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Energy Efficiency Improvement Opportunities for Cement Making

An ENERGY STAR Guide for Energy and Plant Managers

**Ernst Worrell and Christina Galitsky
Environmental Energy Technologies Division**

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January 2004

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Energy Efficiency Improvement Opportunities for Cement Making

An ENERGY STAR[®] Guide for Energy and Plant Managers

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Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making

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ABSTRACT

The cost of energy as part of the total production costs in the cement industry is significant, warranting attention for energy efficiency to improve the bottom line. Historically, energy intensity has declined, although more recently energy intensity seems to have stabilized with the gains. Coal and coke are currently the primary fuels for the sector, supplanting the dominance of natural gas in the 1970s. Most recently, there is a slight increase in the use of waste fuels, including tires. Between 1970 and 1999, primary physical energy intensity for cement production dropped 1%/year from 7.3 MBtu/short ton to 5.3 MBtu/short ton. Carbon dioxide intensity due to fuel consumption and raw material calcination dropped 16%, from 609 lb. C/ton of cement (0.31 tC/tonne) to 510 lb. C/ton cement (0.26 tC/tonne).

Despite the historic progress, there is ample room for energy efficiency improvement. The relatively high share of wet-process plants (25% of clinker production in 1999 in the U.S.) suggests the existence of a considerable potential, when compared to other industrialized countries. We examined over 40 energy efficient technologies and measures and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for each of the measures. The report describes the measures and experiences of cement plants around the world with these practices and technologies.

Substantial potential for energy efficiency improvement exists in the cement industry and in individual plants. A portion of this potential will be achieved as part of (natural) modernization and expansion of existing facilities, as well as construction of new plants in particular regions. Still, a relatively large potential for improved energy management practices exists.

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1. Introduction

As U.S. manufacturers face an increasingly competitive global business environment, they seek opportunities to reduce production costs without negatively affecting product yield or quality. Uncertain energy prices in today's marketplace negatively affect predictable earnings, a concern for publicly traded companies in the beer industry. For public and private companies alike, increasing energy prices are driving up costs and decreasing their value added. Successful, cost-effective investment into energy efficiency technologies and practices meet the challenge of maintaining the output of a high quality product despite reduced production costs. This is especially important, as energy-efficient technologies often include "additional" benefits, such as increasing the productivity of the company.

Energy efficiency is an important component of a company's environmental strategy. End-of-pipe solutions can be expensive and inefficient while energy efficiency can often be an inexpensive opportunity to reduce criteria and other pollutant emissions. Energy efficiency can be an effective strategy to work towards the so-called "triple bottom line" that focuses on the social, economic, and environmental aspects of a business.¹ In short, energy efficiency investment is sound business strategy in today's manufacturing environment.

Voluntary government programs aim to assist industry to improve competitiveness through increased energy efficiency and reduced environmental impact. ENERGY STAR[®], a voluntary program operated by the U.S. Environmental Protection Agency, stresses the need for strategic corporate energy management. ENERGY STAR provides guidance, energy management tools, and strategies for successful corporate energy management programs. This guide reports on research conducted to support ENERGY STAR and its work with the cement industry. This research provides information on potential energy efficiency opportunities for cement plants. Besides technical information, ENERGY STAR provides tools to facilitate stronger corporate energy management practices in U.S. industry, including plant energy benchmarks. ENERGY STAR can be contacted through www.energystar.gov for additional energy management tools that facilitate stronger corporate energy management practices in U.S. industry.

This report reflects an in-depth analysis of the cement industry, and identifies energy savings and carbon dioxide emissions reduction potentials. In this analysis, the cement industry (Standard Industrial Classification 3241) includes establishments engaged in manufacturing hydraulic cements, including portland, natural, masonry, and pozzolana cements.

The production of cement is an energy-intensive process. Annually the cement industry spends over \$1 billion energy purchases. The production of cement results in the emission of carbon dioxide from both the consumption of fuels and from the calcination of limestone. This report briefly describes the various stages in the cement production process. Details on energy consumption in the U.S. cement industry in 1999 are provided, followed by an assessment of various energy efficiency measures applicable to U.S. cement plants.

¹ The concept of the "triple bottom line" was introduced by the World Business Council on Sustainable Development (WBCSD). The three aspects are interconnected as society depends on the economy and the economy depends on the global ecosystem, whose health represents the ultimate bottom line.

2. The 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). 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 either portland cement plants that produce clinker and grind it to make finished cement, or clinker-grinding plants that intergrind clinker obtained elsewhere, with various additives.

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. 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 1999 was portland cement, while masonry cement accounted for 5.0% of U.S. cement output in 1999 (USGS, 2001).

Cement plants are typically constructed in areas with substantial raw materials deposits (e.g. 50 years or longer). There were 117 operating cement plants in the U.S. in 1999, spread across 37 states and in Puerto Rico, owned by 42 companies. Portland cement was produced at 116 plants in 1999, while masonry cement was produced at 83 plants (82 of which also produced portland cement). Clinker was produced at 109 plants (111 including Puerto Rico) in the U.S. in 1999. 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 nearly 86 Mt, excluding Puerto Rico (USGS, 2001). Clinker is produced with either the “wet” or “dry” process. These processes are discussed in detail in chapter 3. Modern plants are constructed in areas where high quality limestone is available, and a high demand for cement exists. These new plants have large capacities.

Clinker production, cement production, and materials consumption trends are quite similar. All three categories experienced gradual growth between 1970 and 1999, with prominent dips in the late 1970s and early 1980s. Clinker production increased from 67 Mt in 1970 to 77 Mt in 1999, at an average rate of 0.4% per year, hitting a low of 55 Mt in 1982, and its current high in 1999 (USGS, various years). Within this slow production increase, the type of facility used to produce clinker changed significantly between 1970 and 1999. 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 25% share in 1999. 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 73% share in 1999, with the remainder being plants classified as wet or dry.

Cement production increased at 0.7% per year between 1970 and 1999, rising from 69 Mt in 1970 to 86 Mt in 1999 (USGS, various years). Portland cement remained the dominant cement type during that time span, maintaining a share between 94% and 96%. Between 1970 and 1999, the clinker to cement ratio (expressed as clinker production divided by cement production) decreased from 0.97 to 0.88 t clinker/t cement. The number of clinker plants has decreased from 169 in 1970 to 111 in 1999, and the number of clinker grinding plants reduced to 6 (a total of 117 facilities in 1999). Thus, average plant capacity has increased.

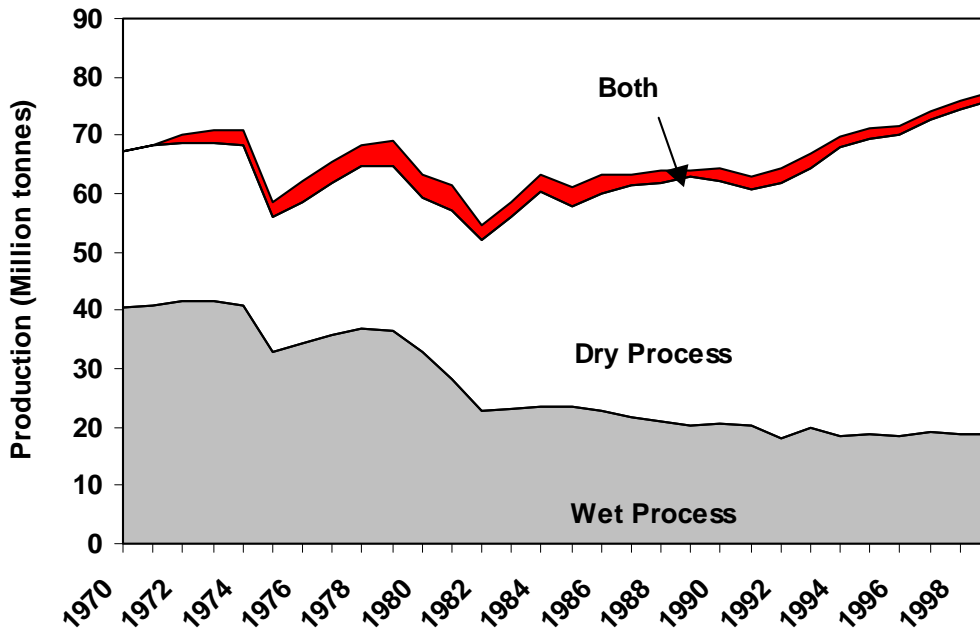


Figure 1. U.S. Clinker Production by Process, 1970 to 1999 (expressed in million metric tons/year). Source: USGS, various years. The term “both” accounts for plants that are not categorized as a wet or dry process plant in the USGS minerals yearbooks.

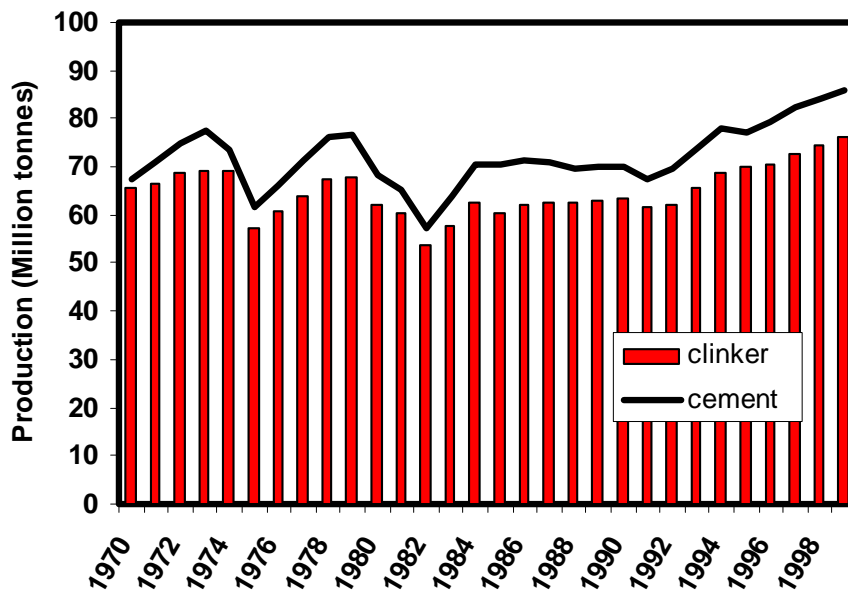


Figure 2. U.S. Cement and Clinker Production, 1970 to 1999 (expressed in million metric tons/year). Source: USGS, various years.

3. Process Description

Mining and Quarrying

The most common raw materials used for cement production are limestone, chalk and clay (Greer et al, 1992). The major component of the raw materials, the limestone or chalk, is usually extracted from a quarry adjacent to or very close to the plant. Limestone provides the required calcium oxide and some of the other oxides, while clay, shale and other materials provide most of the silicon, aluminum and iron oxides required for the manufacture of portland cement. The limestone is most often extracted from open-face quarries but underground mining can be employed (Greer et al., 1992). The raw materials are selected, crushed, ground, and proportioned so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyroprocessing systems (see Figure 3). It is often necessary to raise the content of silicon oxides or iron oxides by adding quartz sand and iron ore, respectively. The quarried material is reduced in size by processing through a series of crushers. Normally primary size reduction is accomplished by a jaw or gyratory crusher, and followed by secondary size reduction with a roller or hammer mill. The crushed material is screened and stones are returned. More than 1.5 tons of raw materials are required to produce one ton of portland cement (Greer *et al.*, 1992; Alsop and Post, 1995).

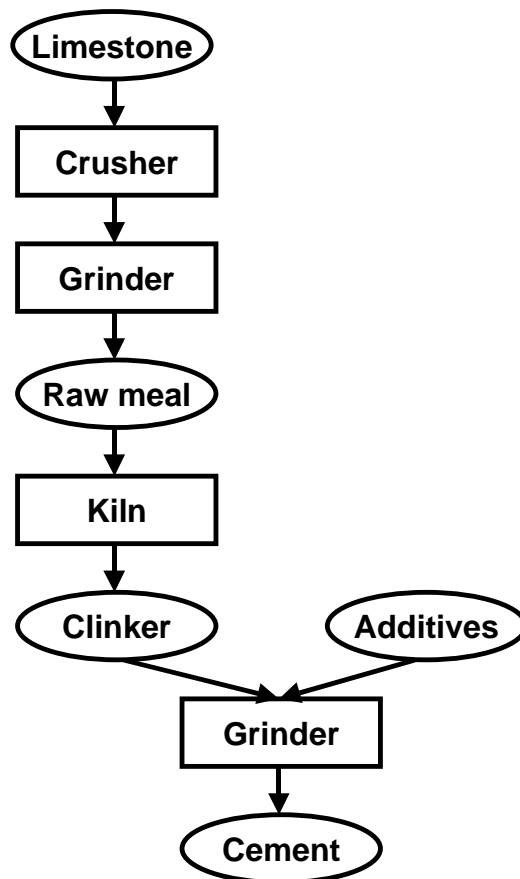


Figure 3. Simplified process schematic for cement making. Limestone is the major process input. However, other raw materials such as clay, shale, sand, quartz or iron ore may be added.

Kiln Feed Preparation

Raw material preparation is an electricity-intensive production step requiring generally about 25-35 kWh/tonne raw material (23-32 kWh/short ton), although it could require as little as 11 kWh/tonne. After primary and secondary size reduction, the raw materials are further reduced in size by grinding. The grinding differs with the pyroprocessing process used. In dry processing, the materials are ground into a flowable powder in horizontal ball mills or in vertical roller mills. In a ball (or tube) mill, steel-alloy balls (or tubes) are responsible for decreasing the size of the raw material pieces in a rotating cylinder, referred to as a rotary mill. Rollers on a round table fulfill this task of comminution in a roller mill. Utilizing waste heat from the kiln exhaust, clinker cooler hood, or auxiliary heat from a stand-alone air heater before pyroprocessing may further dry the raw materials. The moisture content in the kiln feed of the dry kiln is typically around 0.5% (0 - 0.7%).

When raw materials are very humid, as found in some countries and regions, wet processing can be preferable². In the wet process, raw materials are ground with the addition of water in a ball or tube 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, and virtually all of the fuel use. Clinker is produced by pyroprocessing in large kilns. These kiln systems evaporate the inherent water in the raw meal, calcine the carbonate constituents (calcination), and form cement minerals (clinkerization) (Greer *et al.*, 1992).

The main pyroprocessing kiln type used in the U.S. is the rotary kiln. In these rotary 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 countercurrent to the flow of gases and toward the flame-end of the rotary kiln, where the raw meal is dried, calcined, and enters into the sintering zone. 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 chemical uniformity in the raw meal. The water (due to the high moisture content of the raw meal) 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) (COWIconsult *et al.*, 1993; Vleuten, 1994).

In a dry rotary 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 (Cembureau, 1997). Later developments have added multi-stage suspension preheaters (i.e. a cyclone) or shaft preheater. Pre-calciner technology was more recently developed in which a second combustion chamber has been added between the kiln and a conventional pre-heater that allows for further reduction of kiln fuel requirements. The typical fuel consumption of a dry kiln with 4 or 5-stage preheating can vary between 3.2 and 3.5 GJ/tonne clinker

² Originally, the wet process was the preferred process, as it was easier to mix, 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, and improvement of the energy efficiency of the pyroprocessing systems.

(2.7 and 3.0 MBtu/short ton clinker) (COWIconsult *et al.*, 1993), electricity use increases slightly due to the increased pressure drop across the system. 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 preheater, 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). Alkali or kiln dust (KD) bypass systems may be required in kilns to remove alkalis, sulfates, and/or chlorides. Such systems lead to additional energy losses since sensible heat is removed with the bypass gas and dust.

Once the clinker is formed in the rotary kiln, it is cooled rapidly to minimize the formation of a glass phase and ensure the maximum yield of alite (tricalcium silicate) formation, 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 through which air flows perpendicular to the flow of clinker. In the planetary cooler (a series of tubes surrounding the discharge end of the rotary kiln), the clinker is cooled in a counter-current air stream. The cooling air is used as secondary combustion air for the kiln.

Finish Grinding

After cooling, the clinker can be stored in either the clinker dome, silos, bins or outside. 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 to the consistency of face powder. Grinding of cement clinker, together with additions (3-5% gypsum to control the setting properties of the cement) can be done in ball mills, ball mills in combination with roller presses, roller mills, or roller presses (Alsop and Post, 1995). While vertical roller mills are feasible, they have not found wide acceptance in the U.S. Coarse material is separated in a classifier that is re-circulated and returned to the mill for additional grinding to ensure a uniform surface area of the final product.

Power consumption for grinding depends on the surface area required for the final product and the additives used. Electricity use for raw meal and finish grinding depends strongly on the hardness of the material (limestone, clinker, pozzolana 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 3,500 Blaine³ (expressed in cm²/g). (COWIconsult *et al.*, 1993). Traditionally, ball mills are used in finish grinding, while many plants use vertical roller mills. In ball or 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 utilize a high-pressure roller mill and the horizontal roller mill (e.g. Horomill[®]) (Seebach *et al.*, 1996) that are claimed to 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 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).

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 centimetres per gram. The higher the Blaine, the more energy required to grind the clinker and additives (Holderbank, 1993).

Finished cement is stored in silos, tested and filled into bags, or shipped in bulk on bulk cement trucks, railcars, barges or ships. 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.

4. Energy Use and Carbon Dioxide Emissions⁴ in the U.S. Cement Industry

4.1 Historical Energy Use and Carbon Dioxide Emissions Trends

Energy consumption in the U.S. cement industry declined between 1970 and 1999 (see Figure 4). Primary energy use decreased at an average of -0.3% per year, from 555 TBtu (586 PJ) in 1970 to 531 TBtu (560 PJ) in 1999, although production increased over that time span. The overall energy consumption trend in the U.S. cement industry between 1970 and 1999 shows a gradual decline. Energy consumption started to increase in the early 1990s and increased between 1992 and 1999 at an average of 4.5% 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 28% in 1997, while energy consumption of the dry process increased from 38% of total cement energy consumption in 1970 to 68% in 1997.

Since the 1980's the use of waste derived fuels is growing in the cement industry replacing clinker fuels. As Figure 5 shows, by 1999 17% of all fuels were waste derived fuels, e.g. tires, solid and liquid wastes (solvents) (USGS, 2001). USGS has collected data on waste fuel use starting 1992, although waste fuel use started before that time. The trend towards increased waste use will likely increase after successful tests with different wastes in Europe and North America. New waste streams include carpet and plastic wastes, filter cake, paint residue and (dewatered) sewage sludge. The energy recovery efficiency in clinker kilns is often high compared to alternative thermal waste treatments methods, resulting in net energy savings.

The cement industry contributes approximately 5% to all industrial carbon dioxide (CO_2) emissions in the United States (equivalent to approximately 2% of total U.S. CO_2 emissions). CO_2 emissions from fuel consumption in the cement industry in 1999 were virtually back at the 1970 level around 11.9 MtC, despite a drop in the years in between, due to improvements in the pyroprocessing systems. CO_2 emissions from the calcination process increased from 9.3 MtC in 1970 to 10.7 MtC in 1999 due to the increased clinker production. Hence, total carbon dioxide emissions from the cement industry increased to 22.6 MtC (including emissions from power generation). 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 7% fuel share in 1999, 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 61% in 1999, petroleum coke (11% in 1999) and wastes (liquid and solid, 10% in 1999). Oil's share fell from 13% in 1970 (17% in 1973) to 1% in 1999. Electricity's share increased from 7% in 1970 to 11% in 1999.

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

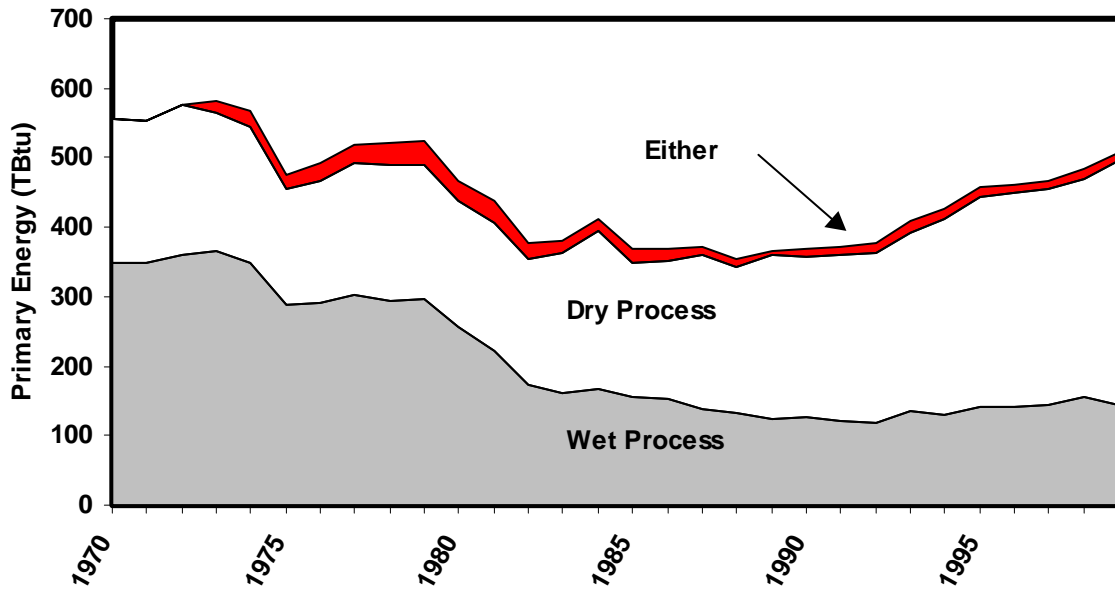


Figure 4. Primary Energy Consumption in U.S. Cement Production by Process, 1970 to 1999 (expressed in TBtu). Source: derived from USGS, various years.

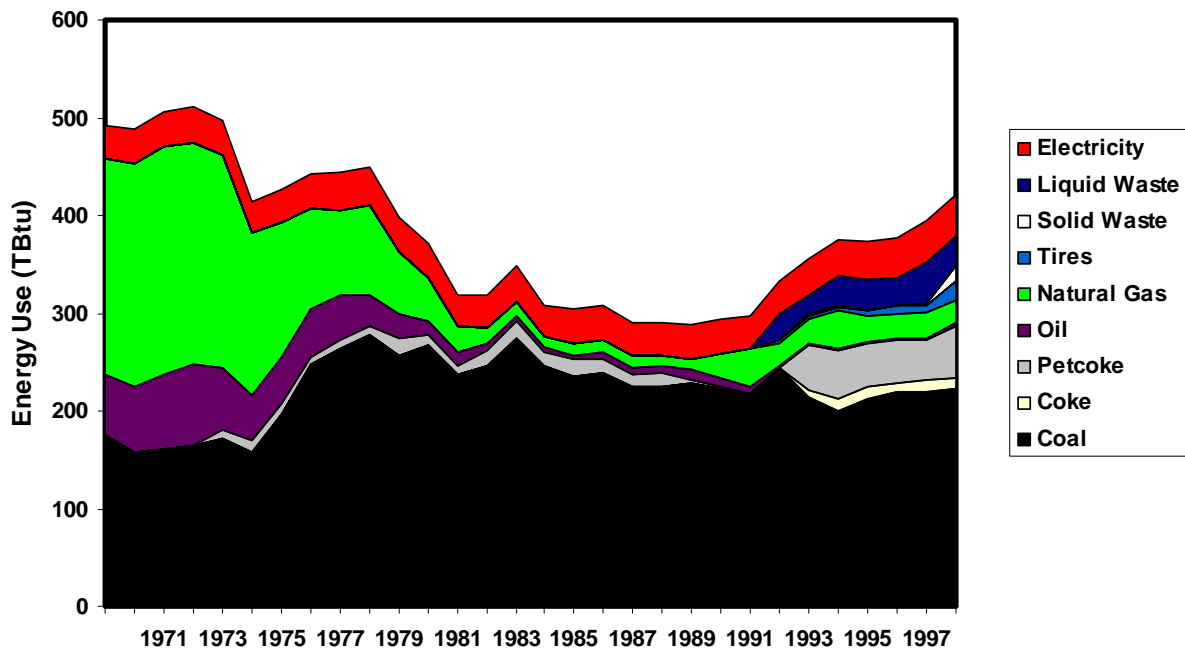


Figure 5. Energy Consumption in U.S. Cement Production by Fuel, 1970 to 1999 (expressed in TBtu). Source: derived from USGS, various years.

4.2 Historical Energy Intensity and Specific Carbon Dioxide Emission Trends

Primary energy intensity in the U.S. cement industry decreased between 1970 and 1999. Primary energy intensity of cement production decreased at an average rate of -1.0% per year from 1970 to 1992, but increased 1.4% /year from 1992 to 1999. Between 1970 and 1999 the primary energy intensity fell from 7.3 MBtu/ton in 1970 to 5.3 MBtu/ton in 1999 (see Figure 6). 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).

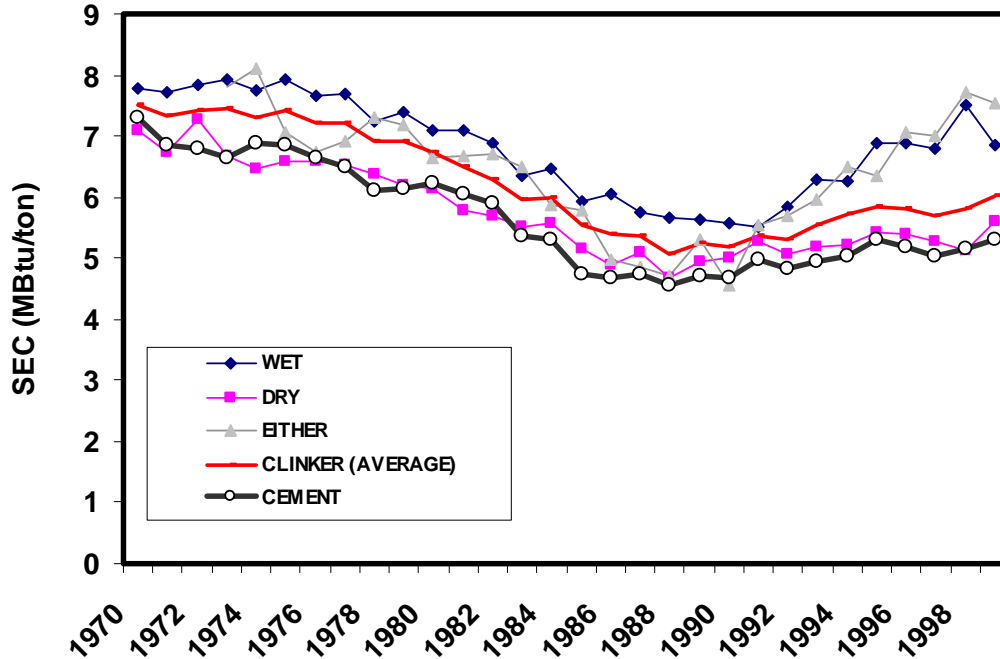


Figure 6. Primary Energy Intensity of U.S. Cement and Clinker Production, 1970 to 1999 (expressed in MBtu/short ton, HHV). This graph excludes use of wastes as kiln fuel between 1977 and 1992, as USGS did not collect this data before 1993. See below for a discussion on the impact of including assumptions on waste use. Source: derived from USGS, various years.

Figure 7 shows the developments in specific fuel and electricity consumption. The figure shows a slow increase in specific electricity consumption, which is due to the increased penetration of the modern dry process (preheater/precalciner technology), but is very small in comparison to fuels consumption. Specific fuel consumption decreases strongly till around 1987, and is stable after that, with a slight growth in recent years.

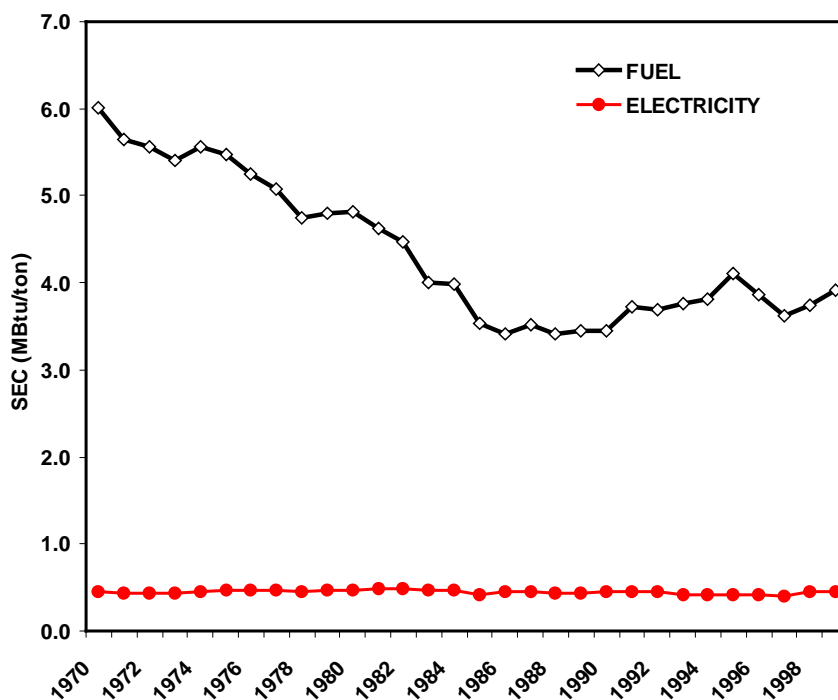


Figure 7. Specific fuel and electricity consumption per ton of cement produced. Energy is expressed as final energy (or site energy) and excludes power generation conversion losses. Fuels include waste fuel use estimates starting in 1977 (based on PCA data, and after 1993 on USGS reported data).

Specific carbon dioxide emissions⁵ from fuel consumption declined from 352 lbC/ton cement (175 kgC/tonne) in 1970 to 304 lbC/ton cement in 1999. Total carbon dioxide emissions (including emissions from limestone calcination for clinker-making) decreased at 0.3% per year, on average, from 609 lbC/ton cement (305 kg C/t) in 1970 to 510 lbC/ton cement (255 kg C/t) in 1999.

Like the energy intensity trend, specific carbon dioxide emissions decreased overall between 1970 and 1990. The specific carbon dioxide emissions from both the wet and dry processes decreased between 1970 and 1999, the wet process at an average of -0.01% per year and the dry process at an average rate of -0.6% 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.

⁵ Carbon dioxide emissions were calculated based on the fuels and electricity consumption as given by USGS (various years), average US power generation efficiency and fuel use as given by the EIA (various years) and clinker production data as given by USGS (various years). Emission factors are provided by EIA and IPCC (1996).

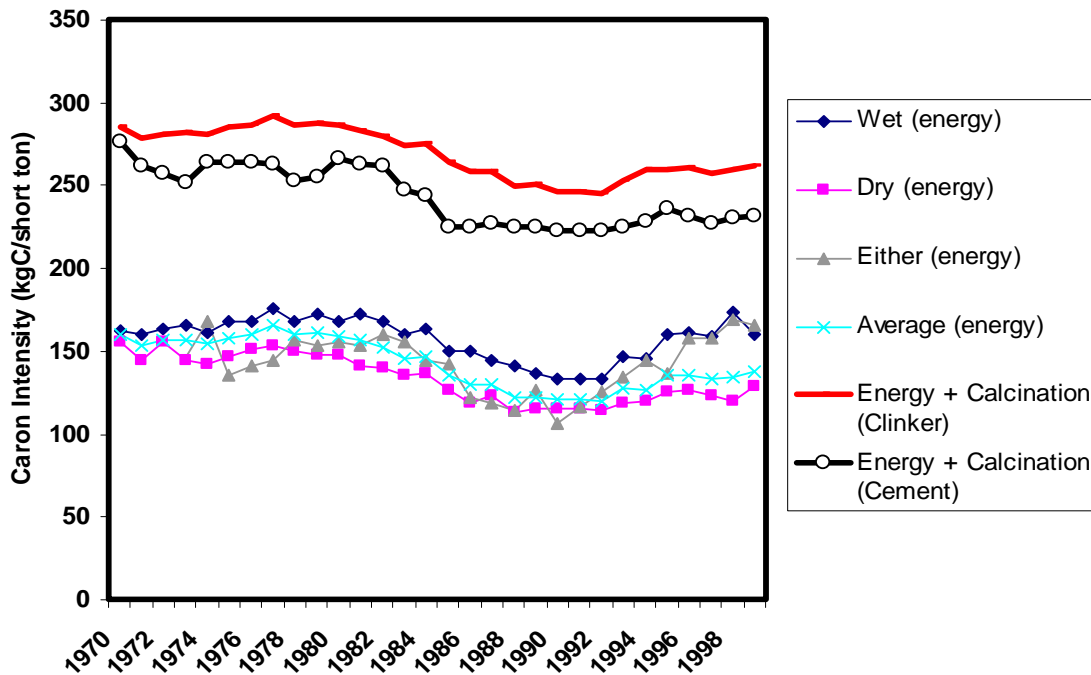


Figure 8. Carbon Intensity of U.S. Cement and Clinker Production, 1970 to 1999 (expressed in kgC/short ton of product). This graph excludes use of wastes as kiln fuel between 1977 and 1992, as USGS did not collect this data before 1993. See below for a discussion on the impact of including assumptions on waste use. Source: derived from USGS, various years.

Figure 6 shows an increasing trend in the energy intensity of the cement industry in recent years. This trend is opposite the trend provided by data of the Portland Cement Association (PCA) in their annual survey. The PCA survey results show a slight but steady decline in energy intensity over the same period. This report is based on energy consumption data collected by the USGS. USGS provides a complete time series of the past 30 years. Both the PCA and USGS datasets on energy use and production trends are very valuable datasets, certainly when compared to those existing for other industrial sectors in the U.S. Given the different approaches and boundaries between both datasets it is impossible to fully understand the differences found for energy use. The uncertainty of the statistical data on energy is estimated at +/-5%, based on the factors discussed below. Comparison of the average specific energy consumption derived from USGS and PCA for 2000 showed that the differences are in that range (van Oss, 2002). There are differences between the USGS and PCA data (based on personal communication with USGS and PCA):

- USGS data before 1993 do not report the use of waste fuels, as it was not collected. Waste use started around the mid-1980's after early experiments in the mid-1970's (Bouse and Kamas, 1987). This means that the USGS data under-represent fuel and hence energy data from the mid-1980's through 1992, especially the period 1990-1992. Note that both surveys may not contain sufficient information to correctly estimate the heat content of liquid waste fuels (see also below). Some private databases contain information starting in 1989 (Lusk, 2002). Industry statistics first report waste fuel use for 1977 (PCA, 1980), approximately 3% of fuels were waste-derived in 1988, and 5.2% of fuels were waste derived in 1989 (PCA, 1990). The impacts of increased waste fuel use have been estimated, starting in 1977 and growing to 1993 levels by 1993, calibrating on the PCA data for 1977-1985, 1988 and 1989. This would lead to increased fuel use of up to 6% by 1992. This would reduce the observed trend in Figure 6 and show only a slight growth in energy intensity in the

1990's. It would also result in almost flat or slightly falling total CO₂ emission intensities (Figure 7) since 1985.

- This report used constant conversion values for the higher (or gross) heating value of the fuels reported by USGS, based on industrial average heating values as reported by the Energy Information Administration (EIA, 1997). The PCA has a more detailed breakdown of the fuels used, which gives a better estimate of fuel use. The PCA data probably provides a better estimate of the energy content of the wastes used, than our estimate.
- This analysis uses primary energy to express energy use. Purchased electricity consumption has been converted to the fuels used to generate the electricity. This report has used the average national conversion efficiency of the public grid for each year as reported by the Energy Information Administration. When using final energy consumption (i.e. adding electricity and fuels directly without including conversion losses) for the analysis of energy intensity trends, our results show a slight annual decline in energy intensity until 1991, relative stabilization between 1991 and 1997, followed by a slight increase in energy intensity in 1998 and 1999.
- The PCA uses an "equivalent ton" (equivalent to 92% clinker + 8% finished cement production) to estimate total cement production, while the USGS uses real reported cement production.
- The PCA only surveys PCA members and the response rate is 90-100% of members (e.g. 91% in 2000); trade association membership has comprised 90-95% of total U.S. capacity during the 1970s and 1990s, and lesser percentages during the 1980s. The PCA survey excludes (energy-intensive) white cement plants and grinding-only plants. The USGS survey includes all of the industry and has a high response rate, equal to 97-98% (or 99% based on total cement production) in recent years.
- Both surveys suffer from occasional poor/error-prone data and the dangers of imposing default values. However, the PCA survey is focused on energy use whereas the fuel and energy information are but one part of the large, general, USGS survey, which may lead to different reports by surveyed companies. Both data sets suffer from order of magnitude and unit reporting, and in both surveys, there may be inconsistent use among plants in the use of conversion factors for the solid and gaseous fuels. One observation can be made regarding the USGS survey's observed increase and the PCA's decrease in intensity in the cement industry. Over the period of the 1990's, it appears that no major gains were made in improving the energy intensity of this industry since any movement in intensity in either direction was only slight or minimal.

5. 1999 Baseline Energy Use and Carbon Dioxide Emissions

In 1999, the U.S. cement industry consumed 427 TBtu (450 PJ) of final energy (about 2% of total U.S. manufacturing energy use) and emitted 22.3 MtC of carbon dioxide⁶ (about 4% of total U.S. manufacturing carbon emissions). Table 1 provides our estimate of 1999 U.S. baseline energy consumption by process. The estimates are based on the throughput of the different processes, energy consumption information provided for the different processes, and the total energy consumption in the U.S. cement industry in 1999.

Table 1. 1999 Energy Consumption and Specific Energy Consumption (SEC) in the U.S. Cement Industry by Process. All energy units are expressed in higher heating value (HHV). Emissions are expressed in metric units (i.e. kg and metric ton).

Process Stage	Energy			Specific Energy Consumption (SEC)			Carbon Dioxide Emissions Energy Use	Carbon Dioxide Emissions Calcination	Carbon Dioxide Intensity
	Fuel (TBtu)	Elec. (TBtu)	Primary Energy (TBtu)	Fuel SEC (MBtu/st)	Elec. SEC (kWh/st)	Primary SEC (MBtu/st)	(MMtCe)	(MMtCe)	(kgC/st)
<i>Wet Process</i>									
Kiln Feed Preparation	0	4	13	0.0	27	0.3	0.2	0.0	4.4
Clinker Production ⁷	125	3	128	6.0	39	6.4	3.2	2.8	268.5
Finish Grinding	0	5	16	0.0	57	0.6	0.2	0.0	9.2
Total Wet Process – Cement	125	12	157	4.8	132	6.3	3.6	2.7	249
<i>Dry Process</i>									
Kiln Feed Preparation	0	15	48	0.0	38	0.4	0.7	0.0	6.1
Clinker Production	254	9	281	4.0	45	4.5	6.7	7.9	231.7
Finish Grinding	0	12	40	0.0	52	0.6	0.6	0.0	8.3
Total Dry Process - Cement	254	36	370	3.6	150	5.2	8.0	7.9	224.2
Total All Cement	379	48	531	3.9	146	5.5	11.6	10.7	230.8

Notes:

- To convert from Trillion Btu to PJ multiply by 1.055. To convert from MBtu/short ton to GJ/tonne multiply by 1.163. To convert from kgC/short ton to kgC/tonne multiply by 1.103. To convert from kgC/st to lbC/st multiply by 2.203.
- All energy units are expressed in Higher Heating Value (HHV), as is common in U.S. energy statistics. International energy statistics generally report energy in Lower Heating Value (LHV). Comparing energy intensities in Table 1 with other countries should only be done after conversion to LHV.
- Unfortunately, available statistics do not allow to further disaggregate energy use for dry kilns into preheater and pre-calciner kilns.

Raw Materials

In 1999, 158 Million short tons (143 Mt) of raw materials were used in the cement industry (USGS, 1999).⁸ It is assumed that 26% of raw materials were for the wet process kilns and 74% of raw materials were used for dry process kilns. Electricity use is estimated at 27 kWh/short ton raw material preparation for wet kilns and 38 kWh/short ton for dry kilns due to the additional processing (COWIconsult *et al.*, 1993; Jaccard and Willis, 1996).

Clinker Production

According to USGS (USGS, 1999) wet process clinker production was 20.8 Million short tons (18.9 Mt) while dry process production was 62.9 Million short tons (57.0 Mt). Accounting for production

⁶ We express carbon dioxide emissions in their carbon equivalent using metric tons. To obtain carbon dioxide emissions expressed in full molecular weight multiply by 44/12.

⁷ Imported clinker into the U.S. is not counted in clinker production, but is included in the energy consumption for finish grinding.

⁸ The import of 4.6 Million tons of clinker (1999) would account for an additional 7.8 Million tons of raw material use. However, we only include materials processed in the U.S. cement industry to determine energy intensities.

from plants with both wet and dry processes on site, USGS gives a total clinker production of 85.2 million short tons (77.3 Mt) in that year. The average U.S. wet kiln fuel intensity in 1999 is estimated at 6.0 MBtu/short ton clinker (7.0 GJ/t) and an average dry kiln fuel intensity of 4.0 MBtu/short ton (4.7 GJ/tonne) (Holderbank, 1993; PCA, 1996b; Jaccard and Willis, 1996; van Oss, 1999). Electricity requirements of 39 kWh/short ton (43 kWh/tonne) are assumed for fuel preparation and for operating the kiln, fans, and coolers for wet kilns and 45 kWh/short ton (50 kWh/tonne) for dry kilns (COWIconsult *et al.*, 1993; Ellerbrock and Mathiak, 1994).

Finish Grinding

The amount of throughput for finish grinding is assumed to be the same as the total amount of cement produced in 1999, 25.8 million short tons (21.8 Mt) for wet cement, 68.1 million short tons (61.8 Mt) for dry cement and 1.8 million short tons (1.7 Mt) for other processes (USGS, 2001). Based on Lowes (1990) and COWIconsult (1993), the average energy requirements for finish grinding are estimated to be 52 kWh/short ton (57 kWh/t) for the newer plants using dry kilns and 57 kWh/short ton (63 kWh/t) for the older wet process plants.

Carbon Dioxide Emissions

Carbon dioxide 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 0.14 tonnes of carbon are emitted for every tonne of clinker produced (UNEP *et al.*, 1996). This amounts to 10.7 MtC given a production of 77.3 million tonnes of clinker (85.3 million short tons) in 1999 (USGS, 2001). Energy consumption data is based on the physical consumption data as provided by the U.S. Geological Survey. The consumption data are multiplied with typical U.S. energy contents for the different fuels, as given by the Energy Information Administration's Manufacturing Energy Consumption Survey (MECS). U.S. Energy Information Administration and U.S. EPA (EIA, 1996, Appendix B) are the sources for 1999 carbon dioxide emission coefficients for the various commercial fuels, except for the Intergovernmental Panel on Climate Change (UNEP *et al.*, 1996) coefficients for coke and breeze. For electricity, the 1999 average fuel mix for electricity generation in the U.S is used.

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

Opportunities exist within U.S. cement plants to improve energy efficiency while maintaining or enhancing productivity. Improving energy efficiency at a cement plant should be approached from several directions. First, plants use energy for equipment such as motors, pumps, and compressors. These important components require regular maintenance, good operation and replacement, when necessary. Thus, a critical element of plant energy management involves the efficient control of crosscutting equipment that powers the production process of a plant. A second and equally important area is the proper and efficient operation of the process. Process optimization and ensuring the most efficient technology is in place is a key to realizing energy savings in a plant's operation. Finally, throughout a plant, there are many processes simultaneously. Fine-tuning their efficiency is necessary to ensure energy savings are realized.

If a corporation owns more than one plant, energy management can be more complex than just considering the needs of a single one. A corporate energy management program helps to ensure energy efficiency is achieved across the company's plants. Whether for a single plant or for an entire corporation, establishing a strong organizational energy management framework is important to implement energy efficiency measures effectively.

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 2 lists the technologies and measures that were considered in this analysis.

Table 2. Energy-Efficient Practices and Technologies in Cement Production.

Raw Materials Preparation	
Efficient transport systems (dry process) Slurry blending and homogenization (wet process) Raw meal blending systems (dry process) Conversion to closed circuit wash mill (wet process) High-efficiency roller mills (dry process) High-efficiency classifiers (dry process) Fuel Preparation: Roller mills	
Clinker Production (Wet)	Clinker Production (Dry)
Energy management and process control Seal replacement Kiln combustion system improvements Kiln shell heat loss reduction Use of waste fuels Conversion to modern grate cooler Refractories Optimize grate coolers Conversion to pre-heater, pre-calciner kilns Conversion to semi-dry kiln (slurry drier) Conversion to semi-wet kiln Efficient kiln drives Oxygen enrichment	Energy management and process control Seal replacement Kiln combustion system improvements Kiln shell heat loss reduction Use of waste fuels Conversion to modern grate cooler Refractories Heat recovery for power generation Low pressure drop cyclones for suspension pre-heaters Optimize grate coolers Addition of pre-calciner to pre-heater kiln Long dry kiln conversion to multi-stage pre-heater kiln Long dry kiln conversion to multi-stage pre-heater, pre-calciner kiln Efficient kiln drives Oxygen enrichment
Finish Grinding	
Energy management and process control Improved grinding media (ball mills) High-pressure roller press High efficiency classifiers	
General Measures	
Preventative maintenance (insulation, compressed air system, maintenance) High efficiency motors Efficient fans with variable speed drives Optimization of compressed air systems Efficient lighting	
Product & Feedstock Changes	
Blended Cements Limestone cement Low Alkali cement Use of steel slag in kiln (CemStar®) Reducing fineness of cement for selected uses	

Not all measures in Table 2 will apply to all plants. Applicability will depend on the current and future situation in individual plants. For example, expansion and large capital projects are likely to be implemented only if the company has about 50 years of remaining limestone reserves onsite. Plants that have a shorter remaining supply are unlikely to implement large capital projects, and would rather focus on minor upgrades and energy management measures.

Although technological changes in equipment can help to reduce energy use, changes in staff behavior and attitude may have a greater impact. Staff should be trained in both skills and the company's general

approach to energy efficiency in their day-to-day practices. Personnel at all levels should be aware of energy use and objectives for energy efficiency improvement. Often this information is acquired by lower level managers but not passed to upper management or down to staff (Caffal, 1995). Programs with regular feedback on staff behavior, such as reward systems, have had the best results. Though changes in staff behavior, such as switching off lights or closing windows and doors, often save only small amounts of energy at one time, taken continuously over longer periods they may have a much greater effect than more costly technological improvements. Most importantly, companies need to institute strong energy management programs that oversee energy efficiency improvement across the corporation. An energy management program will see to it that all employees actively contribute to energy efficiency improvements.

Participation in voluntary programs like EPA's ENERGY STAR program, or implementing an environmental management system such as ISO 14001 can help companies track energy and implement energy efficiency measures. One ENERGY STAR partner noted that combining the energy management programs with the ISO 14001 program has had the largest effect on saving energy at their plants.

6.1 Energy Management Systems and Programs

Improving energy efficiency should be approached from several directions. A strong, corporate-wide energy management program is essential. Crosscutting equipment and technologies such as compressed air and motors, common to most plants and manufacturing industries, including cement, present well-documented opportunities for improvement. Equally important, the production process can be fine-tuned to produce even greater savings. Below are some measures concerning these and other general crosscutting utilities that apply to the cement industry.

Energy management programs. Changing how energy is managed by implementing an organization-wide energy management program is one of the most successful and cost-effective ways to bring about energy efficiency improvements.

An energy management program creates a foundation for positive change and provides guidance for managing energy throughout an organization. In companies without a clear program in place, opportunities for improvement may be known but may not be promoted or implemented because of organizational barriers. These barriers may include a lack of communication among plants, a poor understanding of how to create support for an energy efficiency project, limited finances, poor accountability for measures or perceived change from the status quo. Even when energy is a significant cost for an industry, many companies still lack a strong commitment to improve energy management.

The U.S. EPA, through ENERGY STAR, works with leading industrial manufacturers to identify the basic aspects of an effective energy management program.⁹ The major elements are depicted in Figure 9.

⁹ Read about strategic energy management at www.energystar.gov.

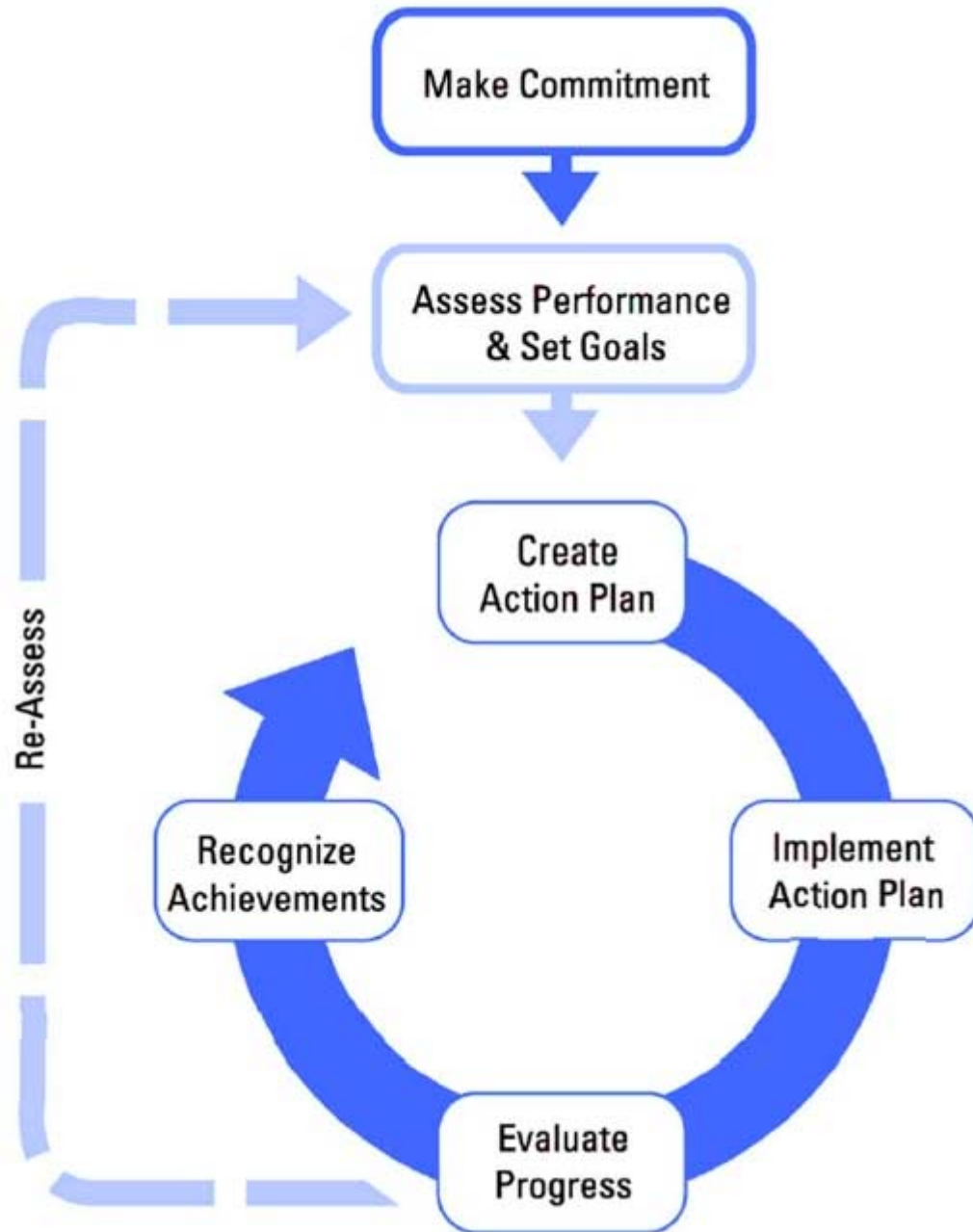


Figure 9: Main Elements of a Strategic Energy Management Program.

A successful program in energy management begins with a strong commitment to continuous improvement of energy efficiency. This involves assigning oversight and management duties to an energy director, establishing an energy policy, and creating a cross-functional energy team. Steps and procedures are then put in place to assess performance, through regular reviews of energy data, technical assessments and benchmarking. From this assessment, an organization is able to develop a baseline of energy use and set goals for improvement. Performance goals help to shape the development and implementation of an action plan. An important aspect for ensuring the successes of the action plan is involving personnel throughout the organization. Personnel at all levels should be aware of energy use and goals for efficiency. Staff should be trained in both skills and general approaches to energy efficiency in day-to-day practices.

In addition, performance results should be regularly evaluated and communicated to all personnel, recognizing high achievement. Some examples of simple tasks employees can do are outlined in Appendix A.

Evaluating performance involves the regular review of both energy use data and the activities carried out as part of the action plan. Information gathered during the formal review process helps in setting new performance goals and action plans and in revealing best practices. Establishing a strong communications program and seeking recognition for accomplishments are also critical steps. Strong communication and receiving recognition help to build support and momentum for future activities.

A quick assessment of an organization's efforts to manage energy can be made by comparing the current program against the table contained in Appendix B.

Support for a business energy management program can come from outside sources as well. Some utility companies work with industrial clients who work together to achieve energy savings. In these cases, utility personnel work directly with the company onsite.

Energy monitoring systems. The use of energy monitoring and process control systems can play an important role in energy management and in reducing energy use. These may include submetering, monitoring, and control systems. They can reduce the time required to perform complex tasks, often improve product and data quality and consistency, and optimize process operations. Typically, energy and cost savings are around 5% or more for many industrial applications of process control systems. These savings apply to plants without updated process control systems; many U.S. plants may already have modern process control systems in place to improve energy efficiency.

6.2 Raw Materials Preparation

Efficient Transport Systems (Dry Process). Transport systems are required to convey powdered materials such as kiln feed, kiln dust, and finished cement throughout the plant. These materials are usually transported by means of either pneumatic or mechanical conveyors. Mechanical conveyors use less power than pneumatic systems. Based on Holderbank, (1993) the average energy savings are estimated at 1.9 kWh/short ton raw material (2.0 kWh/tonne) with a switch to mechanical conveyor systems. Installation costs for the system are estimated at \$2.7/ton raw material production based on the Holderbank study (1993). Conversion to mechanical conveyors is cost-effective when replacement of conveyor systems is needed to increase reliability and reduce downtime.

Raw Meal Blending (Homogenizing) Systems (Dry Process). 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 completely homogenized. Quality control starts in the quarry and continues to the blending silo. On-line analyzers for raw mix control are an integral part of the quality control system (Fujimoto, 1993; Holderbank, 1993).

Most plants use compressed air to agitate the powdered meal in so-called air-fluidized homogenizing silos (using 1-1.4 kWh/ton raw meal). Older dry process plants use mechanical systems, which simultaneously withdraw material from 6-8 different silos at variable rates (Fujimoto, 1993), using 2-2.4 kWh/ton raw meal. Modern plants use gravity-type homogenizing silos (or continuous blending and storage silos) reducing power consumption. 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. 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 0.9-2.3 kWh/ton raw meal (Fujimoto, 1993; Holderbank, 1993; Alsop & Post, 1995; Cembureau, 1997; Gerbec, 1999). Costs for the silo retrofit are estimated at \$3.3/ton raw material (assuming \$550K per silo and an average capacity of 150,000 tonnes annual capacity).

Slurry Blending and Homogenizing (Wet Process). In the wet process the slurry is blended and homogenized in a batch process. The mixing is done using compressed air and rotating stirrers. The use of compressed air may lead to relatively high energy losses because of its poor efficiency. An efficiently run mixing system may use 0.3 – 0.5 kWh/ton raw material (Cembureau, 1997). The main energy efficiency improvement measures for slurry blending systems are found in the compressed air system (see below under plant-wide measures).

Wash Mills with Closed Circuit Classifier (Wet Process). In most wet process kilns, tube mills are used in combination with closed or open circuit classifiers. An efficient tube mill system consumes about 13 kWh/ton (Cembureau, 1997). Replacing the tube mill by a wash mill would reduce electricity consumption to 5-7 kWh/ton (Cembureau, 1997) at comparable investment and operation costs as a tube mill system. When replacing a tube mill a wash mill should be considered as an alternative, reducing electricity consumption for raw grinding by 5-7 kWh/ton, or 40-60%.

Use of Roller Mills (Dry Process). 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. Energy savings of 6-7 kWh/t raw materials (Cembureau, 1997) are assumed through the installation of a vertical or horizontal roller mill. An additional advantage of the inline vertical roller mills is that they can combine raw material drying with the grinding process by using large quantities of low grade waste heat from the kilns or clinker coolers (Venkateswaran and Lowitt, 1988). Various roller mill process designs are marketed.

In 1998, Arizona Portland cement (Rillito, Arizona) installed a roller mill for raw material grinding increasing throughput, flexibility, raw meal fineness and reducing electricity consumption (De Hayes, 1999). In North America, LBNL estimates that over 20% of raw grinding capacity is using roller mills (Holderbank, 1993). The investments are estimated at \$5.0/ton raw material (Holderbank, 1993).

Raw Meal Process Control (Dry process - Vertical Mill). The main difficulty with existing vertical roller mills are vibration trips. Operation at high throughput makes manual vibration control difficult. When the raw mill trips, it cannot be started up for one hour, until the motor windings cool. A model predictive multivariable controller maximizes total feed while maintaining a target residue and enforcing a safe range for trip-level vibration. The first application eliminated avoidable vibration trips (which were 12 per month prior to the control project). The cited increase in throughput was 6% with a corresponding reduction in specific energy consumption of 6% (Martin and McGarel, 2001b), or 0.8 – 1.0 kWh/ton of raw material (based on Cembureau, 1997).

High-efficiency Classifiers/Separators. 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. High efficiency classifiers can be used in both the raw materials mill and in the finish grinding mill.

Standard classifiers may have a low separation efficiency, which leads to the recycling of fine particles, and results in 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).

In 1990, Tilbury Cement (Delta, British Columbia, Canada) modified a vertical roller mill with a high-efficiency classifier increasing throughput and decreasing electricity use (Salzborn and Chin-Fatt, 1993). Case studies have shown a reduction of 2.5-3.4 kWh/ton raw material (Salzborn and Chin-Fatt, 1993; Süsssegger, 1993). 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. The better size distribution of the raw meal may lead to fuel savings in the kiln and improved clinker quality. Investment costs are estimated at \$2/annual ton raw material production based on the Holderbank study (Holderbank, 1993).

6.3 Fuel Preparation

Coal is the most widely used fuel in the cement industry. Fuels preparation is most often performed on-site. Fuels preparation may include crushing, grinding and drying of coal. Coal is shipped “wet” to prevent dust formation and fire during transport. Passing hot gasses through the mill combines the grinding and drying. Coal is the most used fuel in the cement industry, and the main fuel for the vast majority of clinker kilns in the U.S. Most commonly a Raymond bowl mill or a roller mill is used for coal grinding. An impact mill would consume around 45-60 kWh/ton and a tube mill around 25 – 26 kWh/ton (total system requirements) (Cembureau, 1997). Waste heat of the kiln system (e.g. the clinker cooler) is used to dry the coal if needed.

Other advantages of a roller mill are that it is able to handle larger sizes of coal (no pre-crushing needed) and coal types with a higher humidity, and can manage larger variations in throughput. However, tube mills are preferred for more abrasive coal types. Currently, roller mills are the most common coal mills in the U.S. cement industry. Coal roller mills are available for throughputs of 5 to 200 tons/hour. Lehigh Portland Cement installed a vertical roller mill for coal grinding in 1999 at the Union Bridge, Maryland plant. Blue Circle cement has ordered a vertical roller mill for the new kiln line V at the Roberta plant in Calera, Alabama. It has a capacity of 37.5 ton/hour and was commissioned in early 2001. Outside the US, coal grinding roller mills can be found in many countries around the world, e.g. Brazil, Canada, China, Denmark, Germany, Japan and Thailand. All major suppliers of cement technology offer roller mills for coal grinding.

Vertical roller mills have been developed for coal grinding, and are used by over 100 plants around the world (Cembureau, 1997). Electricity consumption for a vertical roller mill is estimated at 16-18 kWh/ton coal (Cembureau, 1997). The investment costs for a roller mill are typically higher than that of a tube mill or an impact mill, but the operation costs are also lower; roughly 20% compared to a tube mill and over 50% compared to an impact mill (Cembureau, 1997), estimating savings at 7-10 kWh/ton coal.

Roller Press for Coal Grinding. Roller presses, like those used for cement and raw material grinding, are generally more efficient than conventional grinding mills. Roller presses can be used to grind raw materials and coal interchangeably, although coal-grinding equipment needs special protection against explosions. Penetration of roller presses is still relatively low in the U.S.

6.4 Clinker Production – All Kilns

Process Control & Management Systems - Kilns. 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 and grindability, 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, or rule-based control strategies. Expert control systems do not use a modeled process to control process conditions, but try to simulate the best human operator, using information from various stages in the process.

One such system, called ABB 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. Other developers also market 'fuzzy logic' control systems, e.g., F.L. Smidth (Denmark) Krupp Polysius (Germany) and Mitsui Mining (Japan).

All report typical energy savings of 3-8%, while improving productivity and availability. For example Krupp Polysius reports typical savings of 2.5 – 5%, with similar increased throughput and increased refractory life of 25 –100%. Ash Grove implemented a fuzzy control system at the Durkee (OR) plant in 1999.

An alternative to expert systems or fuzzy logic is model-predictive control using dynamic models of the processes in the kiln. A model predictive control system was installed at a kiln in South Africa in 1999, reducing energy needs by 4%, while increasing productivity and clinker quality. The payback period of this project is estimated at 8 months, even with typically very low coal prices in South Africa (Martin & McGarel, 2001).

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 allowing for immediate changes in the blend of raw materials. A uniform feed allows for more steady kiln operation, thereby saving ultimately on fuel requirements. Blue Circle's St. Marys plant (Canada) installed an on-line analyzer in 1999 in its precalciner kiln, and achieved better process management as well as fuel savings.

Energy savings from 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%. 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 (U.K.) needed an investment of £203,000 (1987), equivalent to \$0.3/annual tonne clinker (ETSU, 1988), including measuring instruments, computer hardware and training. Holderbank (1993) notes an installation cost for on-line analyzers of \$0.7-1.5/annual ton clinker. A payback period of 2 years or less is typical for kiln control systems, while often much lower payback periods are achieved (ETSU, 1988; Martin and McGarel, 2001).

Process control of the clinker cooler can help to improve heat recovery, material throughput, improved control of free lime content in the clinker and reduce NO_x emissions (Martin et al., 2000). Installing a Process Perfecter[®] (of Pavilion Technologies Inc.) has increased cooler throughput by 10%, reduced free lime by 30% and reduced energy by 5%, while reducing NO_x emissions by 20% (Martin et al.,

1999; Martin et al., 2001). The installation costs equal \$0.32/annual ton of clinker, with an estimated payback period of 1 year (Martin et al., 2001).

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). Improved combustion systems aim to optimise the shape of the flame, the mixing of combustion air and fuel and reducing the use of excess air. Various approaches have been developed. One technique developed in the U.K. for 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 reducing NO_x emissions. Originally developed at the University of Adelaide (Australia), the Gyro-Therm technology can be applied to gas burners or gas/coal dual fuel. The Gyro-Therm burner uses a patented "precessing jet" technology. The nozzle design produces a gas jet leaving the burner in a gyroscopic-like precessing motion. This stirring action produces rapid large scale mixing in which pockets of air are engulfed within the fuel envelope without using high velocity gas or air jets. The combustion takes place in pockets within the fuel envelope under fuel rich conditions. This creates a highly luminous flame, ensuring good radiative heat transfer. 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, Oregon) found fuel savings between 2.7% and 5.7% with increases in output between 5 and 9% (CADDET, 1998; Vidergar and Rapson, 1997). Costs for the technology vary by installation. An average cost of \$0.9/annual ton clinker capacity is assumed based on reported costs in the demonstration projects.

Indirect Firing. Historically the most common firing system is the direct-fired system. Coal is dried, pulverized and classified in a continuous system, and fed directly to the kiln. This can lead to high levels of primary air (up to 40% of stoichiometric). These high levels of primary air limit the amount of secondary air introduced to the kiln from the clinker cooler. Primary air percentages vary widely, and non-optimized matching can cause severe operational problems with regard to creating reducing conditions on the kiln wall and clinker, refractory wear and reduced efficiency due to having to run at high excess air levels to ensure effective burnout of the fuel within the kiln.

In more modern cement plants, indirect fired systems are most commonly used. In these systems, neither primary air nor coal is fed directly to the kiln. All moisture from coal drying is vented to the atmosphere and the pulverized coal is transported to storage via cyclone or bag filters. Pulverized coal is then densely conveyed to the burner with a small amount of primary transport air (Smart and Jenkins, 2000). As the primary air supply is decoupled from the coal mill in multi-channel designs, lower primary air percentages are used, normally between 5 and 10%. The multi-channel arrangement also allows for a degree of flame optimization. This is an important feature if a range of fuels is fired. Input conditions to the multi-channel burner must be optimized to secondary air and kiln aerodynamics for optimum operation (Smart and Jenkins, 2000). The optimization of the combustion conditions will lead to reduced NO_x emissions, better operation with varying fuel mixtures, and reduced energy losses. This technology is standard for modern plants. The majority of U.S. plants have indirect firing systems.

Excess air infiltration is estimated to result in heat losses equal to 65 kBtu/ton (75 MJ/tonne). Assuming a reduction of excess air between 20% and 30% may lead to fuel savings of 130 – 190 kBtu/ton of

clinker. The advantages of improved combustion conditions will lead to a longer lifetime of the kiln refractories and reduced NO_x emissions. These co-benefits may result in larger cost savings than the energy savings alone.

The disadvantage of an indirect firing system is the additional capital cost. In 1997 California Portland's plant in Colton (California) implemented an indirect firing system for their plant, resulting in NO_x emission reductions of 30-50%, using a mix of fuels including tires. The investment costs of the indirect firing system were \$5 Million for an annual production capacity of 680,000 tonnes.

Oxygen Enrichment. Several plants in the U.S. have experimented with the use of oxygen enrichment in the kiln to increase production capacity. Several plants use it to increase production if the local market demand for cement can justify the additional costs for oxygen purchase or production. Experience exists with wet (e.g. TXI, Midlothian, Texas) and dry process kilns (e.g. CPC, Mojave, California; Cemex, Victorville, California). Production increases of around 3-7% have been found on the basis of annual production (Mayes, 2001; Gotro, 2001). Although some authors claim fuel savings due to oxygen enrichment (Leger and Friday, 2001), others do not report net energy savings (Shafer, 2001; Gotro, 2001). Any energy savings will depend on the electricity consumed for oxygen generation (approximately 0.01 kWh/scf) (Shafer, 2001). Oxygen enrichment may result in higher NO_x emissions, if the injection process is not carefully managed (Mayes, 2001). Oxygen enrichment is unlikely to result in net energy savings.

Seals. Seals are used at the kiln inlet and outlet to reduce false air penetration, as well as heat losses. Seals may start leaking, increasing the heat requirement of the kiln. Most often pneumatic and lamella-type seals are used, although other designs are available (e.g. spring-type). Although seals can last up to 10,000 to 20,000 hours, regular inspection may be needed to reduce leaks. Energy losses resulting from leaking seals may vary, but are generally relatively small. Philips Kiln Services reports that upgrading the inlet pneumatic seals at a relatively modern plant in India (Maihar cement), reduced fuel consumption in the kiln by 0.4% (or 0.01 MBtu/ton clinker) (Philips Kiln Services, 2001). The payback period for improved maintenance of kiln seals is estimated at 6 months or less (Canadian Lime Institute, 2001).

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). Refractory choice is the function of insulating qualities of the brick and the ability to develop and maintain a coating. The coating helps to reduce heat losses and to protect the burning zone refractory bricks. Estimates suggest that the development of high-temperature insulating linings for the kiln refractories can reduce fuel use by 0.1-0.34 MBtu/ton (Lowe, 1990; COWIconsult, 1993; Venkateswaran and Lowitt, 1988). Costs for insulation systems are estimated to be \$0.23/annual ton clinker capacity (Lesnikoff, 1999). Structural considerations may limit the use of new insulation materials. The use of improved kiln-refractories may also lead to improved reliability of the kiln and reduced downtime, reducing production costs considerably, and reducing energy needs during start-ups.

Refractories. Refractories protect the steel kiln shell against heat, chemical and mechanical stress. The choice of refractory material depends on the combination of raw materials, fuels and operating conditions. Extended lifetime of the refractories will lead to longer operating periods and reduced lost production time between relining of the kiln, and, hence, offset the costs of higher quality refractories (Schmidt, 1998; van Oss, 2002). It will also lead to additional energy savings due to the relative reduction in start-up time and energy costs. The energy savings are difficult to quantify, as they will strongly depend on the current lining choice and management.

Kiln Drives. A substantial amount of power is used to rotate the kiln. In the U.S. mostly synchronous motors are used (Regitz, 1996) up to 1,000 hp. The highest efficiencies are achieved using a single

pinion drive with an air clutch and a synchronous motor (Regitz, 1996). The system would reduce power use for kiln drives by a few percent, or roughly 0.5 kWh/ton clinker at slightly higher capital costs (+6%).

More recently, the use of AC motors is advocated to replace the traditionally used DC drive. The AC motor system may result in slightly higher efficiencies (0.5 – 1% reduction in electricity use of the kiln drive) and has lower investment costs (Holland, 2001). Using high-efficiency motors to replace older motors or instead of re-winding old motors may reduce power costs by 2 to 8% (see below).

Adjustable Speed Drive for Kiln Fan. Adjustable or variable speed drives (ASDs) for the kiln fan result in reduced power use and reduced maintenance costs. The use of ASDs for a kiln fan at the Hidalgo plant of Cruz Azul Cement in Mexico resulted in improved operation, reliability and a reduction in electricity consumption of almost 40% (Dolores and Moran, 2001) of the 1,000 hp motors. The replacement of the damper by an ASD was driven by control and maintenance problems at the plant. The energy savings may not be typical for all plants, as the system arrangement of the fans was different from typical kiln arrangements. For example, Fujimoto, (1994) notes that Lafarge Canada's Woodstock plant replaced their kiln fans with ASDs and reduced electricity use by 5 kWh/ton (see also section 6.7).

Use of Waste-Derived Fuels. Waste fuels can be substituted for traditional commercial fuels in the kiln. The U.S. cement industry is increasingly using waste fuels (see above). In 1999 tires accounted for almost 5% of total fuel inputs in the industry, while all wastes total about 17% of all fuel inputs. The trend towards increased waste use will likely increase after successful tests with different wastes in Europe and North America. New waste streams include carpet and plastic wastes, filter cake, paint residue and (dewatered) sewage sludge (Hendriks et al., 1999). Cement kilns also use hazardous wastes. Since the early 1990's cement kilns burn annually almost 1 million tons of hazardous waste (CKRC, 2002). The revenues from waste intake have helped to reduce the production costs of all waste-burning cement kilns, and especially of wet process kilns. Waste-derived fuels may replace the use of commercial fuels, and may result in net energy savings and reduced CO₂ emissions, depending on the alternative use of the wastes (e.g. incineration with or without energy recovery).

A cement kiln is an efficient way to recover energy from waste. 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). The high temperatures and long residence times in the kiln destroy virtually all organic compounds, while efficient dust filters may reduce any potential emissions to safe levels (Hendriks et al., 1999; Cembureau, 1997).

Our analysis focuses on the use of tires or tire-derived fuel. Since 1990 more than 30 cement plants have gained approval to use tire-derived fuels, burning around 35 million tires per year (CKRC, 2002). 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 0.5 MBtu/ton clinker. Costs for the installation of the Joliette system ran about \$3.40/annual ton clinker capacity. Costs for less complex systems where the tires are fed as input fuel are \$0.1-\$1/annual ton clinker. Other plants have experience injecting solid and fluid wastes, as well as ground plastic wastes. A net reduction in operating costs (CADDET, 1995; Gomes, 1990, Venkateswaran and Lowitt, 1988) is assumed. Investment costs are estimated at \$1/annual ton clinker for a storage facility for the waste-derived fuels and retrofit of the burner (if needed).

Conversion to Reciprocating Grate Cooler. Four main types of coolers are used in the cooling of clinker: shaft, rotary, planetary and travelling and reciprocating grate coolers. There are no longer any

rotary or shaft coolers in operation in North America. However, some travelling grate coolers may still be in operation. In the U.S., planetary and grate coolers are the coolers of choice. Cembureau (1997) 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.

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 temperature of the clinker leaving the cooler can be as low as 83°C, instead of 120-200°C, which is expected from planetary coolers (Vleuten, 1994)). Tertiary heat recovery (needed for pre-calciners) is impossible with planetary coolers (Cembureau, 1997), limiting heat recovery efficiency. Grate coolers recover more heat than do the other types of coolers. For large capacity plants, grate coolers are the preferred equipment. For plants producing less than 500 tonnes per day the grate cooler may be too expensive (COWIconsult et al., 1993). Replacement of planetary coolers by grate coolers is not uncommon (Alsop and Post, 1995). Grate coolers are standard technology for modern large-scale kilns.

Modern reciprocating coolers have a higher degree of heat recovery than older variants, increasing heat recovery efficiency to 65% or higher, while reducing fluctuations in recuperation efficiency (i.e. increasing productivity of the kiln). When compared to a planetary cooler, additional heat recovery is possible with grate coolers at an extra power consumption of approximately 2.7 kWh/ton 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). Cooler conversion is generally economically attractive only when installing a precalciner, which is necessary to produce the tertiary air (see above), or when expanding production capacity. The cost of a cooler conversion is estimated to be between \$0.4 and \$5/annual ton clinker capacity, depending on the degree of reconstruction needed. Annual operation costs increase by \$0.1/ton clinker (Jaccard and Willis, 1996).

Optimization of Heat Recovery/Upgrade Clinker Cooler. The clinker cooler drops the clinker temperature from 1200°C down to 100°C. The most common cooler designs are of the planetary (or satellite), traveling and reciprocating grate type. In the U.S. 94% of coolers in 1994 were grate coolers. All coolers heat the secondary air for the kiln combustion process and sometimes also tertiary air for the precalciner (Alsop and Post, 1995). Reciprocating 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 2200-5000 tpd) and planetary coolers (used for 10% of the world capacity for plants up to 3300-4400 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 1.1 and 1.4 MBtu/ton 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 0.04-0.07 MBtu/ton clinker through the improved operation of the grate cooler, while Holderbank, (1993) notes savings of 0.14 MBtu/ton clinker for retrofitting a grate cooler. COWIconsult et al. (1993) note savings of 0.07 MBtu/ton but an increase in electricity use of 1.8 kWh/ton. The costs of this measure are assumed to be half the costs of the replacement of the planetary to grate cooler, or \$0.2/annual ton clinker capacity.

A recent innovation in clinker coolers is the installation of a static grate section at the hot end of the clinker cooler. This has resulted in improved heat recovery and reduced maintenance of the cooler. Modification of the cooler would result in improved heat recovery rates of 2-5% over a conventional grate cooler. Investments are estimated at \$0.1 - \$0.3/annual ton clinker capacity (Young, 2002).

6.5 Clinker Production - Wet Process Kilns

Wet Process Conversion to Semi-Dry Process (Slurry Drier). In modernized wet kilns, a slurry drier can be added to dry the slurry before entering the kiln using waste heat from the kiln (Cembureau, 1997). This reduces energy consumption considerably and increases productivity. This is different from a semi-wet process as a gas drier is used instead of a slurry press filter. The drier can be combined with a hammer mill for a reliable and efficient disagglomeration and drying system (Grydgaard, 1998). Gas suspension driers are also considered, but no installation has been built yet (Grydgaard, 1998). Gas suspension driers could increase drying efficiency and potentially reduce fuel consumption in the kiln by up to 1.4 MBtu/ton clinker (Grydgaard, 1998). The principal of preheating/drying is similar to the semi-dry process (or Lepol kiln), although in the semi-dry process dry raw meal (10-12% water) is used instead of slurry (28-48% water). The Lepol kiln uses a traveling grate preheater, and uses dry raw material grinding, followed by a pelletizer that mixes water with the dry meal to form pellets that can be carried by the traveling grate into the rotary kiln. The size of the pellets also determines the size of clinker pellets. The energy needs for water evaporation in a wet process kiln are estimated at over 2 MBtu/ton clinker (Worrell et al., 2001). For comparison, a Lepol kiln consumes about a quarter of that for evaporation, while increasing electricity use by approximately 5-7 kWh/ton clinker (Cembureau, 1997). Evaporation energy needs can be cut in half by adding a slurry drier, reducing fuel consumption by 1 MBtu/ton clinker. Net energy savings are estimated at 0.95 MBtu/ton.

The first plant that coupled a drier directly to the kiln was put in operation in 1982 in Sutham, England (Grydgaard, 1998). The first plant in the U.S. to apply the semi-dry process is Lonestar's Greencastle, Indiana, plant, almost doubling its production capacity to 1.7 million tones per year (anon., 2001). No recent estimates of the costs of adding a slurry drier (including waste heat distribution) to an existing wet process kiln were available for this study.

Wet Process Conversion to Semi-Wet Process (Filter Press System). 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). In the U.S. several plants have tried slurry filters, but have not been very successful. Currently, there seem to be no plants in the U.S. using this technology (Young, 2002). Additional electricity consumption is 3-5 kWh/ton clinker (COWIconsult et al., 1993). In this analysis it is assumed that energy use increases by 4 kWh/ton clinker to reduce the moisture content to 20%. The corresponding fuel savings are 1.0 MBtu/ton (COWIconsult et al., 1993). Jaccard and Willis (1996) estimate the conversion cost to run \$1.6/annual ton clinker capacity with increased operation costs of \$0.1/ton clinker (Jaccard and Willis, 1996).

Wet Process Conversion to Pre-heater/Pre-calciner Kiln. If economically feasible a wet process kiln can be converted to a state-of-the art dry process production facility that includes either a multi-stage preheater, or a pre-heater/pre-calciner. Average specific fuel consumption in U.S. wet kilns is estimated at 6.0 MBtu/ton clinker. Studies of several kiln conversions in the U.S. in the 1980s found fuel savings of 2.9 MBtu/ton or less (Venkateswaran and Lowitt, 1988). In Hranice (Czech Republic) a 1,050 tonne per day wet process plant was converted to a dry kiln plant with a new kiln specific fuel consumption of 2.7 MBtu/ton clinker (Anon., 1994b). Fuel savings of 2.7 MBtu/ton clinker and an increase in power use of about 9 kWh/ton clinker (Vleuten, 1994) are assumed. 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/annual ton clinker capacity and \$100/annual ton clinker capacity (van Oss, 1999; Nisbet, 1996).

6.6 Clinker Production - Dry Process Preheater Kilns

Low Pressure Drop Cyclones for Suspension Preheaters. 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 exhaust gas fan system. Depending on the efficiency of the fan, 0.6-0.7 kWh/ton clinker can be saved for each 50 mm W.C. (water column) the pressure loss is reduced. For most older kilns this amounts to savings of 0.6-1.0 kWh/ton (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 saved 4 kWh/ton clinker (Fujimoto, 1994). Installation of the cyclones can be expensive, however, since it may often entail the rebuilding or the modification of the preheater tower, and the costs are very site specific. Also, new cyclone systems may increase overall dust loading and increase dust carryover from the preheater tower. However, if an inline raw mill follows it, the dust carryover problem becomes less of an issue. A cost of \$2.7/annual ton clinker is assumed for a low-pressure drop cyclone system.

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. Only in long-dry kilns is the temperature of the exhaust gas sufficiently high, to cost-effectively recover the heat through power generation.¹⁰ 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). This report focuses on the steam turbine system since these systems have been installed in many plants worldwide and have proven to be economic (Steinbliss, 1990; Jaccard and Willis, 1996; Neto, 1990). Heat recovery has limited application for plants with in-line raw mills, as the heat in the kiln exhaust is used for raw material drying. While electrical efficiencies are still relatively low (18%), based on several case studies power generation may vary between 10 and 23 kWh/ton clinker (Scheur & Sprung, 1990; Steinbliss, 1990; Neto, 1990). Electricity savings of 20 kWh/ton clinker are assumed. Jaccard and Willis (1996) estimate installation costs for such a system at \$2-4/annual ton clinker capacity with operating costs of \$0.2-0.3/ton clinker. The estimate of the investment costs by Jaccard and Willis (1996) may be on the low side, but found no other recent costs estimates. In 1999, 4 U.S. cement plants cogenerated 486 million kWh (USGS, 2001). 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 GWh.

Dry Process Conversion to Multi-Stage Preheater Kiln. Older dry kilns may only preheat in the chain section of the long kiln, or may have single- or two-stage preheater vessels. Especially, long dry kilns may not have any preheater vessels installed at all. This leads to a low efficiency in heat transfer and higher energy consumption. 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 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 have to be adapted 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.

¹⁰ Technically, organic rankine cycles or Kalina cycles (using a mixture of water and ammonia) can be used to recover low-temperature waste heat for power production, but this is currently not economically attractive, except for locations with high power costs.

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 3.5 MBtu/ton to 3.1 MBtu/ton clinker, while the capacity of the individual kilns was increased from 1650 to 2500 tpd (Duploux 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. Energy savings are estimated at 0.8 MBtu/ton clinker for the conversion which reflects the difference between the average dry kiln specific fuel consumption and that of a modern preheater kiln, based on a study of the Canadian cement industry (Holderbank, 1993). The study estimates the specific costs at \$36-37 US/annual ton capacity for conversion to a multi-stage preheater kiln while Vleuten, 1994 estimates a cost of \$25/annual ton clinker capacity for the installation of suspension pre-heaters.

Installation or Upgrading of a Preheater to a Preheater/Precalciner 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 and reducing thermal NO_x emissions (due to lower combustion temperatures in the pre-calciner). 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 are 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 1100 tpd to 2000-2200 tpd), while reducing specific fuel consumption from 3.06 to 2.63-2.74 MBtu/ton clinker, resulting in savings 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).

Older calciners can also be retrofitted for energy efficiency improvement and NO_x emission reduction. Retrofitting the pre-calciner at the Lengerich plant of Dyckerhoff Zement (Germany) in 1998 reduced NO_x emissions by almost 45% (Mathée, 1999). Similar emission reductions have been found at kilns in Germany, Italy and Switzerland (Menzel, 1997). Ash Grove's Durkee, Oregon original 1979 plant installed new preheaters and a precalciner in 1998, expanding production from 1700 tons/day to 2700 tons/day (Hrizuk, 1999). The reconstruction reduced fuel consumption by 0.14 – 0.6 MBtu/ton clinker (Hrizuk, 1999), while reducing NO_x emissions. Capitol Cement (San Antonio, Texas) replaced an older in-line calciner with a new downdraft calciner to improve production capacity. This was part of a larger project replacing preheaters, installing SO_x emission reduction equipment, as well as increasing capacity of a roller mill. The new plant was successfully commissioned in 1999. Fuel consumption at Capitol Cement was reduced to 2.89 MBtu/ton of clinker (Fraily & Happ, 2001).

Average savings of new calciners can be 0.34 MBtu/ton clinker (Sauli, 1993). Sauli (1993) does not outline the investments made for the conversion project. Vleuten (1994) estimates the cost of adding a precalciner and suspension preheaters at \$28 US/annual tonne annual capacity (it is not clear what is included in this estimate). Jaccard and Willis (1996) estimate a much lower cost of \$8.5/ton clinker capacity. This report assumes a cost of \$15/annual ton clinker. The increased production capacity is likely to save considerably in operating costs, estimated at \$1 /ton (Jaccard & Willis, 1996).

Conversion of Long Dry Kilns to Preheater/Precalciner Kiln. If economically feasible a long dry kiln can be upgraded to the current state of the art multi-stage preheater/precalciner kiln. Energy savings are estimated at 1.2 MBtu/ton clinker for the conversion. These savings reflect the difference

between the average dry kiln specific fuel consumption and that of a modern preheater, pre-calciner kiln 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 \$21-26/ton clinker for a pre-heater, pre-calciner kiln. Jaccard and Willis (1996) give a much lower value of \$8.6/t clinker capacity. A cost of \$25/annual ton clinker capacity is assumed.

6.7 Finish Grinding

Process Control and Management – Grinding Mills. Control systems for grinding operations are developed using the same approaches as for kilns (see above). The systems control the flow in the mill and classifiers, attaining a stable and high quality product. Several systems are marketed by a number of manufacturers. Expert systems have been commercially available since the early 1990's. The Karlstadt plant of Schwenk KG (Germany) implemented an expert system in a finishing mill in 1992, increasing mill throughput and saving energy. The payback is estimated between 1.5 and 2 years in Germany (Albert, 1993). Magotteaux (Belgium) has marketed a control system for mills since 1998 and has sold six units to plants in Germany (Rohrdorfer Zement), Greece (Heracles General Cement), SouthAfrica (PPC Group) and the United Kingdom (UK) (Rugby Group). Experience with a cement mill at the South Ferriby plant of the Rugby Group in the UK showed increased production (+3.3%) and power savings equal to 3%, while the standard deviation in fineness went down as well (Van den Broeck, 1999). Krupp Polysius markets the PolExpert system and reports energy savings between 2.5 and 10% (typically 8%), with increased product quality (lower deviation) and production increases of 2.5 –10%, after installing control systems in finishing mills (Goebel, 2001). Similar results have been achieved with model predictive control (using neural networks) for a cement ball mill at a South-African cement plant (Martin and McGarel, 2001). Pavilion Technologies (US) has developed a new control system using neural networks. Pavilion Technologies reports a 4-6% throughput increase (and corresponding reduction in specific power consumption) for installing a model predictive control system in finish ball mill (Martin et al., 2001). Payback periods are typically between 6 and 8 months (Martin and McGarel, 2001). Penetration of advanced control systems for cement mills in the U.S. is still relatively low. For example, Krupp Polysius has not sold any PolExpert systems in the U.S. despite worldwide sales (Goebel, 2001).

Advanced Grinding Concepts. The energy efficiency of ball mills for use in finish grinding is relatively low, consuming up to 30-42 kWh/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 20-30 kWh/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 roller press, two rollers pressurize the material up to 3,500 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 23 kWh/ton 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 21

kWh/ton (Buzzi,1997) and even for pozzolanic cement with a Blaine of 4000, power use may be as low as 25 kWh/ton (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 (Duploux and Trautwein,1997). New designs of the roller mills allow for longer operation times (> 20,000 hours). The electricity savings of a new finish grinding mill when replacing a ball mill is estimated at 25 kWh/ton cement. The addition of a pre-grinding system to a ball mill will result in savings of 6-22 kWh/ton cement for (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 \$2.3/annual ton cement capacity (Holderbank, 1993) or \$3.3/annual ton cement capacity (Kreisberg, 1993) to high estimates of \$7.3/annual ton cement capacity (COWIconsult *et al.*, 1993). The costs are estimated at approximately \$4/annual ton 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). In 1994 only 8% of cement grinding capacity had installed roller presses.

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, resulting in extra power use in the grinding mill. In high-efficiency classifiers, the material is more cleanly separated, thus reducing over-grinding. High efficiency classifiers or separators have had the greatest impact on improved product quality and reducing electricity consumption.

A study of the use of high efficiency classifiers in Great Britain found a reduction in electricity use of 6 kWh/ton cement 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/ton cement) while other studies estimate 1.7-2.3 kWh/ton cement (Salborn and Chin-Fatt, 1993; Sussegger, 1993). Newer designs of high-efficiency separators aim to improve the separation efficiency further and reduce the required volume of air (hence reducing power use), while optimizing the design. All major suppliers market new classifier designs, e.g. Polysius (SEPOL), F.L.Smith/Fuller and Magotteaux (Sturtevant SD). The actual savings will vary by plant and cement type and fineness required. For example, the electricity savings from installing a new high-efficiency classifier at a cement plant in Origny-Rochefort (France) varied between 0 and 5 kWh/ton (Van den Broeck, 1998), and investment costs of \$2/annual ton finished material based on the Holderbank study (Holderbank, 1993).

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 ball charge distribution 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 include the use of improved liner designs, such as grooved classifying liners. These have the potential to reduce grinding energy use by 5-10% in some mills, which is equivalent to estimated savings of 1.8 kWh/ton cement (Venkateswaran and Lowitt, 1988).

6.8 Plant-Wide Measures

Preventative Maintenance. Preventative maintenance includes training personnel to be attentive to energy consumption and efficiency. Successful programs have been launched in a variety of industries (Caffal, 1995; Nelson, 1994). While many processes in cement production are primarily automated, there still are opportunities, requiring minimal training of employees, to increase energy savings. Also, preventative maintenance (e.g. for the kiln refractory) can also increase a plant's utilization ratio, since it has less downtime 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 or 0.04 MBtu/ton. This is used as the estimate of fuel savings. Lang (1994) notes a reduction of up to 5 kWh for various preventative maintenance and process control measures (typically around 3 kWh/ton). Based on similar programs in other industries, annual and start up costs for implementing this training are estimated to be minimal and would be paid back in less than one year. For preventative maintenance of compressed air systems see below.

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. Based on an analysis of motors in the U.S. Department of Energy's MotorMaster+ software, and a breakdown of motors in a 5,000 tpd cement plant given in Bosche (1993), it is assumed that high-efficiency motors replace existing motors in all plant fan systems with an average cost of \$0.2/annual ton cement capacity.

Adjustable or Variable 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). Decreasing throttling can reduce energy losses in the system 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. For example, Blue Circle's Bowmanville plant (Canada) installed a variable air inlet fan, reducing electricity and fuel use in the kiln (because of reduced inlet air volume), saving C\$75,000/year in energy costs (approximately \$47,000 in U.S. dollars) (CIPEC, 2001). One case study for a modern cement plant estimated potential application for 44% of the installed motor power capacity in the plant (Bösche, 1993). ASDs for clinker cooler fans have a low payback, even when energy savings are the only reason for installing ASDs (Holderbank, 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). In practice savings of 70% are unrealistic (Young, 2002). Fujimoto, (1994) notes that

Lafarge Canada's Woodstock plant replaced their kiln ID fans with ASDs and reduced electricity use by 5 kWh/ton. It is estimated the potential savings are at 15% for 44% of the installed power, or roughly equivalent to 7 kWh/ton 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), can be estimated at roughly 0.8-0.9 \$/annual ton cement capacity. Other estimates vary between \$0.4 and \$2.7/annual ton cement (Holland and Ranze, 1997; Holderbank, 1993).

Compressed Air Systems. Compressed air systems are used in different parts of the plants, i.e. mixing of slurry (in wet process plants) and in the baghouse Pulse-Jet or Plenum Pulse dust collector filters and other parts. Total energy consumption by compressed air systems is relatively small in cement plants, however, it can amount to a considerable expense if the systems run continuously and end-uses are offline. Still, energy efficiency improvement measures may be found in these systems. Compressed air is probably the most expensive form of energy available in a plant because of its poor efficiency. Typically overall efficiency is around 10% for compressed air (LBNL *et al.*, 1998). Because of this inefficiency, if compressed air is used, it should be of minimum quantity for the shortest possible time, constantly monitored and weighed against alternatives.

Maintenance of Compressed Air Systems. Inadequate maintenance can lower compression efficiency and increase air leakage or pressure variability, as well as lead to increased operating temperatures, poor moisture control, and excessive contamination. Improved maintenance will reduce these problems and save energy. Proper maintenance includes the following (LBNL *et al.*, 1998):

- *Keep the compressor and intercooling surfaces clean and foul-free.* Blocked filters increase pressure drop. By inspecting and periodically cleaning filters, the pressure drop may be kept low. Seek filters with just a 1 psig pressure drop over 10 years. The payback for filter cleaning is usually under 2 years (Ingersoll-Rand, 2001). Fixing improperly operating filters will also prevent contaminants from entering into tools and causing them to wear out prematurely. Generally, when pressure drop exceeds 2 to 3 psig, replace the particulate and lubricant removal elements, and inspect all systems at least annually. Also, consider adding filters in parallel that decrease air velocity, and, therefore, decrease air pressure drop. A 2% reduction of annual energy consumption in compressed air systems is projected for more frequent filter changing (Radgen and Blaustein, 2001).
- *Keep motors properly lubricated and cleaned.* Poor motor cooling can increase motor temperature and winding resistance, shortening motor life, in addition to increasing energy consumption. Compressor lubricant should be changed every 2 to 18 months and checked to make sure it is at the proper level. In addition to energy savings, this can help avoid corrosion and degradation of the system.
- *Inspect drain traps* periodically to ensure they are not stuck in either the open or closed position and are clean. Some users leave automatic condensate traps partially open at all times to allow for constant draining. This practice wastes substantial energy and should never be undertaken. Instead, install simple pressure driven valves. Malfunctioning traps should be cleaned and repaired instead of left open. Some auto drains, such as float switch or electronic drains, do not waste air. Inspecting and maintaining drains typically has a payback of less than 2 years (Ingersoll-Rand, 2001).
- *Maintain the coolers* on the compressor to ensure that the dryer gets the lowest possible inlet temperature (Ingersoll-Rand, 2001).
- *Check belts for wear* and adjust them. A good rule of thumb is to adjust them every 400 hours of operation.
- *Replace air lubricant separators* according to specifications or sooner. Rotary screw compressors generally start with their air lubricant separators having a 2 to 3 psid pressure drop at full load. When this increases to 10 psid, change the separator (LBNL *et al.*, 1998).

- *Check water cooling systems* for water quality (pH and total dissolved solids), flow, and temperature. Clean and replace filters and heat exchangers per manufacturer's specifications.

Reduce Leaks. Leaks can be a significant source of wasted energy. A typical plant that has not been well maintained will likely have a leak rate equal to 20 to 50% of total compressed air production capacity (Ingersoll Rand, 2001; Price and Ross, 1989). Leak maintenance can reduce this number to less than 10%. Overall, a 20% reduction of annual energy consumption in compressed air systems is projected for fixing leaks (Radgen and Blaustein, 2001). Estimations of leaks vary with the size of the hole in the pipes or equipment. In addition to increased energy consumption, leaks can make air tools less efficient and adversely affect production, shorten the life of equipment, lead to additional maintenance requirements and increase unscheduled downtime. In the worst case, leaks can add unnecessary compressor capacity.

The most common areas for leaks are couplings, hoses, tubes, fittings, pressure regulators, open condensate traps and shut-off valves, pipe joints, disconnects, and thread sealants. A simple way to detect leaks is to apply soapy water to suspect areas. The best way to detect leaks is to use an ultrasonic acoustic detector, which can recognize the high frequency hissing sounds associated with air leaks. After identification, leaks should be tracked, repaired, and verified. Leak detection and correction programs should be ongoing efforts.

Reducing the Inlet Air Temperature. Reducing the inlet air temperature reduces energy used by the compressor. In many plants, it is possible to reduce inlet air temperature to the compressor by taking suction from outside the building. Importing fresh air can have paybacks of 2 to 5 years (CADDET, 1997b). As a rule of thumb, each 5°F (3°C) will save 1% compressor energy use (CADDET, 1997b; Parekh, 2000).

Maximize Allowable Pressure Dew Point at Air Intake. Choose the dryer that has the maximum allowable pressure dew point, and best efficiency. A rule of thumb is that desiccant dryers consume 7 to 14% of the total energy of the compressor, whereas refrigerated dryers consume 1 to 2% as much energy as the compressor (Ingersoll Rand, 2001). Consider using a dryer with a floating dew point.

Compressor Controls. The objective of any control strategy is to shut off unneeded compressors or delay bringing on additional compressors until needed. All units that are on should be running at full-load, except for one. Positioning of the control loop is also important; reducing and controlling the system pressure downstream of the primary receiver can result in energy consumption of up to 10% or more (LBNL, et al., 1998). Energy savings for sophisticated controls are 12% annually (Radgen and Blaustein, 2001). Start/stop, load/unload, throttling, multi-step, variable speed and network controls are options for compressor controls and described below.

Start/stop (on/off) is the simplest control available and can be applied to reciprocating or rotary screw compressors. For start/stop controls, the motor driving the compressor is turned on or off in response to the discharge pressure of the machine. They are used for applications with very low duty cycles. Applications with frequent cycling will cause the motor to overheat. Typical payback for start/stop controls is 1 to 2 years.

Load/unload control, or constant speed control, allows the motor to run continuously but unloads the compressor when the discharge pressure is adequate. In most cases, unloaded rotary screw compressors still consume 15 to 35% of full-load power while delivering no useful work (LBNL et al., 1998). Hence, load/unload controls can be inefficient.

Modulating or throttling controls allow the output of a compressor to be varied to meet flow requirements by closing down the inlet valve and restricting inlet air to the compressor. Throttling controls are applied

to centrifugal and rotary screw compressors. Changing the compressor control from on/zero/off to a variable speed control can save up to 8% per year (CADDET, 1997b).

Sizing Pipe Diameter Correctly. Inadequate pipe sizing can cause pressure losses, increase leaks and increase generating costs. Pipes must be sized correctly for optimal performance or resized to fit the current compressor system. Increasing pipe diameter typically reduces annual energy consumption by 3% (Radgen and Blaustein, 2001).

Heat Recovery for Water Preheating. As much as 80 to 93% of the electrical energy used by an industrial air compressor is converted into heat. In many cases, a heat recovery unit can recover 50 to 90% of this available thermal energy for space heating, industrial process heating, water heating, makeup air heating, boiler makeup water preheating, industrial drying, industrial cleaning processes, heat pumps, laundries or preheating aspirated air for oil burners (Parekh, 2000). It's been estimated that approximately 50,000 Btu/hour of energy is available for each 100 cfm of capacity (at full load) (LBNL et al., 1998). Paybacks are typically less than one year. Heat recovery for space heating is not as common with water-cooled compressors because an extra stage of heat exchange is required and the temperature of the available heat is lower. However, with large water cooled compressors, recovery efficiencies of 50 to 60% are typical (LBNL et al., 1998). Implementing this measure saves up to 20% of the energy used in compressed air systems annually for space heating (Radgen and Blaustein, 2001).

6.9 Lighting

Energy use for lighting in the cement industry is very small. Still, energy efficiency opportunities may be found that can reduce energy use cost-effectively. Lighting is used either to provide overall ambient lighting throughout the manufacturing, storage and office spaces or to provide low-bay and task lighting to specific areas. High-intensity discharge (HID) sources are used for the former, including metal halide, high-pressure sodium and mercury vapor lamps. Fluorescent, compact fluorescent (CFL) and incandescent lights are typically used for task lighting in offices.

Lighting Controls. Lights can be shut off during non-working hours by automatic controls, such as occupancy sensors which turn off lights when a space becomes unoccupied. Manual controls can also be used in addition to automatic controls to save additional energy in smaller areas. Payback of lighting control systems is generally less than 2 years.

Replace T-12 Tubes by T-8 Tubes. In industry, typically T-12 tubes have been used. T-12 refers to the diameter in 1/8 inch increments (T-12 means 12/8 inch or 3.8 cm diameter tubes). The initial output for these lights is high, but energy consumption is also high. They also have extremely poor efficacy, lamp life, lumen depreciation, and color rendering index. Because of this, maintenance and energy costs are high. Replacing T-12 lamps with T-8 lamps (smaller diameter) approximately doubles the efficacy of the former.

Replace Mercury Lights by Metal Halide or High Pressure Sodium Lights. Where color rendition is critical, metal halide lamps can replace mercury or fluorescent lamps with an energy savings of 50%. Where color rendition is not critical, high pressure sodium lamps offer energy savings of 50 to 60% compared to mercury lamps (Price and Ross, 1989).

Replace Metal Halide HID with High-Intensity Fluorescent Lights. Traditional HID lighting can be replaced with high-intensity fluorescent lighting. These new systems incorporate high-efficiency fluorescent lamps, electronic ballasts and high-efficacy fixtures that maximize output to the work plane. Advantages to the new system are many; they have lower energy consumption, lower lumen depreciation over the lifetime of the lamp, better dimming options, faster start-up and restrike capability, better color

rendition, higher pupil lumens ratings and less glare. (Martin, et al., 2000). High-intensity fluorescent systems yield 50% electricity savings over standard metal halide HID. Dimming controls that are impractical in the metal halide HIDs can also save significant energy. Retrofitted systems cost about \$185 per fixture, including installation costs (Martin, et al., 2000). In addition to energy savings and better lighting qualities, high-intensity fluorescents can help improve productivity and have reduced maintenance costs.

Replace Magnetic Ballasts with Electronic Ballasts. A ballast is a mechanism that regulates the amount of electricity required to start a lighting fixture and maintain a steady output of light. Electronic ballasts save 12-25 percent more power than their magnetic predecessors do (EPA, 2001).

6.10 Product & Feedstock Changes

Alkali Content. In North America, part of the production of the cement industry are cements with a low alkali content (probably around 20-50% of the market), a much higher share than found in many other countries (Holderbank, 1993). In some areas in the U.S., aggregate quality may be such that low-alkali cements are required by the cement company's customers. Reducing the alkali content is achieved by venting (called the by-pass) hot gases and particulates from the plant, loaded with alkali metals. The by-pass also avoids plugging in the preheaters. This becomes cement kiln dust (CKD). Disposal of CKD is regulated under the Resource Conservation and Recovery Act (RCRA). Many customers demand a lower alkali content, as it allows greater freedom in the choice of aggregates. The use of fly-ash or blast-furnace slags as aggregates (or in the production of blended cement, see below) may reduce the need for low-alkali cement. Low alkali cement production leads to higher energy consumption. Savings of 2-5 Kcal/kg per percent bypass are assumed (Alsop and Post, 1995). The lower figure is for precalciner kilns, while the higher figure is for preheater kilns. Typically, the bypass takes 10-70% of the kiln exhaust gases (Alsop and Post, 1995). Additionally, electricity is saved due to the increased cement production, as the CKD would otherwise end up as clinker. For illustrative purposes, assume a 20%-point reduction in bypass volume, resulting in energy savings of 0.16-0.4 MBtu/ton clinker. There are no investments involved in this product change, although cement users (e.g. ready-mix producers) may need to change the type of aggregates used (which may result in costs). Hence, this measure is most successfully implemented in coordination with ready-mix producers and other large cement users.

Blended Cements. The production of blended cements involves the intergrinding of clinker with one or more additives (fly ash, pozzolans, granulated blast furnace slag, silica fume, volcanic ash) in various proportions. The use of blended cements is a particularly 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 cement has been used for many decades and longer around the world.

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). Blended cement was introduced in the U.S. to reduce production costs for cement (especially energy costs), expand capacity without extensive capital costs, to reduce emissions from the kiln. In Europe a common standard has been developed for 25 types of cement (using different compositions for different applications). The European standard allows wider applications of additives. Many other countries around the world use blended cement. Blended cements demonstrate a higher long-term strength, as well as improved resistance to acids and sulfates, while using waste materials for high-value applications. Short-term strength (measured after less than 7 days) may be lower, although cement containing less than 30% additives will generally have setting times comparable to concrete based on portland cement.

In the U.S. the consumption and production of blended cement is still limited. In the U.S., the most prevalent blending materials are fly ash and granulated blast furnace slag. Not all slag and fly ash is suitable for cement production. It is estimated that 68% of the fly ash in the U.S. conforms to ASTM C618 (PCA, 1997). Currently, only a small part of the blast furnace slag is produced as granulated slag, while the majority is air-cooled. Air-cooled slag cannot be used for cement production, and is of lesser value. However, investments in slag processing by slag processors and cement companies will increase this fraction. ASTM Standards exist for different types of blended cements, i.e. C989 (slag cement), C595 and C1157. U.S. EPA (2000) has issued procurement guidelines to support the use of blended cement in (federal) construction projects.

A recent analysis of the U.S. situation cited an existing potential of producing 34 million tons 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 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 10.3 million tons. The reduction in clinker production corresponds to a specific fuel savings of 1.22 MBtu/ton. There is an increase in fuel use of 0.08 MBtu/ton for drying of the blast furnace slags but a corresponding energy savings of 0.17 MBtu/ton for reducing the need to use energy to bypass kiln exit gases to remove alkali-rich dust. Energy savings are estimated at 4-10 Btu/lb 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. In practice, bypass savings may be minimal to avoid plugging of the preheaters, requiring a minimum amount of bypass volume. This measure therefore results in total fuel savings of 1.21 MBtu/ton blended cement. Electricity consumption however is expected to increase due to the added electricity consumption associated with grinding blast furnace slag (as other materials are more or less fine enough).

The costs of applying additives in cement production may vary. Capital costs are limited to extra storage capacity for the additives. However, blast furnace slag may need to be dried before use in

cement production. This can be done in the grinding mill, using exhaust from the kiln, or supplemental firing, either from a gas turbine used to generate power or a supplemental air heater. The operational cost savings will depend on the purchase (including transport) costs of the additives¹¹, the increased electricity costs for (finer) grinding, the reduced fuel costs for clinker production and electricity costs for raw material grinding and kiln drives, as well as the reduced handling and mining costs. These costs will vary by location, and would need to be assessed on the basis of individual plants. An increase in electricity consumption of 15 kWh/ton (Buzzi, 1996) is estimated while an investment cost of \$0.65/ton cement capacity, which reflects the cost of new delivery and storage capacity (bin and weigh-feeder) is assumed.

Limestone Portland Cement. Similar to blended cement, ground limestone is interground with clinker to produce cement, reducing the needs for clinker-making and calcination. This reduces energy use in the kiln and clinker grinding and CO₂ emissions from calcination and energy use. Addition of up to 5% limestone has shown to have no negative impacts on the performance of portland cement, while an optimized limestone cement would improve the workability slightly (Detwiler and Tennis, 1996). Adding 5% limestone would reduce fuel consumption by 5% (or on average 0.3 MBtu/ton clinker), power consumption for grinding by 3.0 kWh/ton cement, and CO₂ emissions by almost 5%. Additional costs would be minimal, limited to material storage and distribution, while reducing kiln operation costs by 5%.

CemStar®. Texas Industries (Midlothian, Texas) in 1994 developed a system to use electric arc furnace (EAF) slags of the steel industry as input in the kiln, reducing the use of limestone. The slag that contains C₃S, which can more easily be converted to free lime than limestone. The slags replace limestone (approximately 1.6 times the weight in limestone). EAFs produce between 110 and 420 pounds of slag per ton of steel (on average 232 lbs/ton) (U.S. DOE-OIT, 1996). EAF steel production is estimated at almost 50 million tons (1999) (45.1 million tonnes). EAF-slag production is estimated at 5.8 million tons, potentially replacing an equal amount of clinker. The CemStar® process allows replacing 10-15% of the clinker by EAF-slugs, reducing energy needs for calcination. The advantage of the CemStar® process is the lack of grinding the slags, but adding them to the kiln in 2 inch lumps. Depending on the location of injection it may also save heating energy. Calcination energy is estimated at 1.6 MBtu/ton clinker (Worrell et al., 2001). Because the lime in the slag is already calcined, it also reduces CO₂ emissions from calcination, while the reduced combustion energy and lower flame temperatures lead to reduced NO_x emissions (Battye et al., 2000). For illustrative purposes alone, using a 10% injection of slags would reduce energy consumption by 0.16 MBtu/ton of clinker, while reducing CO₂ emissions by roughly 11%. Energy savings can be higher in wet kilns due to the reduced evaporation needs. Reductions in NO_x emissions vary by kiln type and may be between 9 and 60%, based on measurements at two kilns (Battye et al., 2000). Equipment costs are mainly for material handling and vary between \$200,000 and \$500,000 per installation. Total investments are approximately double the equipment costs. CemStar® charges a royalty fee (Battye et al., 2000). Costs savings consist of increased income from additional clinker produced without increased operation and energy costs, as well as reduced iron ore purchases (as the slag provides part of the iron needs in the clinker). The iron content needs to be balanced with other iron sources such as tires and iron ore. EPA awarded the CemStar® process special recognition in 1999 as part of the ClimateWise program.

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

¹¹ To avoid disclosing proprietary data, the USGS does not report separate value of shipments data for “cement-quality” fly ash or granulated blast furnace slag, making it impossible to estimate an average cost of the additives.

that energy savings could be achieved. The exact savings will depend on the grindability of the clinker. As a rule of thumb, for each 100 additional Blaine points, grinding power requirements increase by 5% (Holderbank, 1993). Holderbank (1993) reviewed 23 European and 20 North-American plants and found that the European plants use on average 14 kWh/ton less for cement grinding than the North-American plants. Note that finer cement may reduce the amount of concrete needed for a structure, due to the higher strength. It is hard to estimate the total savings due to the many factors affecting strength of concrete and grinding energy requirements. Also, without a detailed assessment of the market and applications of cement, it is difficult to estimate the total potential contribution of this measure to potential energy savings in the U.S. cement industry.

6.11 Advanced Technologies

In this section several advanced technologies for cement production are discussed. 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 vertical cylindrical vessel, 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 NO_x-emissions and a wider variety of the fuels that 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 U.S. 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 NO_x emissions were reduced to 1.7 lbs/ton clinker, compared to 4.6-5.8 lbs/ton for conventional plants due to lower combustion temperatures (Cohen, 1993). The future fuel consumption is estimated at 2.52-2.9 MBtu/ton 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 2.6-2.7 MBtu/ton 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. Mineral polymers can be made from inorganic aluminosilicate 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 aluminosilicates (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. CO₂ 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 CO₂ emissions. Research in this area is still ongoing. The manufacturing of mineral polymers is done at relatively low temperatures. The calcining of aluminosilicates occurs at temperatures of 1290°F (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).

7. Summary and Conclusions

The historic trends for energy efficiency in the U.S. cement industry and the cost-effective energy and carbon dioxide savings that can be achieved in the near future are analyzed in this report. The report focuses on the 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.

The cost of energy as part of the total production costs in the cement industry is significant, warranting attention for energy efficiency to improve the bottom line. Historically, energy intensity has been reducing, although more recently energy intensity seems to have stabilized with little improvement. Coal and coke are currently the primary fuels for the sector, supplanting the dominance of natural gas in the 1970s. Most recently, there is a slight increase in the use of waste fuels, including tires. Between 1970 and 1999, primary physical energy intensity for cement production dropped 1%/year from 7.3 MBtu/short ton to 5.3 MBtu/short ton. Carbon dioxide intensity due to fuel consumption and raw material calcination dropped 16%, from 609 lb. C/ton of cement (0.31 tC/tonne) to 510 lb. C/ton cement (0.26 tC/tonne).

Despite the historic progress, there is ample room for energy efficiency improvement. The relatively high share of wet-process plants (25% of clinker production in 1999) suggests the existence of a considerable potential, when compared to other industrialized countries.

Over 40 energy efficient technologies and measures and estimated energy savings, carbon dioxide savings, investment costs, and operation and maintenance costs for each of the measures were examined. In Tables 3 and 4, the efficiency measures and estimated savings for the dry and wet process plants respectively are summarized.

Substantial potential for energy efficiency improvement exist in the cement industry, and in individual plants. However, part of this potential may only be achieved as part of (natural) stock turnover and expansion of existing facilities. Still, a relatively large potential for improved energy management practices exists.

Table 3. Energy Efficiency Measures in Dry Process Cement Plants. The estimated savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant. More information can be found in the description of the measures above.

Energy Efficiency Measure	Specific Fuel Savings (MBtu/ton cement)	Specific Electricity Savings (kWh/ton cement)	Estimated Payback Period (1) (years)
Raw Materials Preparation			
Efficient Transport System	-	3.2	> 10 (1)
Raw Meal Blending	-	1.5 – 3.9	N/A (1)
Process Control Vertical Mill	-	0.8 – 1.0	1
High-Efficiency Roller Mill	-	10.2 – 11.9	> 10 (1)
High-Efficiency Classifiers	-	4.3 – 5.8	> 10 (1)
Fuel Preparation: Roller Mills	-	0.7 – 1.1	N/A (1)
Clinker Making			
Energy Management & Control Systems	0.10 – 0.20	1.2 – 2.6	1 – 3
Seal Replacement	0.02	-	< 1
Combustion System Improvement	0.10 – 0.39	-	2 – 3
Indirect Firing	0.13 – 0.19	-	N/A
Shell Heat Loss Reduction	0.09 – 0.31	-	1
Optimize Grate Cooler	0.06- 0.12	0 - -1.8	1 – 2
Conversion to Grate Cooler	0.23	-2.4	1 – 2
Heat Recovery for Power Generation	-	18	3
Low-pressure Drop Suspension Preheaters	-	0.5 – 3.5	> 10 (1)
Addition of Preclinker or Upgrade	0.12 – 0.54	-	5 (1)
Conversion of Long Dry Kiln to Preheater	0.36 – 0.73	-	> 10 (1)
Conversion of Long Dry Kiln to Preclinker	0.55 - 1.10	-	> 10 (1)
Efficient Mill Drives	-	0.8 – 3.2	1
Use of Secondary Fuels	> 0.5	-	1
Finish Grinding			
Energy Management & Process Control	-	1.6	< 1
Improved Grinding Media in Ball Mills	-	1.8	8 (1)
High Pressure Roller Press	-	7 – 25	> 10 (1)
High-Efficiency Classifiers	-	1.7 – 6.0	> 10 (1)
Plant Wide Measures			
Preventative Maintenance	0.04	0 – 5	< 1
High Efficiency Motors	-	0 – 5	< 1
Adjustable Speed Drives	-	5.5 – 7.0	2- 3
Optimization of Compressed Air Systems	-	0 – 2	< 3
Efficient Lighting	-	0 – 0.5	N/A
Product Change			
Blended Cement	1.21	-15	< 1
Limestone Portland Cement	0.30	3.0	< 1
Use of Steel Slag in Clinker (CemStar)	0.16	-	< 2
Low Alkali Cement	0.16 – 0.4	N/A	Immediate
Reduced Fineness of Cement for Selected Uses	-	0 – 14	Immediate

Notes:

(1) Payback periods are calculated on the basis of energy savings alone. In reality this investment may be driven by other considerations than energy efficiency (e.g. productivity, product quality), and will happen as part of the normal business cycle or expansion project. Under these conditions the measure will have a lower payback period depending on plant-specific conditions.

Table 4. Energy Efficiency Measures in Wet Process Cement Plants. The estimated savings and payback periods are averages for indication, based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio). The actual savings and payback period may vary by project based on the specific conditions in the individual plant. More information can be found in the description of the measures above.

Energy Efficiency Measure	Specific Fuel Savings (MBtu/ton cement)	Specific Electricity Savings (kWh/ton cement)	Estimated Payback Period (1) (years)
Raw Materials Preparation			
Slurry Blending and Homogenizing		0.1 – 0.6	< 3
Wash Mills with Closed Circuit Classifier	-	10 – 14	> 10 (1)
High-Efficiency Classifiers	-	4.3 – 5.8	> 10 (1)
Fuel Preparation: Roller Mills	-	0.7 – 1.6	N/A (1)
Clinker Making			
Energy Management & Control Systems	0.14 – 0.27	1.0 – 2.0	< 2
Seal Replacement	0.02	-	< 1
Combustion System Improvement	0.15 – 0.55	-	2 – 3
Indirect Firing	0.13 – 0.19	-	N/A
Shell Heat Loss Reduction	0.09 – 0.30	-	1
Optimize Grate Cooler	0.06- 0.13	-	1 – 2
Conversion to Grate Cooler	0.24	-2.4	1 – 2
Conversion to Semi-Dry Process Kiln	0.8 – 1.2	-4 - -6	> 10 (1)
Conversion to Semi-Wet Process Kiln	0.9	-4	> 10 (1)
Conversion to Dry Precliner Kiln	1.9 – 2.7	-9	> 10 (1)
Efficient Mill Drives	-	0.7 – 2.7	1
Use of Secondary Fuels	> 0.5	-	1
Finish Grinding			
Energy Management & Process Control	-	1.6	< 1
Improved Grinding Media in Ball Mills	-	1.8	8 (1)
High Pressure Roller Press	-	7 – 25	> 10 (1)
High-Efficiency Classifiers	-	1.7 – 5.4	> 10 (1)
Plant Wide Measures			
Preventative Maintenance	0.04	0 – 5	< 1
High Efficiency Motors	-	0 – 5	< 1
Adjustable Speed Drives	-	5 – 7	2- 3
Optimization of Compressed Air Systems	-	0 – 5	< 3
Efficient Lighting	-	0 – 0.5	N/A
Product Change			
Blended Cement	1.21	-15	< 1
Limestone Portland Cement	0.30	3.0	< 1
Use of Steel Slag in Clinker (CemStar)	0.16	-	< 2
Low Alkali Cement	0.16 – 0.4	n.a.	Immediate
Reduced Fineness of Cement for Selected Uses	-	0 – 14	Immediate

Notes:

(1) Payback periods are calculated on the basis of energy savings alone. In reality this investment may be driven by other considerations than energy efficiency (e.g. productivity, product quality), and will happen as part of the normal business cycle or expansion project. Under these conditions the measure will have a lower payback period depending on plant-specific conditions.

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APPENDIX A

Basic Energy Efficiency Actions for Plant Personnel

Staff can be trained in both skills and the general approach to energy efficiency in day-to-day practices. Personnel at all levels should be aware of energy use and objectives for efficiency. By passing information to everyone, each employee can save energy. In addition, performance results should be regularly evaluated and communicated to all personnel, recognizing high performers. Examples of some simple tasks employees can do include the following (Caffal, 1995):

- Switch off motors, fans and machines when they are not being used, especially at the end of the working day or shift, and during breaks, when it does not affect production, quality or safety. Similarly, turn on equipment no earlier than needed to reach the correct settings (temperature, pressure) at the start time.
- Switch off unnecessary lights; rely on daylighting whenever possible.
- Use weekend and night setbacks on HVAC in offices or conditioned buildings.
- Report leaks of water (both process water and dripping taps), steam and compressed air. Ensure they are repaired quickly. The best time to check for leaks is a quiet time like the weekend.
- Look for unoccupied areas being heated or cooled, and switch off heating or cooling.
- Check that heating controls are not set too high or cooling controls set too low. In this situation, windows and doors are often left open to lower temperatures instead of lowering the heating.
- Check to make sure the pressure and temperature of equipment is not set too high.
- Prevent drafts from badly fitting seals, windows and doors, and hence, leakage of cool or warm air.
- Carry out regular maintenance of energy-consuming equipment.
- Ensure that the insulation on process heating equipment is effective.

Appendix B

Energy management system assessment for best practices in energy efficiency

ORGANIZATION		SYSTEMS MONITORING		TECHNOLOGY		O & M	
Accountability	Organization	Monitoring & Targeting	Utilities Management	Reviews	Plans	Operation & Maintenance	
0	No awareness of responsibility for energy usage. Energy not specifically discussed in meetings.	No energy manager or "energy champion."	Energy efficiency of processes on site not determined. Few process parameters monitored regularly.	No utilities consumption monitoring.	No specific reviews held.	No energy improvement plans published.	No written procedures for practices affecting energy efficiency.
1	Operations staff aware of the energy efficiency performance objective of the site.	Energy manager is combined with other tasks and roles such that less than 10% of one person's time is given to specific energy activities.	Energy efficiency of site determined monthly or yearly. Site annual energy efficiency target set. Some significant process parameters are monitored.	Utilities (like power and fuel consumption) monitored on overall site basis.	Energy only reviewed as part of other type reviews	Energy improvement plans published but based on an arbitrary assessment of opportunities.	No procedures available to operating staff.
2	Energy efficiency performance indicators are produced and available to operations staff. Periodic energy campaigns. Intermittent energy review meetings.	Energy manager appointed giving greater than 10% of time to task. Occasional training in energy related issues.	Weekly trend monitoring of energy efficiency of processes and of site, monitored against targets. Process parameters monitored against target.	Weekly monitoring of steam/power balance.	Infrequent energy review.	Energy performance plan published based on estimate of opportunities.	Procedures available to operators but not recently reviewed.
3	Energy efficiency performance parameter determined for all energy consuming areas. Operations staff advised of performance. All employees aware of energy policy. Performance review meetings held once/month.	Energy manager in place greater than 30% of time given to task. Adhoc training arranged. Energy performance reported to management.	Daily trend monitoring of energy efficiency of processes and of site, monitored against target. Process parameters monitored against targets.	Daily monitoring of steam/power. Steam & fuel balances adjusted daily.	Regular plant/site energy reviews carried out.	A five-year energy improvement plan is published based on identified opportunities from energy review.	Procedures available to operators and reviewed in the last three years.

ORGANIZATION		SYSTEMS MONITORING		TECHNOLOGY		O & M
Accountability	Organization	Monitoring & Targeting	Utilities Management	Reviews	Plans	Operation & Maintenance
4 Energy efficiency performance parameter included in personal performance appraisals. All staff involved in site energy targets and improvement plans. Regular weekly meeting to review performance.	An energy manager is in place giving greater than 50% time to task. Energy training to take place regularly. Energy performance reported to management and actions followed up.	Same as 3, with additional participation in energy efficiency target setting. Process parameters trended.	Real time monitoring of fuel, steam and steam/power balance. Optimum balances maintained.	Site wide energy studies carried out at least every five years with follow up actions progressed to completion	A ten year energy improvement plan based on review is published and integrated into the Business Plan.	Procedures are reviewed regularly and updated to incorporate the best practices. Used regularly by operators and supervisors.

Appendix C

Support Programs for Industrial Energy Efficiency Improvement

This appendix provides a list of energy efficiency supports available to industry. A brief description of the program or tool is given, as well as information on its target audience and the URL for the program. Included are federal and state programs. Use the URL to obtain more information from each of these sources. An attempt was made to provide as complete a list as possible; however, information in this listing may change with the passage of time.

Tools for Self-Assessment

Steam System Assessment Tool

Description: Software package to evaluate energy efficiency improvement projects for steam systems. It includes an economic analysis capability.

Target Group: Any industry operating a steam system

Format: Downloadable software package (13.6 MB)

Contact: U.S. Department of Energy, Office of Industrial Technologies

URL: <http://www.oit.doe.gov/bestpractices/steam/ssat.html>

Steam System Scoping Tool

Description: Spreadsheet tool for plant managers to identify energy efficiency opportunities in industrial steam systems.

Target Group: Any industrial steam system operator

Format: Downloadable software (Excel)

Contact: U.S. Department of Energy, Office of Industrial Technologies

URL: <http://www.oit.doe.gov/bestpractices/steam/docs/steamtool.xls>

MotorMaster+

Description: Energy-efficient motor selection and management tool, including a catalog of over 20,000 AC motors. It contains motor inventory management tools, maintenance log tracking, efficiency analysis, savings evaluation, energy accounting, and environmental reporting capabilities.

Target Group: Any industry

Format: Downloadable Software (can also be ordered on CD)

Contact: U.S. Department of Energy, Office of Industrial Technologies

URL: <http://mm3.energy.wsu.edu/mmplus/default.stm>

ASDMaster: Adjustable Speed Drive Evaluation Methodology and Application

Description: Software program helps to determine the economic feasibility of an adjustable speed drive application, predict how much electrical energy may be saved by using an ASD, and search a database of standard drives.

Target Group: Any industry

Format: Software package (not free)

Contact: EPRI, (800) 832-7322

URL: <http://www.epri-peac.com/products/asdmaster/asdmaster.html>

AirMaster: Compressed Air System Assessment and Analysis Software

Description: Modeling tool that maximizes the efficiency and performance of compressed air systems through improved operations and maintenance practices

Target Group: Any industry operating a compressed air system

Format: Downloadable software

Contact: U.S. Department of Energy, Office of Industrial Technologies

URL: <http://www.compressedairchallenge.org/>

Pump System Assessment Tool (PSAT)

Description: The tool helps industrial users assess the efficiency of pumping system operations. PSAT uses achievable pump performance data from Hydraulic Institute standards and motor performance data from the MotorMaster+ database to calculate potential energy and associated cost savings.

Target Group: Any industrial pump user

Format: Downloadable software

Contact: U.S. Department of Energy, Office of Industrial Technologies

URL: <http://public.ornl.gov/psat/>

ENERGY STAR Portfolio Manager

Description: Online software tool helps to assess the energy performance of buildings by providing a 1-100 ranking of a building's energy performance relative to the national building market. Measured energy consumption forms the basis of the ranking of performance.

Target Group: Any building user or owner

Format: Online software tool

Contact: U.S. Environmental Protection Agency,

URL: http://www.energystar.gov/index.cfm?c=business.bus_index

Optimization of the insulation of boiler steam lines – 3E Plus

Description: Downloadable software to determine whether boiler systems can be optimized through the insulation of boiler steam lines. The program calculates the most economical thickness of industrial insulation for a variety of operating conditions. It makes calculations using thermal performance relationships of generic insulation materials included in the software.

Target Group: Energy and plant managers

Format: Downloadable software

Contact: Office of Industrial Technologies, U.S. Department of Energy

URL: http://www.oit.doe.gov/bestpractices/software_tools.shtml

Assessment and Technical Assistance

Industrial Assessment Centers

Description: Small- to medium-sized manufacturing facilities can obtain a free energy and waste assessment. The audit is performed by a team of engineering faculty and students from 30 participating universities in the U.S. and assesses the plant's performance and recommends ways to improve efficiency.

Target Group: Small- to medium-sized manufacturing facilities with gross annual sales below \$75 million and fewer than 500 employees at the plant site.

Format: A team of engineering faculty and students visits the plant and prepares a written report with energy efficiency, waste reduction and productivity recommendations.

Contact: U.S. Department of Energy, Office of Industrial Technologies

URL: <http://www.oit.doe.gov/iac/>

Plant-Wide Audits

Description: An industry-defined team conducts an on-site analysis of total energy use and identifies opportunities to save energy in operations and in motor, steam, compressed air, and process heating systems. The program covers 50% of the audit costs.

Target Group: Large plants

Format: Solicitation (put out regularly by DOE)

Contact: U.S. Department of Energy, Office of Industrial Technologies

URL: http://www.oit.doe.gov/bestpractices/plant_wide_assessments.shtml

Manufacturing Extension Partnership (MEP)

Description: MEP is a nationwide network of not-for-profit centers in over 400 locations providing small- and medium-sized manufacturers with technical assistance. A center provides expertise and services tailored to the plant, including a focus on clean production and energy-efficient technology.

Target Group: Small- and medium-sized plants

Format: Direct contact with local MEP Office

Contact: National Institute of Standards and Technology, (301) 975-5020

URL: <http://www.mep.nist.gov/>

Small Business Development Center (SBDC)

Description: The U.S Small Business Administration (SBA) administers the Small Business Development Center Program to provide management assistance to small businesses through 58 local centers. The SBDC Program provides counseling, training and technical assistance in the areas of financial, marketing, production, organization, engineering and technical problems and feasibility studies, if a small business cannot afford consultants.

Target Group: Small businesses

Format: Direct contact with local SBDC

Contact: Small Business Administration, (800) 8-ASK-SBA

URL: <http://www.sba.gov/sbdc/>

ENERGY STAR – Selection and Procurement of Energy-Efficient Products for Business

Description: ENERGY STAR identifies and labels energy-efficient office equipment. Look for products that have earned the ENERGY STAR. They meet strict energy efficiency guidelines set by the EPA. Office equipment included such items as computers, copiers, faxes, monitors, multifunction devices, printers, scanners, transformers and water coolers.

Target Group: Any user of labeled equipment.

Format: Website

Contact: U.S. Environmental Protection Agency

URL: http://www.energystar.gov/index.cfm?c=business.bus_index

Training

Best Practices Program

Description: The Best Practices Program of the Office for Industrial Technologies of U.S. DOE provides training and training materials to support the efforts of the program in efficiency improvement of utilities (compressed air, steam) and motor systems (including pumps). Training is provided regularly in different regions. One-day or multi-day trainings are provided for specific elements of the above systems. The Best Practices program also provides training on other industrial energy equipment, often in coordination with conferences. A clearinghouse provides answers to technical questions and on available opportunities: 202-586-2090 or <http://www.oit.doe.gov/clearinghouse/>

Target Group: Technical support staff, energy and plant managers

Format: Various training workshops (one day and multi-day workshops)

Contact: Office of Industrial Technologies, U.S. Department of Energy

URL: <http://www.oit.doe.gov/bestpractices/training/>

ENERGY STAR

Description: As part of ENERGY STAR's work to promote superior energy management systems, energy managers for the companies that participate in ENERGY STAR are offered the opportunity to network with other energy managers in the partnership. The networking meetings are held monthly and focus on a specific strategic energy management topic to train and strengthen energy managers in the development and implementation of corporate energy management programs.

Target Group: Corporate and plant energy managers

Format: Web-based teleconference

Contact: Climate Protection Partnerships Division, U.S. Environmental Protection Agency

URL: <http://www.energystar.gov/>

Financial Assistance

Below we summarize the major federal programs that provide assistance for energy efficiency investments. Many states also offer funds or tax benefits to assist with energy efficiency projects (see below for State Programs).

Industries of the Future - U.S. Department of Energy

Description: Collaborative R&D partnerships in nine vital industries. The partnership consists of the development of a technology roadmap for the specific sector and key technologies, and cost-shared funding of research and development projects in these sectors.

Target Group: Nine selected industries: agriculture, aluminum, chemicals, forest products, glass, metal casting, mining, petroleum and steel.

Format: Solicitations (by sector or technology)

Contact: U.S. Department of Energy – Office of Industrial Technologies

URL: <http://www.oit.doe.gov/industries.shtml>

Inventions & Innovations (I&I)

Description: The program provides financial assistance through cost-sharing of 1) early development and establishing technical performance of innovative energy-saving ideas and inventions (up to \$75,000) and 2) prototype development or commercialization of a technology (up to \$250,000). Projects are performed by collaborative partnerships and must address industry-specified priorities.

Target Group: Any industry (with a focus on energy-intensive industries)

Format: Solicitation

Contact: U.S. Department of Energy – Office of Industrial Technologies

URL: <http://www.oit.doe.gov/inventions/>

National Industrial Competitiveness through Energy, Environment, and Economics (NICE³)

Description: Cost-sharing program to promote energy efficiency, clean production, and economic competitiveness in industry through state and industry partnerships (large and small business) for projects that develop and demonstrate advances in energy efficiency and clean production technologies. Applicants must submit project proposals through a state energy, pollution prevention, or business development office. Non-federal cost share must be at least 50% of the total cost of the project.

Target Group: Any industry

Format: Solicitation

Contact: U.S. Department of Energy – Office of Industrial Technologies

URL: <http://www.oit.doe.gov/nice3/>

Small Business Administration (SBA)

Description: The Small Business Administration provides several loan and loan guarantee programs for investments (including energy-efficient process technology) for small businesses.

Target Group: Small businesses

Format: Direct contact with SBA

Contact: Small Business Administration

URL: <http://www.sba.gov/>

State and Local Programs

Many state and local governments have general industry and business development programs that can be used to assist businesses in assessing or financing energy-efficient process technology or buildings. Please contact your state and local government to determine what tax benefits, funding grants, or other assistance they may be able to provide your organization. This list should not be considered comprehensive but instead merely a short list of places to start in the search for project funding. Below we summarize selected programs earmarked specifically for support of energy efficiency activities.

California – Public Interest Energy Research (PIER)

Description: PIER provides funding for energy efficiency, environmental, and renewable energy projects in the state of California. Although there is a focus on electricity, fossil fuel projects are also eligible.

Target Group: Targeted industries (e.g. food industries) located in California

Format: Solicitation

Contact: California Energy Commission, (916) 654-4637

URL: <http://www.energy.ca.gov/pier/funding.html>

California – Energy Innovations Small Grant Program (EISG)

Description: EISG provides small grants for development of innovative energy technologies in California. Grants are limited to \$75,000.

Target Group: All businesses in California

Format: Solicitation

Contact: California Energy Commission, (619) 594-1049

URL: <http://www.energy.ca.gov/research/innovations/index.html>

Indiana – Industrial Programs

Description: The Energy Policy Division of the Indiana Department of Commerce operates two industrial programs. The Industrial Energy Efficiency Fund (IEEF) is a zero-interest loan program (up to \$250,000) to help Indiana manufacturers increase the energy efficiency of manufacturing processes. The fund is used to replace or convert existing equipment, or to purchase new equipment as part of a process/plant expansion that will lower energy use. The Distributed Generation Grant Program (DGGP) offers grants of up to \$30,000 or up to 30% of eligible costs for distributed generation with an efficiency over 50% to install and study distributed generation technologies such as fuel cells, micro turbines, cogeneration, combined heat & power and renewable energy sources. Other programs support can support companies in the use of biomass for energy, research or building efficiency.

Target Group: Any industry located in Indiana

Format: Application year-round for IEEF and in direct contact for DGGP

Contact: Energy Policy Division, (317) 232-8970.

URL: http://www.in.gov/doc/businesses/EP_industrial.html

Iowa – Alternate Energy Revolving Loan Program

Description: The Alternate Energy Revolving Loan Program (AERLP) was created to promote the development of renewable energy production facilities in the state.

Target Group: Any potential user of renewable energy

Format: Proposals under \$50,000 are accepted year-round. Larger proposals are accepted on a quarterly basis.

Contact: Iowa Energy Center, (515) 294-3832

URL: <http://www.energy.iastate.edu/funding/aerlp-index.html>

New York – Industry Research and Development Programs

Description: The New York State Energy Research & Development Agency (NYSERDA) operates various financial assistance programs for New York businesses. Different programs focus on specific topics, including process technology, combined heat and power, peak load reduction and control systems.

Target Group: Industries located in New York

Format: Solicitation

Contact: NYSERDA, (866) NYSERDA

URL: <http://www.nyserda.org/industry/industrialprograms.html>

Wisconsin – Focus on Energy

Description: Energy advisors offer free services to identify and evaluate energy-saving opportunities, recommend energy efficiency actions, develop an energy management plan for business; and integrate elements from national and state programs. It can also provide training.

Target Group: Industries in Wisconsin

Format: Open year round

Contact: Wisconsin Department of Administration, (800) 762-7077

URL: <http://focusonenergy.com/page.jsp?pageId=4>