \frac{\text{Annualized Investment} + \text{Annual Change in O\&M Costs}}{\text{Annual Energy Savings}} \qquad (1)$$

The annualized investment is calculated as: Capital Cost x $\dfrac{d}{(1-(1+d)^{-n})}$ (2)

where d is the discount rate and n is the lifetime of the conservation measure. CCEs are calculated for each measure that can be applied in a certain sector or subsector (e.g. steelmaking) and then ranked in order of increasing CCE. Once all options have been properly ranked, a conservation supply curve can be constructed. Defining "cost-effective" involves choosing a discount rate that reflects the desired perspective (e.g. customer, society). Then all measures that fall below a certain energy price, such as the average price of energy for the sector, can be defined as cost-effective.

The CCEs are plotted in ascending order to create a conservation supply curve. This curve is a snapshot of the total annualized cost of investment for all of the efficiency measures being considered at that point in time. The width of each option or measure (plotted on the horizontal axis) represents the annual energy saved by that option. The height (plotted on the vertical axis) shows the option's CCE.

The advantage of using a conservation supply curve is that it provides a clear, easy-to-understand framework for summarizing a variety of complex information about energy efficiency technologies, their costs, and the potential for energy savings. The curve can avoid double counting of energy savings by accounting for interactions between measures, is independent of prices, and also provides a framework to compare the costs of efficiency with the costs of energy supply technologies.

This conservation supply curve approach also has certain limitations. In particular, the potential energy savings for a particular sector are dependent on the measures that are listed and/or analyzed at a particular point in time. There may be additional energy efficiency measures or technologies that do not get included in an analysis, so savings may be underestimated. The costs of efficiency improvements (initial investment costs plus operation and maintenance costs) does not include all the transaction costs for acquiring all the appropriate information needed to evaluate and choose an investment and there may be additional investment barriers as well that are not accounted for in the analysis.

Many analysts use internal rate of return (IRR) to rate the cost effectiveness of various investments, which is the value of the discount rate to make the net benefits stream equal to the initial investment. A key difference between CCE and IRR is that with an IRR the fuel price for the analysis period is included in the calculation (since energy savings are quantified on a dollar basis), and therefore has a direct effect on the evaluation of a measure. With the CCE calculation changes in fuel prices will not change the CCE of a measure but will change the number of measures that are considered cost effective.

For our analysis, we used a 30% real discount rate, reflecting the cement industry's capital constraints and preference for short payback periods and high internal rates of return. We use an industry average weighted fuel cost in our calculation based on energy data provided by the Portland Cement Association, U.S. Geological Survey, and cost data from EIA (U.S. DOE, EIA, 1997). We include a weighted fuel cost and we use the source price of electricity.

In the process of developing the supply curves we also noted that several efficiency measures provide other environmental benefits in addition to energy savings. For example, production of blended cement will reduce the land-filling of waste materials like fly-ash, and will lenghten the life-time of limestone reserves. More efficient pre-calciner kilns will not only reduce energy use but also NOx, and SOx emissions from the kiln. While we believe that including quantified estimates of other benefits would increase the number of cost-effective efficiency options, we have not included such estimates in this current work. This is a subject, however, that merits continued research.

Conservation Supply Curve for Cementmaking (without product change)

We identified cost-effective energy savings of 48 PJ and carbon emissions reductions of 1.0 MtC for cement making in 1994 which represents 11% of total U.S. cement industry's energy use and 5.4% of the total carbon emissions (including calcination). Figure 9 ranks the energy efficiency measures in a conservation supply curve; the cost-effective measures are those which fall below the average weighted energy supply cost for 1994, and are therefore cost effective at 1994 energy prices using a discount rate of 30%. Table 3 provides a list of the measures ranked by their cost of conserved energy, internal rate of return, and their simple payback periods.

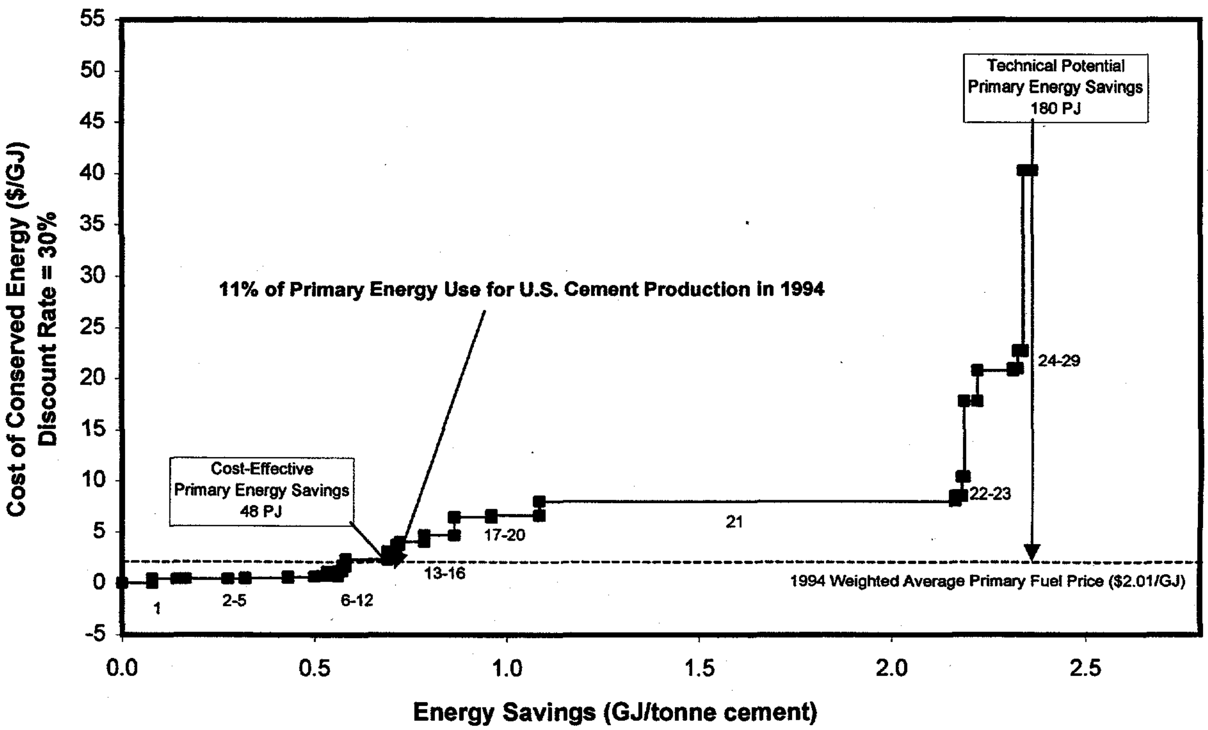


Figure 9. Energy conservation supply curve for energy efficiency measures in the U.S. cement industry. The measures exclude the production of blended cement. The horizontal axis depicts the cumulative primary energy savings (expressed in GJ/tonne cement). The vertical axis represents the cost of conserved energy (expressed in $/GJ primary energy saved), using a discount rate of 30%. The numbers of the measures and names can be found in Table 3.

Table 3. Energy efficiency improvement measures in the U.S. cement industry, ranked by CCE. The simple payback period and internal rate of return are also given.

	Energy Efficiency Measure	Primary Energy Savings (GJ/tonne)	Carbon Dioxide Emission Reduction (ktC)	CCE Primary Energy ($/GJ-saved)	Internal rate of Return (%)	Simple Payback Period (years)
1	Preventative maintenance	0.08	219	0.04	1254%	0.1
2	Kiln heat loss reduction (w)	0.06	58	0.50	107%	0.9
3	Kiln heat loss reduction (d)	0.02	62	0.50	107%	0.9
4	Use of waste fuels (w)	0.11	101	0.50	107%	0.9
5	Use of waste fuels (d)	0.04	120	0.50	107%	0.9
6	Conversion to semi-wet kiln	0.11	104	0.56	114%	0.9
7	Clinker cooler grate (w)	0.07	62	0.68	6%	1.3
8	Clinker cooler grate (d)	0.06	163	0.68	79%	1.3
9	Conversion to grate cooler (w)	0.02	16	0.76	102%	1.0
10	Conversion to grate cooler (d)	0.02	48	0.76	101%	1.0
11	High efficiency motors	0.03	35	1.17	33%	2.8
12	Kiln combustion system (w)	0.01	11	1.23	44%	2.3
13	Kiln combustion system (d)	0.01	25	1.72	31%	3.2
14	Process control system	0.11	361	2.32	20%	4.3
15	Variable speed drives	0.02	30	3.08	6%	7.3
16	Cogeneration (steam)	0.01	7	3.72	N/A	> 25
17	Roller press/Horomill	0.06	69	4.03	7%	10.3
18	Precalciner on preheater kiln	0.08	210	4.69	18%	5.4
19	Conversion to preheater kiln	0.10	261	6.46	8%	12.1
20	Conversion to precalciner kiln	0.12	338	6.67	8%	12.5
21	Wet to precalciner kiln conversion	1.08	1009	8.03	7%	13.0
22	Pre-grinding- HP roller mill	0.02	19	8.51	N/A	21.7
23	Improved grinding media	0.01	6	10.35	N/A	24.6
24	High efficiency classifiers (d)	0.03	44	17.77	N/A	18.8
25	High efficiency roller mill	0.09	117	20.74	N/A	> 25
26	Low pressured drop cyclones	0.01	11	20.94	N/A	> 25
27	High efficiency classifiers (w)	0.01	14	22.69	N/A	>25
28	Mechanical transport systems (d)	0.01	9	40.32	N/A	> 25
29	Mechanical transport systems (w)	0.02	9	40.32	N/A	> 25

Note: (d): applies to dry process kilns; (w): applies to wet process kilns.

The analysis shows that there is a large technical potential for energy efficiency improvement (excluding product changes) of 180 PJ, or 40%. However, only a small part is cost-effective at current investment and energy costs. This limits the potential to 11% (or 48 PJ). Due to the carbon dioxide emissions from calcination the overall effect on carbon dioxide emissions is divided by a factor two, when compared to energy efficiency improvement. The analysis shows that retrofit measures for efficiency improvement (e.g. capital-intensive kiln conversions) alone limit the potential for energy efficiency improvement. However, in practice new plants will be built to replace aging facilities, or to supply cement to regions with high growth in cement consumption. In recent years new energy-efficient kilns have been built in the Pacific Northwest, Florida and Utah. Capital stock turnover is hence an important driver for energy efficiency in an industry with capital intensive lay-outs, despite the large contribution of energy costs to total production costs.

Conservation Supply Curve for Cementmaking (with product change)

The discussion above assumes that the U.S. cement industry will produce the same product mix as in 1994. However, many countries in the world produce blended cement with a lower clinker content, as discussed in section V, which can reduce the energy intensity of cement considerably. Producing blended cements may have synergetic effects, as it can help to replace the most energy intensive kilns in a given region (depending on various conditions, e.g. transport distances of resources, limestone reserves). In this section we assess the role of clinker replacement by cementious additives. We assume that the use of additives will reduce the total amount of clinker produced, maintaining the cement production level of 1994. Hence, energy efficiency measures in clinker making will provide lower total energy savings. The results are presented in Figure 10.

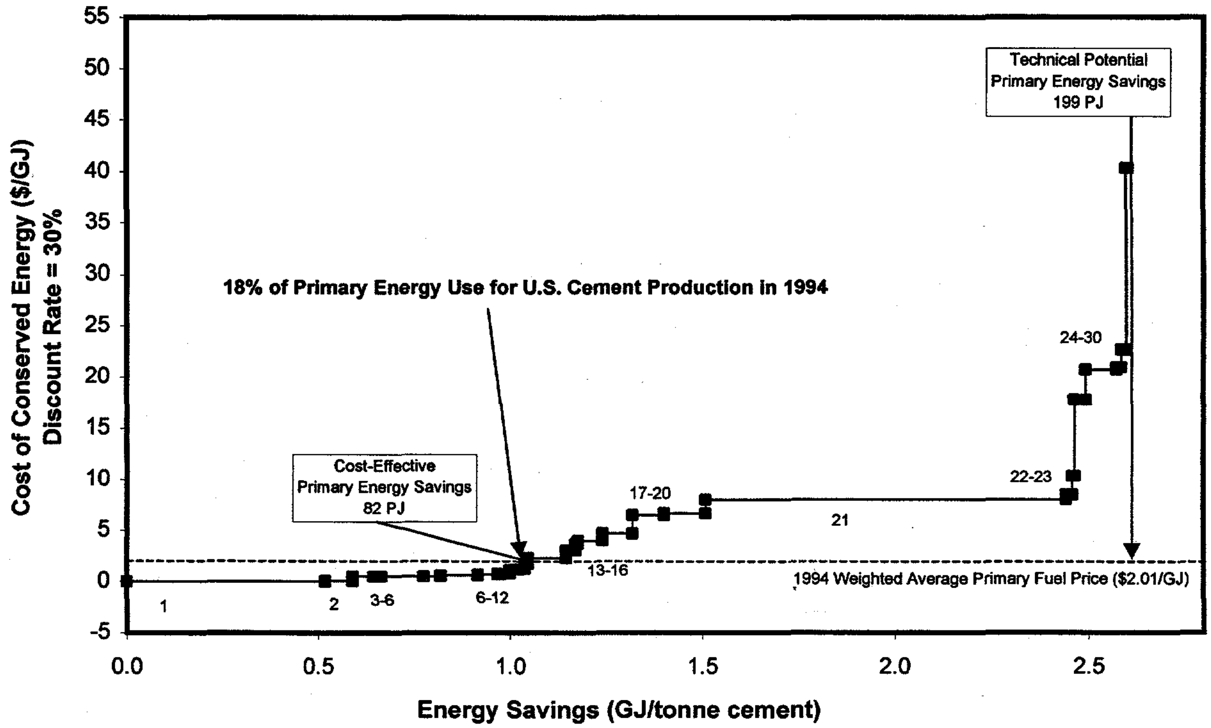


Figure 10. Energy conservation supply curve for energy efficiency measures in the U.S. cement industry, including the production of blended cement (measure 1). The horizontal axis depicts the cumulative primary energy savings (expressed in GJ/tonne cement). The vertical axis represents the cost of conserved energy (expressed in $/GJ primary energy saved), using a discount rate of 30%.

The switch to the production of blended cement, replacing 15% of 1994 clinker production, does not affect the technical potential for energy efficiency improvement much, as it increases to 181 PJ. However, the cost-effective potential increases to 18%. The effects on carbon dioxide emissions are more profound, due to the reduced clinker production, reducing emissions from energy use and limestone calcination. The total technical potential for carbon dioxide emissions is almost 5.3 MtC (or 28%) and the cost-effective potential is estimated at 3.1 MtC (or 16%).

We have assumed that both dry and wet process cement plants are taken out of production in equal shares. In practice, the introduction of blended cement may curb the production of the less efficient kilns, and may impact energy use more. Ready-mix producers are among the largest users of cement in the U.S. Ready-mix producers already use fly-ash in the production of concrete. However, no statistical information is available on the actual use in concrete making. Although, ready-mix producers use additives, the intergrinding of additives at the cement plant may have additional benefits over use at the ready-mix producer (see above). The use of additives at the cement plant may not affect the concrete production process, but additional research is needed to assess the potential impact, and net impact on energy intensity for concrete-making.

Table 5 summarises the results of the technical and economic analysis of the potentials for energy efficiency improvement in the U.S. cement industry, based on the 1994-reference situation. Although some changes have taken place in the technologies used in the U.S. cement industry, e.g. a new clinker plant has started production at Devil's Slide (UT) and other plants have been rebuilt, there have been no dramatic changes in the industry. Still, the potential impact of some of the measures may be different today compared to 1994. We used 1994, as that was the latest year for which energy data was available with the Department of Energy's Energy Information Administration, at a suitable aggregation level. A regular update of this study may be needed to account for the dynamics of the industry in the assessment of energy efficiency potentials, as well as development in cement-making technology.

Table 5. Summary of the technical and cost-effective potential for energy efficiency improvement in the U.S. cement industry, and impact on carbon dioxide emissions, for the reference year 1994. Carbon dioxide emission reduction is expressed as share of the total emissions (including emissions from calcination in the clinker-making).

	Energy Efficiency Improvement		Carbon Dioxide Emissions	
	Technical Potential (PJ)	Cost-Effective Potential (PJ)	Technical Potential (MtC)	Cost-Effective Potential (MtC)
Current productmix	180 (40%)	48 (11%)	3.5 (18%)	1.0 (5%)
Blended cement	199 (45%)	82 (18%)	5.3 (28%)	3.1 (16%)

VII. Summary and Conclusions

We have analyzed historic trends for energy efficiency in the U.S. cement industry, as well as identifying cost-effective energy and carbon dioxide savings that can be achieved in the near future. We discuss this industry at the aggregate level (Standard Industrial Classification 324), which includes establishments engaged in manufacturing hydraulic cements, including portland, natural, masonry, and pozzolana when reviewing industry trends and when making international comparisons. We also focus on the aggregate level for a detailed analysis of energy use and carbon dioxide emissions by process, specific energy efficiency technologies and measures to reduce energy use and carbon dioxide emissions, and the energy efficiency and carbon dioxide emissions reduction potential for cement production in the U.S.

Reviewing the industry as a whole, we found that U.S. steel plants are relatively old and total production has fluctuated little in the recent past, though the composition of production has changed significantly. Coal and coke are currently the primary fuels for the sector, supplanting the dominance of natural gas in the 1970s. Between 1970 and 1997, primary physical energy intensity for cement production dropped 30%, from 7.9 GJ/t to 5.6 GJ/t, while carbon dioxide intensity from fuel consumption (carbon dioxide emissions expressed in tonnes of carbon per tonne cement) dropped 25%, from 0.16 tC/tonne to 0.12 tC/tonne. Total carbon dioxide intensity due to fuel consumption and clinker calcination dropped 17%, from 0.29 tC/tonne to 0.24 tC/tonne.

We examined 30 energy efficient technologies and measures and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for each of the measures. We constructed an energy conservation supply curve for U.S. cement industry which found a total cost-effective reduction of 0.6 GJ/tonne of cement, consisting of measures having a simple payback period of 3 years or less. This is equivalent to potential energy savings of 11% of 1994 energy use for cement making and a savings of 5% of total 1994 carbon dioxide emissions by the U.S. cement industry.

Assuming the increased production of blended cement in the U.S., as is common in many parts of the world, the technical potential for energy efficiency improvement would not change considerably. However, the cost-effective potential, would increase to 1.1 GJ/tonne cement or 18% of total energy use, and carbon dioxide emissions would be reduced by 16% (due to the reduced clinker production). This demonstrates that blended cement production could be key to a cost-effective strategy for energy efficiency improvement and carbon dioxide emission reductions in the U.S. cement industry.

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