Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making

An ENERGY STAR® Guide for Energy and Plant Managers

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An ENERGY STAR® Guide for Energy and Plant Managers

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ABSTRACT

The cost of energy as part of the total production costs in the cement industry is significant, typically at 20 to 40% of operational costs, 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. A variety of waste fuels, including tires, steadily increase their share in fuel use. Between 1970 and 2010, primary physical energy intensity for cement production dropped 1.2% per year from 7.3 MBtu/short ton to 4.5 MBtu/short ton. Carbon dioxide intensity due to fuel consumption and raw material calcination dropped 24%, from 610 lb C/ton of cement (0.31 tC/tonne) to 469 lb C/ton cement (0.23 tC/tonne).

Despite the historic progress, there is ample room for energy efficiency improvement. The share of wet-process plants decreased from 60% in 1970 to about 7% of clinker production in 2010 in the U.S. The remaining plants suggest the existence of a considerable potential, when compared to other industrialized countries. We examined over 50 energy-efficient technologies and measures and estimated energy savings, carbon dioxide emission 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.

Table of Contents

Tables

Figures

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. 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 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. This guide reports on research conducted to support ENERGY STAR and its work with the cement industry. Research provides information on potential energy efficiency opportunities for cement plants. Besides technical information, ENERGY STAR has tools to facilitate stronger corporate energy management practices in U.S. industry, including plant energy benchmarks. ENERGY STAR resources are available through www.energystar.gov/industry. Additional energy management resources specific to cement production can be found on the ENERGY STAR Industries in Focus webpage[2] for the cement 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 pozzolanic cements.

[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] See: www.energystar.gov/industry

The production of cement is an energy-intensive process. Typically, energy consumption accounts for 20-40% of production costs. In 2008, the U.S. cement industry spent about $1.7 billion to purchase energy; around $0.75 billion of this was for electricity and $0.9 billion for fuels. 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 2009 and 2010 are provided, followed by an assessment of various energy efficiency measures applicable to U.S. cement plants.

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. About 97% of the cement produced in the U.S. in 2010 was Portland cement, while masonry cement accounted for 3% of U.S. cement output (USGS, 2012a).

Cement plants are typically constructed in areas with substantial raw materials deposits (e.g. 50 years or longer). There were 110 operating cement plants in the U.S. in 2010, spread across 37 states and Puerto Rico. Portland and blended cement was produced at 110 plants in 2010, while masonry cement was produced at 71 plants. Clinker was produced at 100 plants (102 including Puerto Rico) in the U.S. in 2010. Total cement production of U.S. cement plants in 2010 was about 66 Mt (excluding Puerto Rico); about 4% higher than the production in 2009 (64 Mt), which was the lowest since 1983 (USGS, 2012a). 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 2008, with prominent dips in the late 1970s, early 1980s and late 2000s. Clinker production increased from 67 Mt in 1970 to 80 Mt in 2008, at an average rate of 0.4% per year, hitting a low of 55 Mt in 1982 and a high of 90 Mt in 2006 (see Figure 1) (USGS, various years). In 2009, clinker production dropped to 57 Mt, a decrease of 28.5% within a single year, to slightly increase to 60 Mt in 2010. In 2009, several plants or kilns were permanently shut down, while multikiln plants had idled “extra” kilns (USGS, 2011a). The 2010 capacity utilization was 55%, slightly higher from the 49% in 2009, and significantly lower from the 73% in 2008 (USGS, various years). The type of facility used to produce clinker changed significantly between 1970 and 2010. Clinker produced with the wet process decreased at an average of 5.7% per year, falling from a 60% share of total clinker production in 1970 to a 7% share in 2010. Clinker produced with the dry process increased at an average of 1.8% per year, increasing from a 40% share of total clinker production in 1970 to a 91% share in 2010, with the remainder being plants classified as wet or dry.

Cement production in the U.S. (including Puerto Rico) increased at 0.6% per year between 1970 and 2008, rising from 69 Mt in 1970 to 88 Mt in 2008, to drop drastically in 2009 to 65 Mt due to the economic downturn (see Figure 2). In 2010, the cement production was 67 Mt; an increase of 3.6 % from the 2009 level. The 2010 cement production was 23% lower from the 2008 production and 33% lower from the highest output in 2005 (101 Mt) (USGS, various years). Portland cement remained the dominant cement type during that time span, maintaining a share between 95% and 97%. Between 1970 and 2010, the clinker to cement ratio (expressed as clinker production divided by cement production) decreased from 0.97 to 0.90 t clinker/t cement. The number of clinker plants has decreased from 169 in 1970 to 102 in 2010 (including Puerto Rico), and the number of clinker grinding plants reduced to 4 (a total of 106 facilities in 2010). Thus, average plant capacity has increased.

According to ECRA (2009) a new state-of-the-art cement plant with capacities of 2, 1 and 0.5 million tonnes would require an investment of $180, $235, and $350 per tonne of clinker respectively.

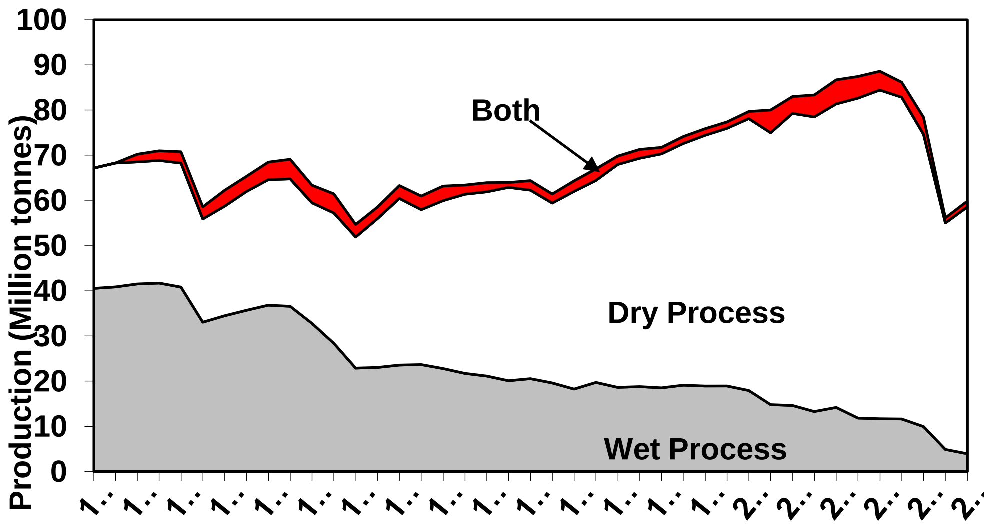

Figure 1. U.S. clinker production by process, 1970 to 2010 (expressed in million metric tons per year). Source: USGS, various years. For the period 1970-2003, USGS data on clinker production by process include Puerto Rico. The term "both" accounts for plants that are not categorized as a wet or dry process plant in the USGS minerals yearbooks.

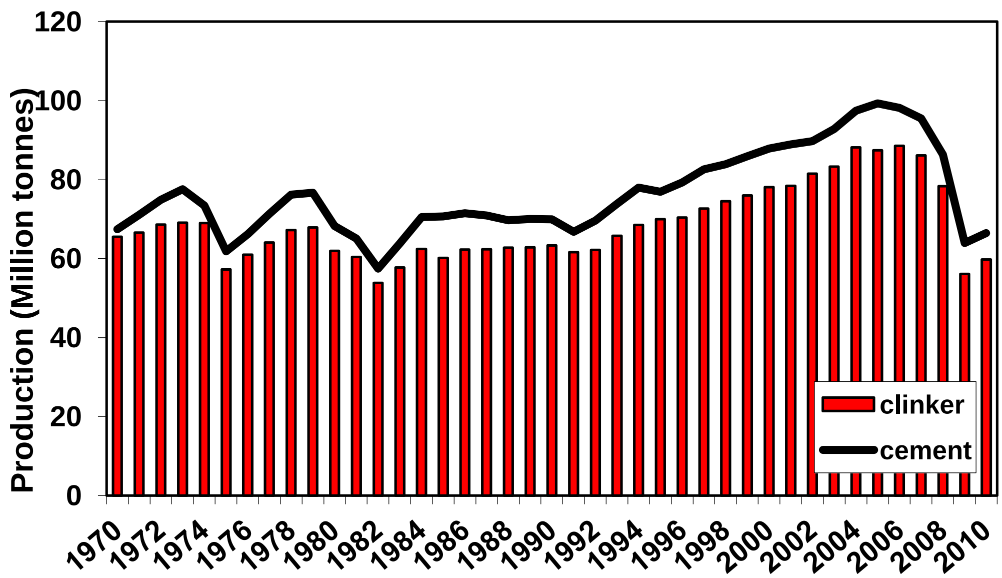

Figure 2. U.S. cement and clinker production, 1970 to 2010 (expressed in million metric tons per year). Source: USGS, various years. Clinker and cement produced in Puerto Rico is excluded.

3. Process Description

3.1 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, pre-homogenized, 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. The crushed material is screened and stones are returned. In the cement industry, the primary crushing of raw materials takes place in single- or twin-rotor hammer crushers (mills) or impact crushers. The use of jaw crushers in cement plants has been decreasing and nowadays, they are mainly used in small cement plants in combination with roll or gyratory crushers for the crushing of hard and abrasive materials (Chatterjee, 2004). The average power consumption for crushing is estimated to range between 0.5 and 0.9 kWh/ton of raw material (Chatterjee, 2004). The gyratory crusher has a power consumption of 0.34-0.50 kWh/ton of raw material (Chatterjee, 2004), and is currently recognized as best available technology (Worrell et al., 2008a).

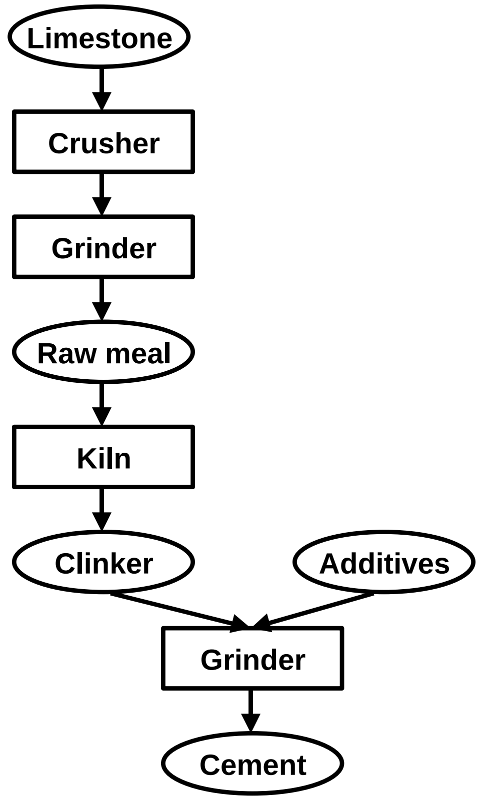

Figure 3. Simplified process schematic for cement making. Limestone is the major process input. However, other raw materials such as clay, shale, sand, quartz or iron ore may be added.

Best practices for the preblending of raw materials are considered a longitudinal store system with a bridge scraper or bucket wheel reclaimer, or a circular store system with a bridge scraper reclaimer. The energy use is estimated at 0.34 kWh/ton raw material (Worrell et al., 2008a). 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).

3.2 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 10 kWh/tonne (9 kWh/short ton) (Harder, 2010b). 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 preferable[3]. 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 plants with wet kilns use more water per ton of cement than plants with dry kilns. Water consumption in wet plants lies within 23-130 gallons/ton clinker (93-560 liters/tonne cement) (IPPC, 2010). In contrast, modern state-of-the-art plants have very low process water consumption of approximately 16 gallons/ton cement (70 liters/tonne cement) (IEA-ETSAP, 2010). Except for wet and semi-dry grinding, water is also used in some cases for lowering the temperature of exhaust gases (when the raw mill is not in operation), in flame cooling (to reduce NOx emissions) and in enhancing the cooling requirements of the clinker cooler (IPPC, 2010). In general, dry and semi-dry cement plants use only limited amounts of water, while effluent not created as water is recycled.

3.3 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. Energy use in wet kilns ranges between 4.9 and 8.8 MBtu/ton clinker, with a

[3] 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.

typical value of 6.0 MBtu/ton clinker (U.S. EPA, 2007a), while according to the IPPC (2010) energy use ranges between 4.3-5.5 MBtu/ton clinker.

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). Long dry kilns have significantly lower heat requirements than wet kilns, with an average fuel use of 4.5 MBtu/ton clinker (U.S. EPA, 2007a). Later developments have added multi-stage suspension preheaters (i.e. a cyclone) or shaft preheaters. Although the more preheater stages lead to less energy consumed (see Table 1), when the raw materials or fuel used has a high moisture content, it can be more energy efficient to operate the kiln with fewer preheater stages and use the extra heat for drying (Bolwerk et al., 2006).

Table 1. Heat requirements for dry kilns with different number of preheater stages

Preheater Stages	**GJ/tonne clinker**		**MBtu/ton clinker**	
3 cyclone stages	3.4	3.8	2.92	3.27
4 cyclone stages	3.2	3.6	2.75	3.09
5 cyclone stages	3.1	3.5	2.66	3.01
6 cyclone stages	3.0	3.4	2.58	2.92

Source: ECRA, 2009

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. Precalciner kilns have an energy consumption of about 3.3 MBtu/ton clinker (U.S. EPA, 2007a). The most efficient pre-heater, pre-calciner kilns use approximately 2.5 MBtu/ton clinker (2.9 GJ/tonne clinker) (Anon, 1994a; Somani et al., 1997; Su, 1997; Steuch and Riley, 1993; IPPC, 2010). 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. There are more parameters that affect energy use such as the plant size and design, kiln capacity, raw material and fuel moisture content, as well as fuel calorific value.

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.

In a dry kiln cement plant, electricity use is typically broken down as follows (ECRA, 2009): 38% cement grinding, 24% raw material grinding, 22% clinker production including grinding of solid fuels, 6% raw material homogenization, 5% raw material extraction, and 5% conveying and packaging.

Among all different types of kilns, wet kilns were found to have the higher NOx emission levels (average of 9.7 lb NOx/tonne of clinker) while dry kilns with a precalciner have the lowest with an average of 3.8 lb NOx/tonne clinker (U.S. EPA, 2007a).

3.4 Finish Grinding

After cooling, the clinker can be stored in 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). Currently, most new plants and plant expansions in the U.S. adopt the highly efficient vertical roller mills for grinding cement. Coarse material is separated in a classifier that is recirculated 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 Blaine[4] (expressed in cm^2/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

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[4] 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).

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).

Finished cement is stored in silos, tested and filled into bags, or shipped in bulk in 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). Electricity use for lighting and other miscellaneous equipment is estimated at approximately 1.2% of the overall electricity use (Heijningen et al., 1992). The power consumption for packing depends on the share of cement packed in bags.

4. Energy Use and Carbon Dioxide Emissions[5] in the U.S. Cement Industry

4.1 Historical Energy Use and Carbon Dioxide Emission Trends

Energy consumption in the U.S. cement industry declined between 1970 and 2010 (see Figure 4). Primary energy use decreased at an average of 0.6% per year, from 555 TBtu (586 PJ) in 1970 to 442 TBtu (466 PJ) in 2008, although production increased over that time span. The further decrease in energy consumption to 332 TBtu (350 PJ) in 2010 is primarily an effect of the reduced levels in cement production. The overall energy consumption trend in the U.S. cement industry between 1970 and 2010 shows a gradual decline. Energy consumption started to increase in the early 1990s and increased between 1992 and 2005 at an average of 2.0% per year, followed by a decrease of 4.7% per year between 2005 and 2008, and a steep decrease of 25% between 2008 and 2010 as an outcome of the economic recession. The share of the two main clinker-making processes in energy consumption changed drastically between 1970 and 2010. While the wet process consumed 62% of total cement energy consumption in 1970, it used only 10% in 2010, while energy consumption of the dry process increased from 37% of total cement energy consumption in 1970 to 88% in 2010.

Since the 1980s the use of waste-derived fuels has grown in the cement industry, replacing a portion of traditional fuels. As Figure 5 shows, by 2010 16% of all fuels were waste derived fuels, e.g. tires, solid and liquid wastes (solvents). USGS has collected data on

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

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 4% to all industrial carbon dioxide (CO_2) emissions in the United States (equivalent to approximately 2% of total U.S. CO_2 emissions). In 2009, the calcination of clinker was the second largest source (after natural gas production) of CO_2 emissions not related to fuel consumption. In 2009, the cement industry was responsible for 35% of industrial process CO_2 emissions (equivalent to approximately 1% of total U.S. CO_2 emissions) (EIA, 2011b). 2008 CO_2 emissions from fuel consumption (including CO_2 emissions from alternative fuels) in the cement industry were virtually back at the level of 1975, around 10 MtC, despite a drop in the years in between, due to improvements in the pyroprocessing systems. In 2010, due to the decrease in clinker production CO_2 emissions from fuel consumption dropped to 7.3 MtC. CO_2 emissions from the calcination process increased from 9.3 MtC in 1970 to 10.8 MtC in 2008 due to the increased clinker production. In 2010, the low level of CO_2 emissions from calcination, 8.3 MtC, was due to the lower clinker production. Hence, total carbon dioxide emissions from the cement industry increased to 20.8 MtC in 2008, to decrease in 2009 to 15.6 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 4% (incl. landfill gas) fuel share in 2010, 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 68% in 2010, petroleum coke (16% in 2010), tires (3% in 2010) and wastes (liquid and solid, 13% in 2010). Oil's share fell from 13% in 1970 (17% in 1973) to 0.4% in 2010. Electricity's share increased from 7% in 1970 to 12% in 2010.

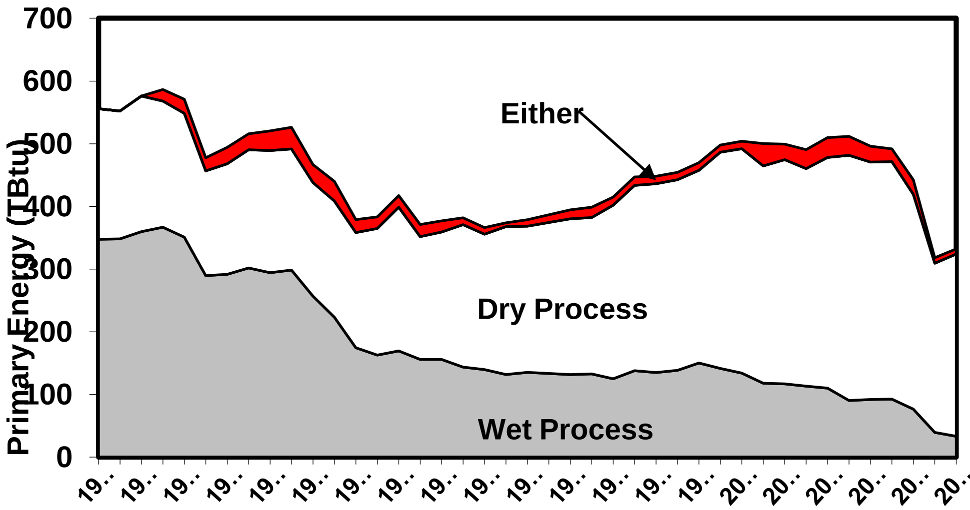

Figure 4. Primary energy consumption in U.S. cement production by process, 1970 to 2010 (expressed in TBtu). Source: derived from USGS, various years. For the period 1970-2003 USGS data on energy use include Puerto Rico.

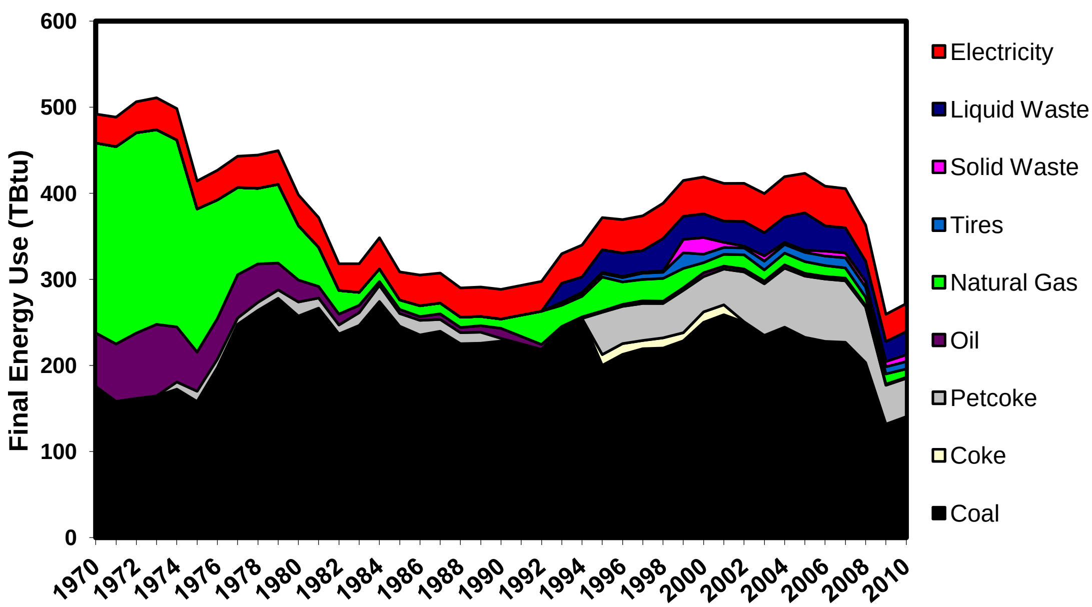

Figure 5. Final energy consumption in U.S. cement production by fuel, 1970 to 2010 (expressed in TBtu). Source: derived from USGS, various years. For the period 1970-2003 USGS data on energy use include Puerto Rico.

4.2 Historical Energy Intensity and Specific Carbon Dioxide Emission Trends

Primary energy intensity in the U.S. cement industry decreased between 1970 and 2010. Primary energy intensity of cement production decreased at an average rate of 2.4% per year from 1970 to 1988, increased by 0.8% per year from 1988 to 1999, but decreased again by 1.1% per year between 1999 and 2010. Between 1970 and 2010 the primary energy intensity fell from 7.3 MBtu/ton in 1970 to 4.5 MBtu/ton in 2010 (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).

The average primary energy use of the U.S. cement industry decreased by 0.51 MBtu/ton clinker within a period of 10 years (1997-2008) (Boyd and Zhang, 2011). This outcome is in accordance with our estimates of 0.55 MBtu/ton clinker improvement of energy within the same period.

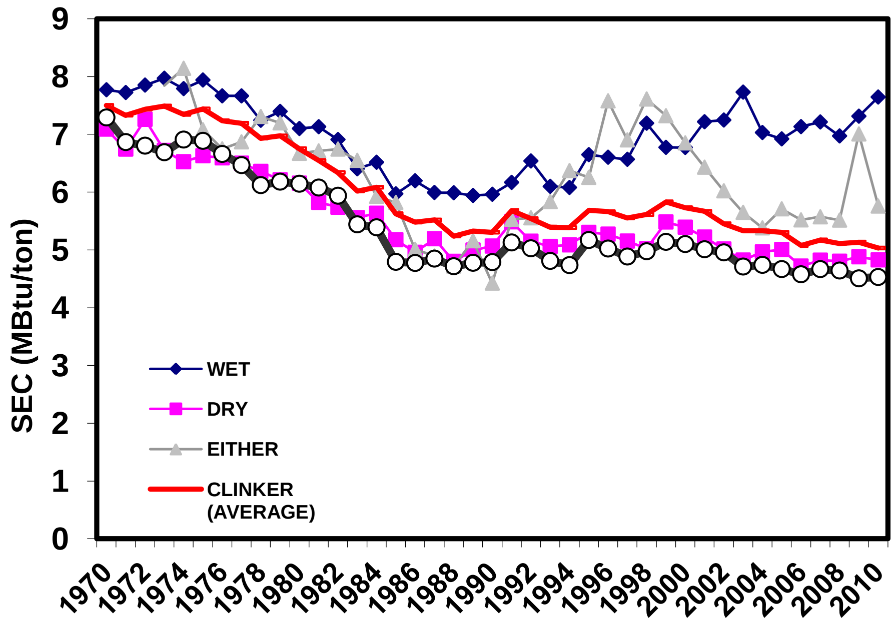

Figure 6. Primary energy intensity of U.S. cement and clinker production, 1970 to 2010 (expressed in MBtu/short ton, HHV). This graph excludes use of wastes as kiln fuel between 1977 and 1992, as USGS did not collect this data before 1993. Source: derived from USGS, various years. Energy intensities in the period 1970-2003 include Puerto Rico.

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 fuel consumption. Specific fuel consumption decreases strongly until around 1987, slightly grows between 1991 and 2000, and slightly decreases in recent years. In 2010, the average fuel use was 3.3 MBtu/ton cement (3.8 GJ/tonne cement), very slightly higher from that in 2009 (3.2 MBtu/ton or 3.8 GJ/tonne). Fuel requirements in clinker production decreased by 1.5%, from 3.68 MBtu/ton clinker (4.28 GJ/tonne clinker) in 2009 to 3.62 MBtu/ton clinker (4.22 GJ/tonne clinker) in 2010. The decrease in the average fuel requirements for clinker production, is the result of the closure in 2009 of two cement plants that operated wet kilns, the closure of the wet kilns in two combination plants, and the addition of a dry kiln at a previously wet plant (USGS, 2012a). In 2010, the average electricity use was 0.44 MBtu/ton cement (0.52 GJ/tonne cement), decreased very slightly by 0.8% from that in 2009. The 2009 increase in electricity use reflected disruptions in operation (idling, repairs, upgrades), and higher clinker production volumes from dry plants (only 9% of clinker was produced in wet kilns) (USGS, 2011a). In general, dry kilns are characterized by higher power requirements due to their more sophisticated layout.

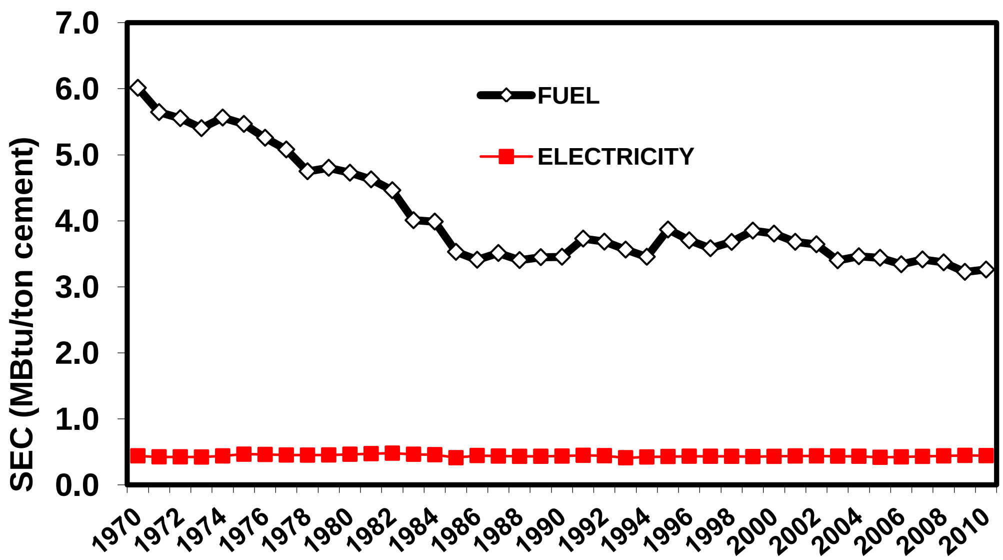

Figure 7. Specific fuel and electricity consumption per ton of cement produced. Energy is expressed as final energy (or site energy) and excludes power generation conversion losses. Fuels include waste fuel use estimates starting in 1977 (based on PCA data, and after 1993 on USGS reported data). Energy intensities in the period 1970-2003 include Puerto Rico.

Specific carbon dioxide emissions[6] from fuel consumption declined from 352 lbC/ton cement (175 kgC/tonne) in 1970 to 220 lbC/ton cement (110 kgC/tonne) in 2010. Total carbon dioxide emissions (including emissions from limestone calcination for clinker-making) decreased at 0.7% per year, on average, from 609 lbC/ton cement (305 kgC/tonne) in 1970 to 469 lbC/ton cement (234 kgC/tonne) in 2010. Carbon dioxide emissions from calcination are estimated based on a standard emission factor for limestone calcination (0.14 tC/tonne clinker) (Hanle et al., 2006). However, this factor can be lower as blast furnace slag and fly

[6] 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). The emission factors used for the various commercial fuels are taken from U.S. EPA (2009) and for electricity generation from EIA (2011a).

ash (noncarbonate raw materials) are used in the cement kilns as substitutes for limestone. In 2010, about 3.7 million tonnes of noncarbonate materials were used in the U.S. kilns (USGS, 2012a), decreasing the emissions from calcination from 8.3 MtC to 8.0 MtC; a decrease of about 2.8%.

Like the energy intensity trend, specific carbon dioxide emissions decreased overall between 1970 and 2010. The specific carbon dioxide emissions from the wet process increased between 1970 and 2010 at an average of 0.1% per year while the specific carbon dioxide emissions from the dry process decreased at an average rate of 1.0% per year during the same period.

The increased dry process clinker production capacity, improved energy efficiency, and decreasing clinker/cement-production ratio reduced the specific carbon dioxide emissions, while the substantial fuel shifts towards more carbon intensive fuels like coal and coke contributed to an increase in specific carbon dioxide emissions (see Figure 8). Overall, fuel mix trends were more than offset by energy intensity reductions, leading to an overall decrease in specific carbon dioxide emissions.

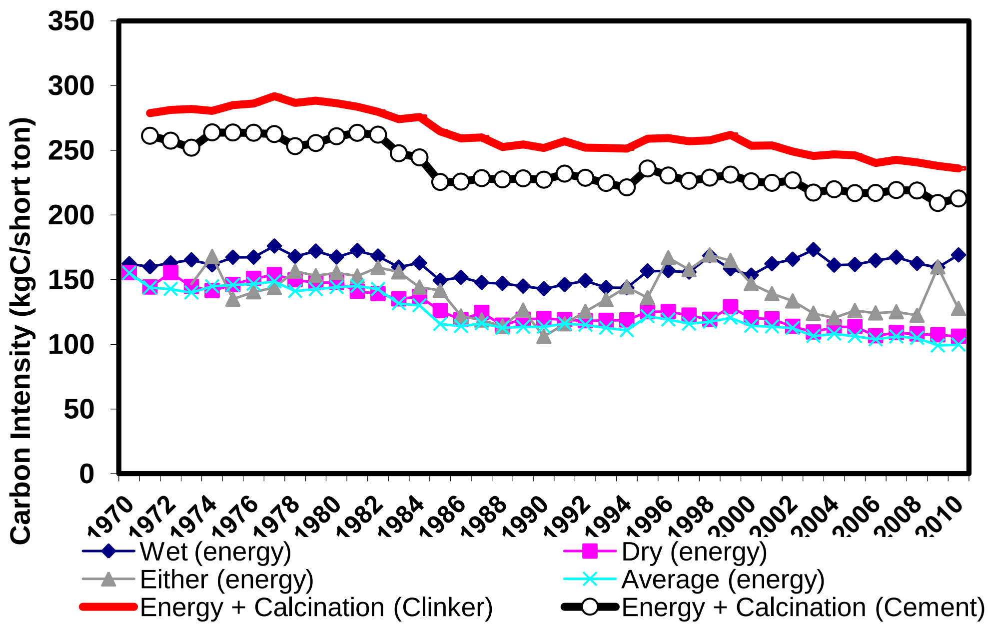

Figure 8. Carbon intensity of U.S. cement and clinker production, 1970 to 2010 (expressed in kgC per short ton of product). This graph excludes use of wastes as kiln fuel between 1977 and 1992, as USGS did not collect this data before 1993. Source: derived from USGS, various years.

5. 2009 Baseline Energy Use and Carbon Dioxide Emissions

In 2009, the U.S. cement industry consumed 259 TBtu (273 PJ) of final energy (about 2.5% of total U.S. manufacturing energy use) and emitted 14.7 MtC of carbon dioxide[7] (about 4.0% of total U.S. manufacturing carbon emissions). Table 2 provides an estimate of 2009 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 2009.

[7] 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.

Table 2. 2009 Energy consumption and Specific Energy Consumption (SEC) in the U.S. cement plants 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	Fuel (Tbtu)	Elec. (Tbtu)	Primary Energy (Tbtu)	Fuel SEC MBtu/st	Elec. SEC kWh/st	Primary SEC Mbtu/st	Carbon Dioxide Emissions Energy Use (MMtCe)	Carbon Dioxide Emissions Calcination (MMtCe)	Carbon Dioxide Intensity (kgC/st)
Wet Process									
Kiln Feed Preparation	0	1	3	0.0	28	0.3	0.1	0.0	4.4
Clinker Production[7]	37	1	39	5.8	29	6.1	0.9	0.8	265.0
Finish Grinding	0	2	5	0.0	62	0.6	0.1	0.0	9.7
Total Wet Process - Cement	37	3	47	4.9	131	6.2	1.0	0.8	240.2
Dry Process									
Kiln Feed Preparation	0	11	30	0.0	32	0.3	0.5	0.0	5.0
Clinker Production	191	6	209	3.4	33	3.8	5.0	7.0	220.6
Finish Grinding	0	11	32	0.0	54	0.5	0.5	0.0	8.4
Total Dry Process - Cement	191	28	271	3.1	134	4.4	6.0	7.0	209.0
Total All Cement	**228**	**42**	**318**	**3.3**	**133**	**4.6**	**7.0**	**7.7**	**212.4**

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 2 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.

5.1 Raw Materials

In 2009, 110 Million short tons (100 Mt) of raw materials were used in the cement industry (USGS, 2011a).[8] It is assumed that 11% of raw materials were used for the wet process kilns and 89% of raw materials were used for dry process kilns. Electricity use is estimated at 28 kWh/short ton raw material preparation for wet kilns and 32 kWh/short ton for dry kilns (COWIconsult et al., 1993; Jaccard and Willis, 1996).

5.2 Clinker Production

According to USGS (2011a) wet process clinker production was 5.36 Million short tons (4.87 Mt) while dry process production was 55.2 Million short tons (50.1 Mt). Accounting for production from plants with both wet and dry processes on site, USGS gives a total clinker production of 61.8 Million short tons (56.1 Mt) in that year. The average U.S. wet kiln fuel intensity in 2009 is estimated at 5.8 MBtu/short ton clinker (6.8 GJ/t) and an average dry kiln fuel intensity of 3.4 MBtu/short ton (4.0 GJ/tonne) (Holderbank, 1993; PCA, 1996; Jaccard and Willis, 1996; van Oss, 1999; IPPC, 2010). Electricity requirements of 29 kWh/short ton (32 kWh/tonne) are assumed for fuel preparation and for operating the kiln, fans, and coolers for wet kilns and 33 kWh/short ton (36 kWh/tonne) for dry kilns (COWIconsult et al., 1993; Ellerbrock and Mathiak, 1994). Although electricity use in dry kiln plants is higher than in wet kiln plants, as wet plants get older this difference is limited.

5.3 Finish Grinding

The amount of throughput for finish grinding is assumed to be the same as the total amount of cement produced in 2009, 7.5 million short tons (6.8 Mt) for wet cement, 61.7 million short tons (56.0 Mt) for dry cement and 1.2 million short tons (1.1 Mt) for other processes (USGS, 2011a). 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 60 kWh/short ton (66 kWh/t) for the older wet process plants.

5.4 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 (0.51 tonnes of CO_2) are emitted for every tonne of clinker produced (Hanle et al., 2006). This amounts to 7.7 MtC given a production of 56.1 million tonnes of clinker (61.9 million short tons) in 2009 (USGS, 2011a). 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) and the Energy Information Administration's Annual Energy Outlook (for recent years) (EIA, various years). U.S. EPA (2009) is the source for 2009 carbon dioxide

[8] The import of 1.4 Million tons of clinker (2009) would account for an additional 2.1 Million tons of raw material use. However, we only include materials processed in the U.S. cement industry to determine energy intensities.

emission coefficients for the various commercial fuels. For electricity, the 2009 average fuel mix for electricity generation in the U.S is used (EIA, 2011a).

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

To simplify comparisons the following conversion factors were used: 0.93 tons clinker per ton of cement, 1.55 tons of raw materials per ton of cement, and 1.67 tons of raw materials per ton of clinker. All conversions were based on data reported by USGS for the year 2008 (USGS, 2010).

Table 3. Energy-efficient practices and technologies in cement production

Raw Materials Preparation	
Efficient transport systems (dry process)	
Raw meal blending systems (dry process)	
Slurry blending and homogenization (wet process)	
Conversion to closed circuit wash mill (wet process)	
Advanced raw meal grinding (dry process)	
Separate raw material grinding (dry process)	
Raw meal process control (dry process)	
High-efficiency classifiers/separators	
Fuel preparation: Roller mills	
Clinker Production (Wet)	**Clinker Production (Dry)**
Energy management and process control	Energy management and process control
Kiln combustion system improvements	Kiln combustion system improvements
Mineralized clinker	Mineralized clinker
Indirect firing	Indirect firing
Oxygen enrichment	Oxygen enrichment
Mixing air technology	Mixing air technology
Seal replacement	Seal replacement
Kiln shell heat loss reduction	Kiln shell heat loss reduction
Refractories	Preheater shell heat loss reduction
Efficient kiln drives	Refractories
Conversion to modern grate cooler	Efficient kiln drives
Optimize grate coolers	Conversion to modern grate cooler
Conversion to semi-dry kiln (slurry drier)	Optimize grate coolers
Conversion to semi-wet kiln (filter press	

system) Conversion to pre-heater, pre-calciner kiln	Conversion to modern grate cooler Optimize grate coolers Low pressure drop cyclones for suspension pre-heaters Heat recovery for power generation Long dry kiln conversion to multi-stage pre-heater kiln Increase the number of preheater stages (from 5 to 6) Addition of pre-calciner to pre-heater kiln Long dry kiln conversion to multi-stage pre-heater, pre-calciner kiln
Finish Grinding	
Energy management and process control Vertical roller mills Horizontal roller mills High-pressure roller presses – pre-grinding High-pressure roller presses – finish grinding High efficiency classifiers Improved grinding media (ball mills)	
General Measures	
Preventative maintenance (insulation, compressed air system, maintenance) High efficiency motors Optimization of compressed air systems High efficiency fans Efficient lighting Efficient dust collectors	

Product & Feedstock Changes
High Alkali cement
Blended Cements
Limestone Portland cement
Reducing fineness of cement for selected uses
Use of steel slag in kiln (CemStar®)
Use of fly ash and blast furnace slag in kiln
Use of cement kiln dust in kiln
Use of calcareous oil shale in kiln
Lower lime saturation factor
Fuel change
Switch from coal to oil/natural gas
Alternative fuels (biomass and waste)
Tire derived fuel

Not all measures in Table 3 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.

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. Section 6.8 shows measures concerning these and other general crosscutting utilities that apply to the cement industry.

Although technological changes in equipment conserve energy, changes in staff behavior and attitude can also have a great impact. Energy efficiency training programs can help a company's staff incorporate energy efficiency practices into their day-to-day work routines.

Personnel at all levels should be aware of energy use and company objectives for energy efficiency improvement. Often such information is acquired by lower-level managers but neither passed up to higher-level management nor passed down to staff (Caffal, 1995). Energy efficiency 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 can have a much greater effect than some other more costly technological improvements.

Establishing formal management structures and systems for managing energy that focus on continuous improvement are important strategies for helping companies manage energy use and implement energy efficiency measures. The U.S. EPA's ENERGY STAR program has developed a framework for energy management based on the observed best practices of leading companies. Other management frameworks, such as ISO 14001, can be used to ensure better organizational management of energy. One ENERGY STAR partner noted that using energy management programs in combination with the ISO 14001 program has had a greater impact on conserving energy at its plants than any other strategy.

Improving energy efficiency in cement manufacturing should be approached from several directions. A strong, corporate-wide energy management program is essential. Ideally, such a program would include facility, operations, environmental, health, and safety, and management personnel. Energy efficiency improvements to cross-cutting technologies,[9] such as the use of energy-efficient motors and the optimization of compressed air systems, present well-documented opportunities for energy savings. Optimizing system design and operations, such as maximizing process waste heat recovery, can also lead to significant reductions in energy use. In addition, production processes can often be fine-tuned to produce similar savings.

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.

Energy efficiency does not happen on its own. A strong energy management program creates a foundation for positive change and provides guidance for managing energy throughout an organization. Energy management programs also help to ensure that energy efficiency improvements do not just happen on a one-time basis, but rather are continuously identified and implemented in an ongoing process of continuous improvement. Furthermore, without the backing of a sound energy management program, energy efficiency improvements might not reach their full potential due to lack of a systems perspective and/or the support of proper maintenance and follow-up.

[9] Cross-cutting technologies are defined as equipment that is commonly used in many different industries, such as boilers, pumps, motors, compressed air systems, and lighting.

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 organizational inertia to changes from the status quo. Even when energy is a significant cost, many companies still lack a strong commitment to improve energy management.

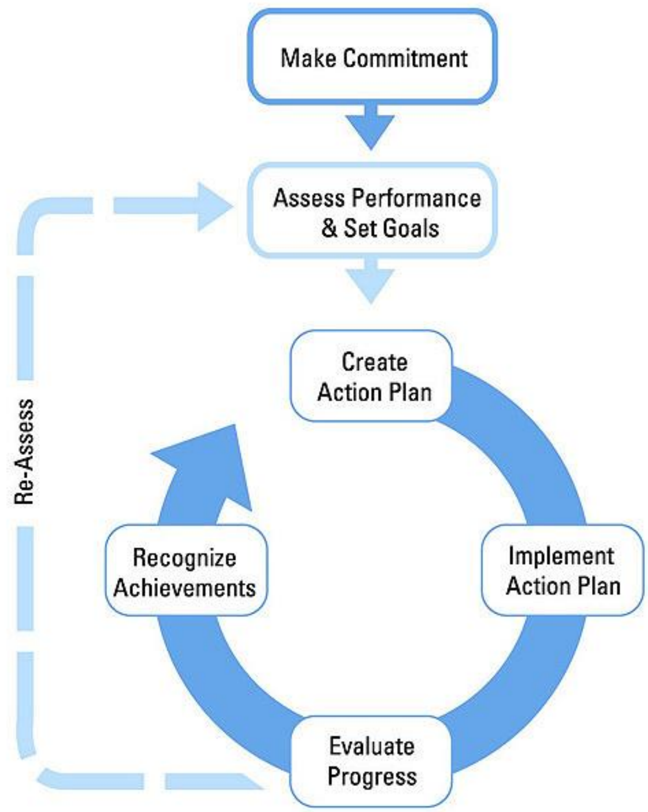

Figure 9. Main elements of a strategic energy management program, ENERGY STAR Guidelines for Energy Management

The U.S. EPA, through the ENERGY STAR program, works with many leading industrial manufacturers to identify the basic aspects of effective energy management programs.[10] The major elements in a strategic energy management program are depicted in Figure 9.

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[10] Read about strategic energy management at www.energystar.gov .

A successful program in energy management begins with a strong organizational 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 (see the following section). 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 success 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.

Progress evaluation 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. Once best practices are established, the goal of the cross-functional energy team should be to replicate these practices throughout the organization. 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 its current energy management program against the ENERGY STAR Energy Program Assessment Matrix provided in Appendix B.

As discussed above, internal support for an energy management program is crucial; however, support for energy management programs can come from outside sources as well. Facility audits can be a particularly effective form of outside support. For example, the U.S. Department of Energy (DOE) sponsors 26 Industrial Assessment Centers (IACs) at universities across the United States. These IACs offer small and medium sized manufacturing facilities free assessments of plant energy and waste management performance and recommend ways to improve efficiency. Since the early 1980s, IAC assessments of U.S. cement plants have identified over 160 energy efficiency improvement opportunities, with an average annual savings of about $130,000 and an average simple payback of 1.4 years per recommendation (IAC, 2012).

The U.S. DOE sponsors similar audits for large manufacturing plants under the Better Buildings, Better Plants (BBBP) program, which replaced the *Save Energy Now* program. As of 2006, nearly 30 *Save Energy Now* audits were conducted for the U.S. cement industry (U.S. DOE, 2012). Appendix D provides additional information on U.S. DOE programs, as well as a host of other external resources that can aid in identifying energy efficiency opportunities.

Energy teams. The establishment of an energy team is an important step toward solidifying a commitment to continuous energy efficiency improvement.[11] The energy team should primarily be responsible for planning, implementing, benchmarking, monitoring, and evaluating the organizational energy management program. However, its duties can also include delivering training, communicating results, and providing employee recognition (U.S. EPA, 2006).

In forming an energy team, it is necessary to establish the organizational structure, designate team members, and specify roles and responsibilities. Senior management needs to perceive energy management as part of the organization's core business activities. Thus, ideally the energy team leader will be someone at the corporate level who is empowered by support from senior-level management. The energy team should also include members from each key operational area within an organization and be as multi-disciplinary as possible to ensure a diversity of perspectives. It is crucial to ensure adequate organizational funding for the energy team's activities, preferably as a line item in the normal budget cycle as opposed to a special project.

Prior to the launch of an energy team, a series of team strategy meetings should be held to consider the key initiatives to pursue as well as potential pilot projects that could be showcased at the program's kickoff. The energy team should then perform facility audits with key plant personnel at each facility to identify opportunities for energy efficiency improvements. As part of the facility audits, the energy team should look for best practices in action to help highlight success stories and identify areas for inter-plant knowledge transfer.

A key function of the energy team is to develop mechanisms and tools for tracking and communicating progress and for transferring the knowledge gained through facility audits across an organization. Examples of such mechanisms and tools include best practice databases, facility benchmarking tools, intranet sites, performance tracking scorecards, and case studies of successful projects. Corporate energy summits and employee energy fairs are also effective means of information exchange and technology transfer.

To sustain the energy team and build momentum for continuous improvement, it is important that progress results and lessons learned are communicated regularly to managers and employees. It is also important that a recognition and rewards program is put in place.

A checklist of key steps for forming, operating, and sustaining an effective energy management team is offered in Appendix C.

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[11] For a comprehensive overview of establishing, operating, and sustaining an effective energy management team, please consult the U.S. EPA's *Teaming Up to Save Energy* guide available at http://www.energystar.gov/ (U.S. EPA, 2006).

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.

Although energy management systems are already widely disseminated in various industrial sectors, the performance of the systems can still be improved, which will reduce costs and increase energy savings further.

Specific energy savings and payback periods for overall adoption of energy monitoring and control systems vary greatly from plant to plant and company to company. A variety of process control systems are available for virtually any industrial process, and a wide body of literature is available assessing control systems in most industrial sectors. Table 4 provides an overview of classes of process control systems.

Table 4. Classification of control systems and typical energy efficiency improvement potentials

System	Characteristics	Typical energy savings (%)
Monitoring and Targeting	Dedicated systems for various industries, well established in many countries and sectors	Typical savings 4-17%, average 8% , based on experiences in the UK
Computer Integrated Manufacturing (CIM)	Improvement of overall economics of process, e.g. stocks, productivity and energy	> 2%
Process control	Moisture, oxygen and temperature control, air flow control "Knowledge based, fuzzy logic"	Typically 2-18% savings

Note: The estimated savings are valid for specific applications (e.g. lighting energy use). The energy saving cannot be added, due to overlap of the systems. Sources: (Caffal, 1995, Martin et al., 2000b).

Modern control systems are often not solely designed for energy efficiency, but rather for improving productivity, product quality, and the efficiency of a production line. Applications of advanced control and energy management systems are in varying development stages and can be found in all industrial sectors. Control systems result in reduced downtime, reduced maintenance costs, reduced processing time, and increased resource and energy efficiency, as well as improved emissions control. Many modern energy-efficient technologies depend heavily on precise control of process variables, and applications of process control systems are growing rapidly. Modern process control systems exist for virtually any industrial process. Still, large potentials exist to implement control systems and more modern systems enter the market continuously.

Process control systems depend on information of many stages of the processes. A separate but related and important area is the development of sensors that are inexpensive to install, are reliable, and will analyze in real-time. Development aims at the use of optical, ultrasonic, acoustic, and microwave systems that should be resistant to aggressive environments (e.g. oxidizing environments in a furnace or chemicals in chemical processes) and withstand high temperatures. Information from the sensors is used in control systems to adapt the process conditions, based on mathematical ("rule"-based) or neural networks and "fuzzy logic" models of the industrial processes.

Neural network-based control systems have successfully been used in the cement (kilns), food (baking), non-ferrous metals (alumina, zinc), pulp and paper (paper stock, lime kiln), petroleum refineries (process, site), and steel industries (electric arc furnaces, rolling mills).

New energy management systems that use artificial intelligence, fuzzy logic (neural network), or rule-based systems mimic the "best" controller, by using monitoring data and learning from previous experiences.

Process knowledge based systems (KBS) have been used in design and diagnostics, but are still not widely used in industrial processes. KBS incorporates scientific and process information and applies reasoning processes and rules in the management strategy. A recent demonstration project in a sugar beet mill in the UK using model based predictive control system demonstrated a 1.2% reduction in energy costs, while increasing product yield by almost one percent and reducing off-spec product from 11% to 4%. This system had a simple payback period of 1.4 years (CADDET 2000a).

Research for advanced sensors and controls is ongoing in all sectors, and is funded with both public and private research funds. Several projects within the Advanced Manufacturing Office (formerly known as the Industrial Technologies Program) are attempting to develop more advanced control technologies. Outside the United States, there is much attention in Japan and Europe to the development and demonstration of advanced controls. Future steps include further development of new sensors and control systems, demonstrations at a commercial scale, and dissemination of the benefits of control systems in a wide variety of industrial applications.

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/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). Operational costs would decrease by about $0.1/ton raw material (Hollingshead and Venta, 2009). Replacing pneumatic conveyors with high capacity bucket elevators for raw material transfer to the preheaters and the blending silos can reduce power consumption by 2/3, while the investment cost is estimated at $0.4/ton raw material (Bojdys, 2002). The replacement of pneumatic conveying systems with mechanical transport systems for two kiln feeds in two Indian cement plants resulted in energy savings of 0.7-1.3 kWh/ton of raw material while the investment costs ranged between $0.2 and $0.9/ton raw material (UNFCCC, 2008a). Conversion to mechanical conveyors is cost-effective when replacement of conveyor systems is needed to increase reliability and reduce downtime. As the investment costs found in literature vary drastically, to determine the actual investment costs and payback period of such a project a site specific assessment is required.

An improved dense phase pneumatic conveying pipe system has shown to offer substantial energy savings, smaller needs in dedusting equipment and lower wear (Dikty et al. 2008). The bulk material is supplied through feeding devices (i.e. pump, pressure vessel) to a fluidized conveying (FLC) line. The conveying gas coming from the compressed air generator is divided into two streams; one gas stream is supplied at the entrance of the FLC pipe, while the other gas stream travels in parallel to the FLC pipe, in a so called aeration pipe, supplying air at several points to the FLC pipe. In this way, the transferred material is raised from the bottom of the pipe and flows into the gas stream in a similar process to an air activated gas conveyor (AAGC). The air flow needs to be controlled in order to avoid blockages. The use of an FLC pipe conveying system instead of a conventional pipe system in two cement plants resulted in 38-47% energy savings, while the dedusting air quantity decreased by 61% (Dikty, et al. 2008). Energy savings are estimated at 1.0 kWh/ton raw material.

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).

Improved raw material blending may reduce heat requirements by 0.02 MBtu/ton clinker and power requirements by 0.73 kWh/ton raw material, while production could also increase by 5% (Hollingshead and Venta, 2009). The investment cost was estimated at $1.8/ton raw material with an additional operational cost of $0.01/ton (Hollingshead and Venta, 2009).

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). Power requirements in modern gravity-type silos (inverted cone or multi outlet) range between 0.1-0.5 kWh/ton raw meal (Chatterjee, 2004; F.L.Smidth, 2007; IBAU HAMBURG, 2009). Multi outlet gravity type silos have the lower power consumption of about 0.1 kWh/ton raw material (Chatterjee, 2004). 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 0.5-2.3 kWh/ton raw meal (Fujimoto, 1993; Holderbank, 1993; Alsop & Post, 1995, Cembureau, 1997; Gerbec, 1999; Chatterjee, 2004). 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%. Water addition during raw material grinding needs to be controlled in order to obtain slurry with a close to optimum water content (32-40% water content) and reduce fuel consumption in the kiln (IPPC, 2010). Chemical additives may be used to reduce water use.

Advanced Raw Meal Grinding (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. Vertical roller mills, for a medium raw material hardness and medium fineness product, require less energy than 9 kWh/ton (Harder, 2010b). Energy savings of 6 and 7 kWh/ton raw materials (Cembureau, 1997; Hollingshead and Venta, 2009) are assumed through the installation of a vertical or horizontal roller mills. 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.

Rollers are pressed down using spring or hydraulic pressure while hot gas is supplied during grinding for raw material drying (Chatterjee, 2004). These air-swept vertical roller mills can handle materials containing up to 20% moisture while ball mills can handle moisture levels of about 12% (Chatterjee, 2004). 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 uses roller mills. Estimates on investment costs vary widely from $5/ton raw material (Holderbank, 1993) to $24/ton raw material (Hollingshead and Venta, 2009). Operational costs will decrease by $0.20/ton (Hollingshead and Venta, 2009). Vertical roller mills have 10-20% higher capital costs when compared to ball mills (Schneider, 2008). In 2003, Ciment Québec in Canada increased capacity by 50 mtph and improved raw meal fineness by replacing an old vertical roller mill with a new one (Papillon et al., 2004). The investment cost for a new grinding plant is estimated at $5.6/ton raw material; however the investment cost for a new vertical roller mill (keeping the old plant foundation and peripherals) is estimated at $1.8/tonne raw material (Papillon et al., 2004).

The use of roller presses is limited to the grinding of non-abrasive materials with low moisture content. Energy use can be 50% lower when compared to ball mills (Schneider, 2008). According to Chatterjee (2004) with the use of roller presses in combination with a V-separator, energy requirements can be as low as 14 kWh/ton raw material. At the TXI cement plant in California, the replacement of the highly inefficient ball mills with high-pressure roller presses increased throughput and reduced energy use from 19.1 kWh/ton to 7.8-8.1 kWh/ton resulting in approximately 58% energy savings (Klotz et al., 2009). The investment cost is estimated at $4.9/ton raw material (Klotz et al., 2009).

With the use of horizontal roller mills (Horomill®) energy use can be 50% lower than in ball mills (Schneinder, 2008). If the raw materials have high moisture levels, an external dryer will be required (Schneinder, 2008). In a cement plant in Mexico, electricity use for grinding limestone and clay in a Horomill® was reported to range between 6 and 7 kWh/ton of raw material (Wang and Forssbergh, 2003).

Separate Raw Material Grinding (Dry process). Different raw materials are characterized by different grindability. Materials harder to grind, such as sand and blast furnace slag, require higher amounts of energy to reach the desired particle fineness and decrease the throughput of the combined material grinding system. It can be more efficient to grind the materials with a high proportion in the raw mix in mills with low specific energy use, and the ones harder to grind in vertical roller mills or ball mills (ECRA, 2009).

When all materials are ground together, softer components may be ground finer than required, while harder components may not be sufficiently ground. Separate raw material grinding, will allow a more precise particle size distribution of different raw meal components, with favorable effects on raw mill burnability and energy use. Electricity savings are estimated at 0.55-0.77 kWh/ton raw meal (ECRA, 2009). The investment cost is substantial when a vertical mill is replaced by a ball mill and high pressure grinding rolls, estimated by ECRA (2009) at approximately $15/ton raw material. When two ball mills are already in use, the replacement of one ball mill with high pressure rollers will require a much lower investment (ECRA, 2009). This measure is considered financially sensible when high rates of hard-to-grind materials (i.e. slag) are used.

Raw Meal Process Control (Dry process). 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). Vasavadatta Cement, in India, used roller presses for raw meal grinding. With the installation of the Automation Expert System, by F.L.Smidth, production increased by 8% while power use decreased by 5%.

High-Efficiency Classifiers/Separators. A recent development in efficient grinding technologies is the use of high-efficiency (third generation) classifiers or separators. Classifiers separate the finely ground particles and recycle coarse particles back to the mill. High-efficiency classifiers can be used in both the raw materials mill and in the finish grinding mill.

Old, first generation classifiers did not make use of fresh air as they were equipped with an internal fan and had low separation efficiencies of 50-60%. Second generation classifiers (60-75% separation efficiency) have improved air recirculation and separate centrifugal movement. The high-efficiency classifiers of the third generation, 80-90% separation efficiency, have an improved air distribution system and advanced control of the air-flow (Chatterjee, 2004).

In high-efficiency classifiers, the material stays longer in the separator, leading to sharper separation, thus reducing overgrinding. Various concepts of high-efficiency classifiers have been developed (Holderbank, 1993; Süssegger, 1993). 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; Süssegger, 1993). Replacing a conventional classifier with a high-efficiency classifier has led to 15% increases in the grinding mill capacity (Holderbank, 1993; ECRA, 2009) 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 $2.0/annual ton raw material production (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. A vertical roller mill was ordered for the new kiln line V at the Roberta plant in Calera, Alabama with a capacity of 37.5 ton/hour. The mill 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, developed for coal grinding in the cement industry, have been widely accepted, and have achieved an 86% market share. Electricity consumption for a vertical roller mill is estimated at 16-18 kWh/ton coal (Cembureau, 1997). MPS vertical roller coal mills, currently considered best practice (Worrell et al., 2008a), have low power requirements; 9-33 kWh/ton anthracite, 5-11 kWh/ton pit coal, 7-17 kWh/ton lignite, 6-15 kWh/ton petroleum coke (Burkhard and York, 2005). 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). The replacement of tube mills with the highly efficient MPS vertical roller mills will result in 14-21 kWh/ton of coal lower power consumption (Burkhard and York, 2005).

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 under a variety of fuels. 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. Modern systems use so-called “fuzzy logic” or expert control, or rule-based control strategies. Expert control systems do not use a modelled 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 (MPC) 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 and McGarel, 2001a). Several benefits derived from the application of an MPC system on the dry precalciner of a Capitol Cement plant in Mexico. The product quality improved, kiln operation stabilized, excess O_2 content and NOx emissions decreased, tertiary air temperature increased while product throughput increased (Boe et al., 2005).

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. The installation of a Pavillion process control system in the kiln of Dyckerhoff’s site in Germany, increased the feed rate by 4.2%, and stabilized the use of alternative fuels in the kiln beyond 50% of fuel input.

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%. According to ECRA (2009), energy use in a kiln that utilizes a process control system is 0.04-0.17 MBtu/ton clinker lower when compared to a kiln without a process control system, while electricity use may also be lower by 0-0.9 kWh/ton. 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. ECRA (2009) estimates an investment cost of $0.16-0.22/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, 2001a).

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 NOx 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 NOx 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 optimize 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).

The recirculation of combustion gases from the end of the kiln back to the flame region improves flame stability and protects the kiln surface from burning particles (Manias, 2004). Internal recirculation can be achieved with a bluff body placed in the center of the burner nozzle or with the use of a swirl in the fuel or the primary air jet stream. Whether the swirl will be used in the primary air or the fuel will depend on the fuel fired. Effective designs of gas firing systems make use of a swirl for both primary air and fuel, typical oil firing systems make use of a swirl only for primary air, while solid fuel firing systems do not normally require a swirl to achieve flame stability (Manias, 2004). Great care is required, as high rates of recirculation can have adverse effects on fuel efficiency and create extreme combustion conditions.

A recent technology that has been demonstrated in several locations is the Gyro-Therm technology that improves gas flame quality while reducing NOx 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% (CADDET, 1997a). 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; Videgar et al., 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. The average payback period is estimated to less than a year (FCT, 2009).

Mineralized Clinker. Mineralizers and fluxes are substances used to improve raw mill burnability. Fluxes (i.e. Al_2O_3 and Fe_2O_3) can lower the viscosity of the melt, and the temperature at which clinker starts to form. Mineralizers (i.e. fluorine) promote the formation of clinker. With the use of mineralizers, the temperature in the sintering zone can be reduced, resulting in less fuel consumption. A 360^oF (200^oK) temperature decrease can result in 5% fuel savings. Lower sintering temperatures could also decrease the formation of NOx emissions by 10-15%; with reductions of up to 50% being reported (IPPC, 2010). The use of mineralizers requires great care as high mineralizer quantities can decrease the setting time and the development of early compressive strength in concrete.

Fuel savings are estimated at 0.04-0.11 MBtu/ton clinker while electricity requirements could increase by 0-0.9 kWh/ton clinker (ECRA, 2009). The fuel savings can be easily offset by the high costs of the fluxing agent/mineralizer. The use of alternative fuels with high fluoride content could be cost-effective but their availability is limited. No significant investment is required although usually weigh feeders, and pneumatic conveying equipment will have to be installed (F.L.Smidth, 1995).

In 2004, one plant in North America used fluorspar at a rate of 0.5% CaF_2 in combination with potassium sulfate. The outcome was improved kiln operation, lower levels of kiln dust formation and energy savings of 0.10 MBtu/t clinker (Johansen and Bhatty, 2004). In the past, more plants in North America used mineralizers, and although they achieved marginal energy savings, increase in production by 5-10% and in some cases improved clinker grindability, they also had to deal with severe coating formation and preheater blockages by volatiles and fines (Bhatty, 1996).

In Europe there are several cement plants successfully producing mineralized clinker (IPPC, 2010). Åalborg Portland, in Denmark, uses a well regulated content of fluoride and gypsum, and achieves 3% energy savings and 50% NOx emission reduction while they produce a highly hydraulic reactive product which allows them to substitute clinker with filler (ESP dust) at high rates of up to 20% (Borgholm et al., 1996). Clinker substitution results in significant energy and CO_2 emission savings. According to F.L. Smidth energy savings of 0.05-0.11 MBtu/ton clinker have been achieved in several plants, while in one case the energy use for grinding was reduced by 40% (F.L.Smidth, 1995).

There are two ways to profit from increased raw meal burnability (Johansen and Bhatty, 2004): i) by reducing the sintering temperature, and ii) by maintaining the temperature at previous levels and shortening the retention time. A shorter retention time is equivalent to an increase in throughput, resulting in fuel savings from the decrease in heat losses from the cooler, kiln, and preheater. Incentives for using mineralizers can come from increased production, longer refractory lifetime, preparing coarser raw mix, and the ability to use low cost fuels (high sulfur content) (Johansen and Bhatty, 2004; F.L.Smidth, 1995). The greatest advantage though, is the production of a product characterized by increased hydraulic activity that creates a significant potential for clinker substitution (Borgholm et al., 1996).

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. The majority of U.S. plants have indirect firing systems. 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%. Depending on the secondary air temperature, a 5-10% primary air reduction translates into 43-69 kBtu/ton clinker energy savings in conventional cement kilns and about half of this in modern kilns (ECRA, 2009). 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 NOx emissions, better operation with varying fuel mixtures, and reduced energy losses. This technology is standard for modern plants. The investment cost for the retrofit of a mono-channel burner into a multi-channel burner is estimated by Hollingshead and Venta (2009) at $1.20/annual ton clinker capacity. Energy savings range between 43 and 54 kBtu/ton clinker (ECRA, 2009; Hollingshead and Venta, 2009) while production is reported to increase by 5% (Hollingshead and Venta, 2009).

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 NOx 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. The investment to switch from a direct to an indirect firing system is estimated at $8.4/annual ton clinker capacity (Hollingshead and Venta, 2009). The result will be a reduction in fuel use by 162 kBtu/ton clinker and an increase in production by 10%, while power use is expected to increase by 0.5 kWh/ton clinker due to the power needs of conveyor blowers, high pressure fans and dust collectors (Hollingshead and Venta, 2009). In 1997 CalPortland's plant in Colton (California) implemented an indirect firing system for their plant, resulting in NOx 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 3-10% have been found on the basis of annual production (Mayes, 2001; Gotro, 2001; Staudt, 2009a), while according to a number of short term experiments, an oxygen enrichment of 30-35% resulted in 25-50% increase in cement kiln capacity (ECRA, 2009). In one facility a 3-5% decrease in fuel use was reported (Staudt, 2009a). According to ECRA (2009), energy savings in the range of 86-172 kBtu/ton clinker may result, while power use is expected to increase by 9-32 kWh/ton clinker._Any energy savings will depend on the electricity consumed for oxygen generation (approximately 0.01 kWh/scf) (Shafer, 2001). Oxygen enrichment is unlikely to result in net energy savings. Also, if the injection process is not carefully managed higher NOx emissions may result (Mayes, 2001). The investment cost for an oxygen enrichment system, based on a 2 million tonne per year clinker capacity plant, is estimated at $3.2-6.3/ton clinker (ECRA, 2009; Staudt, 2009a). 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).

Mixing Air Technology (MAT). The injection of a high-pressure air stream into the kiln results in improved mixing of the stratified gas layers created within the kiln. The result is improved burnability, reduced fuel use, lower emissions and improved kiln stability (Staudt, 2009b). Mixing air technology, developed by Cadence, can be used in combination with Mid Kiln Firing or Riser Duct Firing system. Typically, a Mid Kiln Firing system can replace about 15% of heat requirements with alternative fuels. Further alternative fuel replacement will lower the flame temperature and jeopardize the production of high quality clinker. When MAT is adopted, the alternative fuel substitution rate can increase by another 15% in long kilns, 8% in preheater kilns, and 4% in precalciner kilns (Cadence, 2010a; Cadence 2010b). MAT can also be beneficial without Mid Kiln Firing. MAT can decrease NOx emissions by facilitating staged combustion, SO_2 emissions by improving oxidizing conditions in areas where there is ample free lime, CO emissions and CO_2 emissions as the kiln output will slightly increase. The investment cost is estimated at $1.1/ton clinker (assuming $520,000 per kiln and an average kiln capacity of 440,000 tonnes). Fixed annual costs will be similar to that of a low NOx burner. Power use may increase by 0.023 kWh/ton clinker (Staudt, 2009b). Improved heat transfer can reduce heat demand by 5% in preheater kilns and by 0-1% in precalciner kilns (Cadence, 2010b). MAT is mainly installed in wet, long dry and preheater kilns and although not very common, MAT can also be installed in precalciners to facilitate staged combustion (Staudt, 2009b).

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 is prudent to control 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 (Lowes, 1990; COWIconsult, 1993; Venkateswaran and Lowitt, 1988). Case studies from three cement plants in China have reported energy savings of 0.35-0.54 MBtu/ton clinker (ITIBMIC, 2004). 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.

Preheater Shell Heat Loss Reduction. The outer part of the upper preheater vessels and the cooler housing can also be insulated. The energy savings are estimated at about 17 kBtu/ton clinker, at an investment cost of $0.30/ton (Hollingshead and Venta, 2009).

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. An investment cost of $0.60/ton clinker is estimated to reduce energy use by 54 kBtu/ton clinker (Hollingshead and Venta, 2009).

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 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.

Conversion to Efficient Clinker Cooler Technology. Four main types of coolers are used in the cooling of clinker: shaft, rotary, planetary, travelling (2nd generation) and modern reciprocating grate coolers (3rd generation. 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 grate coolers (3rd generation) have a higher degree of heat recovery (70-75% heat recuperation efficiency) than existing grate coolers (2nd generation) (50-65% heat recuperation efficiency), while they also reduce fluctuations in recuperation efficiency (i.e. increasing productivity of the kiln) (ECRA, 2009). When compared to planetary or rotary coolers, additional heat recovery is possible with grate coolers at an extra power consumption of 0.9 to 5.4 kWh/ton clinker (COWIconsult et al., 1993; Vleuten, 1994; ECRA, 2009; Hollingshead and Venta, 2009). 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. Depending on the degree of reconstruction needed (new exhaust fan, shortening of the kiln, new cooler filters) investment costs may vary widely. The cost of converting a planetary cooler into an efficient reciprocating grate cooler of the latest generation, with a 6,600 tons/day capacity, is estimated by ECRA (2009) at $9.4-12.6/ton clinker. Hollingshead and Venta (2009) estimate the investment cost at $10/ton clinker. Annual operation costs increase by $0.5-0.2/ton clinker (Jaccard and Willis, 1996; Hollingshead and Venta, 2009; ECRA, 2009) while a 20% increase in throughput is expected (Hollingshead and Venta, 2009).

In recent years several new concepts of clinker coolers have been introduced. The Cross-Bar Cooler, 4th generation, developed by F.L.Smidth, has a completely static grate floor and the clinker travels from the one side of the cooler to the other via moving thrust bars. Other clinker coolers based on similar principles are the Polytrack developed by Polysius, the Eta Cooler by Claudius Peters and the Pyrofloor cooler by KHD. One of the latest developments in clinker coolers, 5th generation, was developed in 2010 by CemProTec and it consists of a revolving disc instead of traveling grates. This new type of clinker cooler, although not yet proven in full-scale, can achieve 100% transport efficiency and is characterized by lower wear.

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 2,200-5,000 tpd) and planetary coolers (used for 10% of the world capacity for plants up to 3,300-4,400 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. Hollingshead and Venta (2009) estimate the energy savings from upgrading an old clinker cooler at 0.08 MBtu/ton clinker, corresponding to an increase in throughput of 4%. The cost for retrofitting an old grate cooler to a modern reciprocating grate cooler is estimated at $0.6-1.8/annual ton clinker capacity (ECRA, 2009; Hollingshead and Venta, 2009).

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. In a cement plant in India, the replacement of a number of the jet ring coolers with static grate coolers achieved energy savings of 0.08 MBtu/ton clinker (Goyenka et al., 2000). 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. Cement plants employing the semi-dry process can be advantageous when they need to process raw materials with high moisture content or raw materials that contain high levels of sulphur that would in case of a dry process plant, require a complex gas scrubbing system (Harder, 2010a). 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 tonnes 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. 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). Hollingshead and Venta (2009) estimated the energy savings at 0.64 MBtu/ton clinker. 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). In another study (Hollingshead and Venta, 2009), the investment cost for filter presses and conveyer equipment is estimated at $3.70/ton clinker while $0.20/ton clinker are the additional operating costs.

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 5.8 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. In 2006, Padeswood Works (UK) replaced two wet kilns, with a preheater precalciner kiln and reduced energy use by 1.9 MBtu/ton clinker (IPPC, 2010). Energy savings could be higher if waste was not used as fuel. The cost of converting a wet plant to a dry process plant may be high, as it involves the demolition and reconstruction of an existing facility, except for half of the kiln. Costs may vary between $50/annual ton clinker capacity and $100/annual ton clinker capacity (van Oss, 1999; Nisbet, 1996). Hollingshead and Venta (2009), estimate the investment required for installing preheaters/precalciner, new vertical raw mill and new cooler, at $155/ton clinker. Due to improvements in grinding (new mill), electricity use will decrease by 15 kWh/ton clinker. Clinker production is expected to increase by 50%.

6.6 Clinker Production – Dry Process 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 older kilns this amounts to savings of 0.6-1.4 kWh/ton (Birch, 1990; ECRA, 2009). Electricity savings of 3 kWh/ton clinker and an increase in capacity of 3% have also been reported (Hollingshead and Venta, 2009). 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. The investment cost for replacing 3 cyclone stages was estimated by ECRA (2009) at $5.0-6.3/annual ton clinker capacity while in another study (Hollingshead and Venta, 2009), the cost for replacing the inlet and the outer cyclones was estimated at $3.5/annual ton clinker. The replacement of older preheaters with low pressure drop preheaters can be economically sensible when the preheater tower does not have to be rebuilt (ECRA, 2009).

Heat Recovery for Power Generation. 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 used for raw material and fuel drying or for power generation. Heat recovery for cogeneration can result in significant electricity savings of up to 30% and primary energy savings of up to 10% (Khurana et al., 2002; Engin and Ari, 2005; VDZ and PENTA, 2008). Cogeneration has limited application for plants with in-line raw mills, as the heat in the kiln exhaust is used for raw material drying. In addition, the excess heat availability will depend on seasonal rainfall and geology (IPPC, 2010). Only in long-dry kilns is the temperature of the exhaust gas sufficiently high, to cost-effectively recover the heat for power generation via a conventional power generating system.[12] Steam 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). Other bottom cycle cogeneration systems include the Organic Rankine Cycle (ORC) (also referred to as ORMAT energy converter [OEC]) where a refrigerant is used instead of water, with a boiling point much lower than water, and the Kalina Cycle. ORC and Kalina Cycles can operate efficiently at low and moderate heat temperatures (Börrnert, 2011; Carolyn, 2009). Steam turbine systems have been installed in many plants worldwide and have proven to be economic (Steinbliss, 1990; Jaccard and Willis, 1996; Neto, 1990). While electrical efficiencies are still relatively low (up to 20-25%), based on several case studies power generation may vary between 10 and 23 kWh/ton clinker (Scheur & Sprung, 1990; Steinbliss, 1990; Neto, 1990, ECRA, 2009); approximately 7-9 kWh/ton clinker from the cooler's waste air and 8-11 kWh/ton clinker from the kiln gases (ECRA, 2009). In China, higher power generation levels of 22-36 kWh/ton clinker are obtained with supplementary fired boilers (VDZ and PENTA, 2008). For a waste heat recovery system electricity savings of 20 kWh/ton clinker are assumed. ECRA (2009) estimates the investment costs of a waste heat power generation unit for a 2 million tonne per year clinker producing facility at $9-16/ton clinker. Operational costs are estimated to decrease by $0.4-1.5/ton clinker. A 4,100 tpd four stage preheater cement plant in India installed an 8 MW waste heat recovery power plant with a capital investment of $19 million (VDZ and PENTA, 2008). In 2010, 3 U.S. cement plants generated 226 million kWhs (USGS, 2012a).

The more efficient the clinker kiln, the lower temperature the waste gases will be. For a 6-stage pre-heater kiln, exhaust gases can be significantly below 572^{o}F (300^{o}C) (Börrnert and Bürki, 2010). The varying temperature of grate cooler exhaust air, ranging between 330-560^{o}F (165-304^{o}C), results in complications in operation of the steam turbines. It has been observed that in order to overcome this, exhaust air temperatures are raised by adding extra fuel in the kilns, increasing the specific energy use to unacceptable levels (Bronicki, no date; Legmann and Citrin, 2004). ORC systems can operate with waste heat temperatures lower than 200^{o}F (93^{o}C) (Carolyn, 2009). An example of successful application of ORC in the cement industry is the Heidelberg Cement plant in Lengfurt, Germany, where unused waste heat from the grate cooler 572^{o}F (300^{o}C) is used to generate 1,300 kW of electricity, satisfying approximately 10% of the plant's electricity needs and reducing CO_2 emissions by 7,000 tons per year (Bronicki, no date). A new ORC plant, is currently under construction in Switzerland,

[12] 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.

and is expected to generate 20% of the plant's electricity requirements by utilizing waste gases from the pre-heater and the clinker cooler (Börrnert, 2011). As reported by Börrnert (2011) an additional benefit will be the reduction in water use, by stopping the water spraying in the conditioning tower; pre-heater gases will now be cooled by the heat exchanger in the power plant. ORC and Kalina Cycles can generate 1.3-1.7 times more electricity than conventional steam systems (Bell, 2007) however, they are characterized by higher investment costs. Investment costs for Organic Rankine Cycle systems are estimated at $1,300-4,000/kW and for Kalina Cycle systems at $1,100-3,000/kW (Carolyn, 2009; Bell, 2007; Mirolli, 2005). A Rankine cycle power plant would cost about $1,100-1,400/kW (Bell, 2007).

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. 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 (see Table 1). 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 (Duplouy and Trautwein, 1997). In the same project, the power consumption was reduced by 25%, due to the replacement of fans and the finish grinding mill. 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.

Turning a long-dry kiln into a preheater kiln would result in even higher fuel savings of about 1.4 MBtu/ton clinker while it would decrease the operational and maintenance costs by $0.10/ton (Hollingshead and Venta, 2009). Hollingshead and Venta (2009) estimated the investment costs for a new pyroline (half kiln) and minor improvements of the grinding system at $105/annual ton clinker.

Increase the Number of Preheater Stages. The addition of a preheater stage will not always result in system energy savings. The optimum number of stages is determined by the moisture content of the fuel and raw materials that needs to be dried. When the raw materials' moisture content is above 8%, the drying heat requirements are high and it is more cost- and energy-effective to operate the kiln with a 4 or even a 3-stage preheater (Bolwek et al., 2006). A kiln with a 3-stage preheater will use over 0.2 MBtu/ton more energy than a 5-stage preheater (see Table 1) however, by using the heat from exit gases for material drying, plant's efficiency will not be affected (Bolwek et al., 2006).

According to Hollingshead and Venta (2009) the energy savings for increasing from a 5- to a 6-stage preheater are around 0.12 MBtu/ton clinker while production will increase by 3%. The investment cost was estimated at $15/annual ton clinker, including the costs for exit duct modifications and tower structural improvements. In another study (ECRA, 2009) the costs for adding two preheater stages were estimated at $2-5/annual ton clinker without including the site specific costs that concern tower modification or rebuilding or fan replacements. Vikram Cement in India added a sixth preheater stage to its preheater kiln and saved 0.1 MBtu/ton clinker (0.111 GJ/tonne) while electricity use increased by 1.1 kWh/ton. The capital costs were $2.6 per ton clinker (19.RMB/t clinker) (UNFCCC, 2008b). Adding a preheater stage can be a considerable rebuild for a cement plant, and the adoption of such an energy efficiency measure could trigger permit adaptation, require new source review and extra measures in order to meet the BACT requirements.

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 NOx 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 NOx emission reduction. Retrofitting the pre-calciner at the Lengerich plant of Dyckerhoff Zement (Germany) in 1998 reduced NOx 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 NOx 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 SOx 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 Kiln 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.

According to Hollingshead and Venta (2009), the throughput can increase by 40%, while clinker cooler and material grinding upgrades will need to take place in order to handle the increase in capacity. Energy savings are about 0.9 MBtu/ton clinker while no change in power consumption is expected. Operation and maintenance costs are expected to decrease by $0.10/ton clinker. The investment costs are estimated by Hollingshead and Venta (2009) at $115/ton clinker annually, significantly higher than other studies, as upgrades in the clinker cooler and raw grinding systems are also taken into account. According to another study (ECRA, 2009), energy use will be reduced by 0.85 MBtu/ton clinker while electricity may decrease by up to 5 kWh/ton clinker.

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, 2001a). F.L.Smidth markets the ProcessExpert® system, which has shown to increase the throughput and reduce energy use in roller presses. At Vasavadatta Cement (India), throughput increased by 8% and energy use decreased by 5% in the cement mill, while in the coal mill throughput increased by 9% and energy use decreased by 3%. 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 a finish ball mill (Martin et al., 2001). Titan America, with the implementation of Pavillions' APC (Advanced Process Control) cement solution in two facilities in Roanoke, Virginia, achieved an annual reduction in energy costs of more than $120,000 and a significant increase in mill throughput, while it also improved product quality. Electricity use decreased by 3.5 kWh/ton clinker and mill throughput increased by 4.8 and 5.7% in the two mills. In another application of Pavillions' process control system at Dyckerhoffs' site in Germany, mill throughput increased by 4.5-9.3%, while energy use decreased by 2.4-5.8% depending on the type of cement being ground. Payback periods are typically between 6 and 8 months (Martin and McGarel, 2001a).

A new advancement in cement grinding is the real-time particle size measurement. The on-line Insitec Fineness Analyzer from Malvern Instruments is a laser diffraction system that generates real-time particle size data. In this way cement is ground as much as required in order to meet specifications (Levonian et al., 2009). Florida Rock Industries, with the use of Pavillion's Cement Grinding Application and the Insitec Fineness Analyzer, reduced electricity use for grinding by 17% and increased 1-day strength by 15%. Based only on the energy savings the payback period was estimated to less than 2 years. Vulcan Materials Company in Alabama had prior to any advancement in process control, specific electricity consumption for cement grinding of about 41.8 kWh/ton cement. With the use of Pavillion's APC system, electricity use dropped to 39.1 kWh/ton cement. When the Insitec Fineness Analyzer was also employed, electricity use dropped to 33.3 kWh/ton cement (Levonian et al., 2009). The 1-day strength increased by 15% with a product Blaine 10% lower than before. As product quality increased, C_3S (alite) levels (see also the paragraph on decrease in Lime Saturation Factor) could be reduced, decreasing in this way the plant's operational costs.

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 18-30 kWh/ton clinker, including roller mills, and roller presses which can be used in combination with ball mills for pre-grinding, or as stand-alone units for finish grinding (Alsop and Post, 1995; Cembureau, 1997; Seebach et al., 1996; Hendriks et al., 2004; Harder, 2010a; Harder, 2010b; Schnatz, 2009; Schneider, 2008). Some new mill concepts may lead to a reduction in operation costs of as much as 30-40% (Sutoh et al., 1992). New designs of the roller mills allow for longer operation times (> 20,000 hours).

Replace Ball Mills with Vertical Roller Mills

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). Typical roller mills have capacities of 200 tph. However, high capacity, 350 tph roller mills using 4 or more rollers, have also been developed (Harder, 2010b). 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). The typical energy use for roller mills lies within 18 to 20 kWh/t clinker, depending on cement fineness. In 2002, Phoenix Cement Company installed the first vertical roller mill used for cement grinding in the United States, and decreased power consumption by 15 kWh/ton cement (Simmons et al., 2005). In 2006, CalPortland Cement plant in Mojave replaced several ball mills with a state-of-the-art vertical roller mill system and decreased power use for cement grinding by 40% (Coppinger, 2010). In India, a cement plant achieved savings in power consumption of about 15 kWh/ton slag cement (3400 Blaine) (Keyssner and Abraham,_2005). Power savings will depend on cement fineness and are estimated at 9-20 kWh/t cement. In literature, investment costs vary widely from $6.6/ton cement (Price et al., 2009) to $39/ton cement (Hollingshead and Venta, 2009). Maintenance costs will increase by $0.17/ton cement (Hollingshead and Venta, 2009). Although it has been indicated that process advantages cannot justify the high installation costs of a vertical roller mill for a new cement grinding line, the comparison of the actual installation costs of the first vertical roller mill for cement grinding in the U.S. and a closed circuit ball mill system, is in favor of a vertical roller mill (Terembula, 2004). Vertical roller mills can achieve increased cement fineness; however, due to variations in particle size distribution and therefore cement performance, extra quality control will be required (ECRA, 2009; Fortsch, 2005).

Replace Ball Mills with Horizontal Roller Mills (Horomill®)

A new mill concept is the Horomill®, first demonstrated in Italy in 1993 (Buzzi, 1997). Nowadays, there are more than 40 Horomills® installed around the world mainly used for cement grinding (Harder, 2010b). 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 700-1,000 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 3,200 cm^2/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; Wang and Forssberg, 2003). According to more recent estimates, energy use lies within 16 to 19 kWh/ton cement (Hendriks et al., 2004). Typical energy savings for replacing a ball mill with a horizontal roller mill are 30% for cement grinding and 40% for slag grinding, while for raw material grinding they can reach up to 50% (Schneider, 2008). A recent development in horizontal roller mills is the BETA-mill. In a BETA-mill the bed thickness and the grinding pressure can be adjusted independently, achieving in this way even higher energy efficiencies (Schneider, 2008). Main barrier to the wide acceptance of Horomills® is its low throughput. Currently, the largest Horomill in operation has a capacity of 120 tph (Harder, 2010b). Equipment wear is similar to high pressure roller mills. The investment cost is estimated to be similar to high-pressure roller presses at $16/ton cement (Hollingshead and Venta, 2009).

Use High-Pressure Roller Presses With/Without Ball Mills

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). When a ball mill is already in use, the addition of high-pressure roller presses, also known as high-pressure grinding rolls (HPGR), is considered the most preferable way to increase capacity and reduce energy use (Harder, 2010a). In a high-pressure roller press system, two rollers pressurize the material up to 3,500 bar (Buzzi, 1997), improving the grinding efficiency dramatically (Seebach et al., 1996). Several grinding system configurations can be employed such as pregrinding, hybrid grinding, semi-finish grinding and finish grinding. Depending on product fineness but also on system configuration energy use can decrease by 10-50% (Harder, 2010a; Patzelt, 1992; Schnatz, 2009; Schneider, 2008, Chatterjee, 2004) while capacity can increase by 100% compared to close circuit ball mill grinding systems (Harder, 2010a; Patzelt, 1993; Schneider, 2008). In general, the higher the amount of cement ground in the roller presses, the more significant the energy savings will be (Harder, 2010a; Aydoğan et al. 2006). Finish grinding systems with roller presses appear to have the lowest energy consumption of 17-19 kWh/ton cement (Schnatz, 2009; Harder, 2010b). In combined grinding circuits the energy use can range between 22 and 34 kWh/ton (Schnatz, 2009; Aydoğan et al. 2006; Benzer et al., 2011). Table 5, shows the energy use of several circuit configurations using high-pressure roller presses and ball mills based on a study from Aydoğan et al. (2006).

Table 5. Specific energy consumption of HPGR circuits in a variety of configurations

Configuration	Overall circuit specific energy use (kWh/ton)	HPGR circuit specific energy use (kWh/ton)
Open circuit HPGR – closed circuit ball mill grinding	34.19	4.05
Open circuit HPGR with partial recycling – closed circuit ball mill grinding	29.57	8.93
Hybrid grinding	29.85	-
Closed circuit HPGR – closed circuit ball mill grinding	21.65	8.02

Semi-finish grinding	23.03	9.80

Source: Aydoğan et al. 2006

The addition of a pre-grinding system to a ball mill will result in savings of 6-20 kWh/ton cement (Cembureau, 1997; Holland et al., 1997; Scheur and Sprung, 1990). Energy savings from the addition of roller presses as a pre-grinder are estimated at 5.4-10 kWh/ton cement (Sukkar et al., 2005; Hollingshead and Venta, 2009; Benzer et al., 2011). Energy savings for replacing ball mills with roller presses for finish grinding are estimated at 11-25 kWh/ton cement. Capital cost estimates for installing a new roller press vary widely in 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). Hollingshead and Venta (2009) estimate that investment costs for a roller press system used for finished grinding at $16/ton cement while for a roller press used in combination with an existing ball mill, the changes are considered minimal, and investment costs are estimated at $6.5/ton clinker. The capital costs of roller press systems are lower than those for other systems (Kreisberg, 1993) or at least comparable (Patzelt, 1993). With the use of roller presses the feed size of the ball mills is significantly altered, therefore several adjustments in ball size and load, compartment length and diaphragms will need to take place in order to fully utilize the benefits of roller presses (Aydoğan et al., 2006).

High Efficiency Classifiers/Separators. A recent development in efficient grinding technologies is the use of high-efficiency, third generation, 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 1.7-3.9 kWh/ton cement (Salborn and Chin-Fatt, 1993; Sussegger, 1993; Hollingshead and Venta, 2009; ECRA, 2009; Simmons et al., 2005). 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.Smidth/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) while at Cementir's cement plant, in Taranto (Italy) electricity use decreased by 7 kWh/ton cement

(Pottier and Niel, 2008). The replacement of old classifiers with highly-efficient, third generation classifiers, at Phoenix Cement, Germany, achieved reliable operation and availability, while it also improved product quality and increased throughput (ZKG, 2010). The investment costs are estimated between $1.5 and $3.0/ton cement (Holdebank, 1993; ECRA, 2009; Hollingshead and Venta, 2009; ZKG, 2010; Clauser, 2010).

Improved Grinding Media. Around 60% of all mills in cement plants are ball mills (PCA, 2012). Thus, the energy savings potential from improving the operating parameters of existing ball mills will be substantial. Although the market share of vertical mills has increased, ball mills are still the type of mills most usually ordered (Harder, 2010b). Reasons are that i) ball mills are used in combination with roller presses, ii) a conversion to high-efficiency separators often requires upgrading or purchasing ball mills, and iii) sometimes ball mills are purchased as stand-by mills (Harder, 2010b). 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). Improper ball size distribution and filling level can reduce grinding efficiency by 5-20% (Longhurst, 2010), while the ball weight and the material transfer and discharge diaphragms also affect the grinding efficiency (Longhurst, 2010; Harder, 2010b). An improvement of the ball grading can result in about 10% energy savings (Harder, 2010b). Improved balls and liners made of high chromium steel is one such material but other materials are also possible. The use of improved liner designs, such as grooved classifying liners, 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). However, according to Fortsch (2006), it is possible that plants using classifying liners in ball mills that have installed high-efficiency classifiers will not be profitable, while in some cases an increase in power use may be observed. The investment cost to upgrade balls, liners and diaphragm is estimated at $2.44/ton cement (Hollingshead and Venta, 2009).

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, and improve process stability. 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 startup 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.

Motor Systems

This chapter presents a number of energy efficiency measures available for motors in industrial applications.[13] Additional measures that are specific to pumps, fans, and compressed air systems are offered in later chapters of this Energy Guide.

In the cement industry, motors are responsible for the majority of electricity consumption. Motors are used to drive fans and blowers, rotate the kiln, transport raw materials and finished products, and most importantly, to grind raw material and cement. More than 500 to 700 motors of various capacities can be used in a single cement plant (Worrell et al., 2008b).

When considering energy efficiency improvements to a facility's motor systems, it is important to take a "systems approach." A systems approach strives to optimize the energy efficiency of entire motor systems (i.e., motors, drives, driven equipment such as pumps, fans, and compressors, and controls), not just the energy efficiency of motors as individual components. A systems approach analyzes both the energy supply and energy demand sides of motor systems as well as how these sides interact to optimize total system performance, which includes not only energy use but also system uptime and productivity.

A systems approach typically involves the following steps. First, all applications of motors in a facility should be located and identified. Second, the conditions and specifications of each motor should be documented to provide a current systems inventory. Third, the needs and the actual use of the motor systems should be assessed to determine whether or not motors are properly sized and also how well each motor meets the needs of its driven equipment. Fourth, information on potential repairs and upgrades to the motor systems should be collected, including the economic costs and benefits of implementing repairs and upgrades to enable the energy efficiency improvement decision-making process. Finally, if upgrades are pursued, the performance of the upgraded motor systems should be monitored to determine the actual cost savings (SCE, 2003).

The motor system energy efficiency measures below reflect important aspects of this systems approach, including matching motor speeds and loads, proper motor sizing, and upgrading system components.

Motor Management Plan. A motor management plan is an essential part of a plant's energy management strategy. Having a motor management plan in place can help companies realize long-term motor system energy savings and will ensure that motor failures are handled

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[13] The U.S. DOE's Advanced Manufacturing Office provides a variety of resources for improving the efficiency of industrial motor systems, which can be consulted for more detailed information on many of the measures presented in this chapter. For a collection of tips, tools, and industrial case studies on industrial motor system efficiency, visit the U.S. DOE's website for Motor Systems at: http://www1.eere.energy.gov/manufacturing/tech_deployment/motors.html. The Motor Decisions Matter[SM] Campaign also provides a number of excellent resources for improving motor system efficiency (http://www.motorsmatter.org/).

in a quick and cost effective manner. The Motor Decisions Matter^{SM} Campaign suggests the following key elements for a sound motor management plan (MDM, 2012):

1. Creation of a motor survey and tracking program.
2. Development of guidelines for proactive repair/replace decisions.
3. Preparation for motor failure by creating a spares inventory.
4. Development of a purchasing specification.
5. Development of a repair specification.
6. Development and implementation of a predictive and preventive maintenance program.

It is important to develop a selection of preferred premium efficiency motors to replace existing motors at failure. Otherwise, it is likely that the motors will be replaced by less efficient alternatives.

The Motor Decisions Matter^{SM} Campaign's *Motor Planning Kit* contains further details on each of these elements (MDM, 2012).

Strategic Motor Selection. Several factors are important when selecting a motor, including motor speed, horsepower, enclosure type, temperature rating, efficiency level, and quality of power supply. When selecting and purchasing a motor, it is also critical to consider the life-cycle costs of that motor rather than just its initial purchase and installation costs. Up to 95% of a motor's costs can be attributed to the energy it consumes over its lifetime, while only around 5% of a motor's costs are typically attributed to its purchase, installation, and maintenance (MDM, 2012). Life cycle costing (LCC) is an accounting framework that allows one to calculate the total costs of ownership for different investment options, which leads to a more sound evaluation of competing options in motor purchasing and repair or replacement decisions. A specific LCC guide has been developed for pump systems (Fenning et al., 2001), which also provides an introduction to LCC for motor systems.

The selection of energy-efficient motors can be an important strategy for reducing motor system life-cycle costs. Energy-efficient motors reduce energy losses through improved design, better materials, tighter tolerances, and improved manufacturing techniques. With proper installation, energy-efficient motors can also run cooler (which may help reduce facility heating loads) and have higher service factors, longer bearing life, longer insulation life, and less vibration.

To be considered energy efficient in the United States, a motor must meet performance criteria published by the National Electrical Manufacturers Association (NEMA). The Consortium for Energy Efficiency (CEE) has described the evolution of standards for energy-efficient motors in the United States, which is helpful for understanding "efficient" motor nomenclature (CEE, 2007):

- NEMA Energy Efficient (NEMA EE) was developed in the mid-1980s to define the term “energy efficient” in the marketplace for motors. NEMA Standards Publication No. MG-1 -2011, Table 12-11 defines efficiency levels for a range of different motors (NEMA, 2012).

- The Energy Policy Act of 1992 (EPAct) required that many commonly used motors comply with NEMA “energy efficient” ratings if offered for sale in the United States.

- In 1996, the CEE Premium Efficiency Criteria specification was designed to promote motors with higher efficiency levels than EPAct required, for the same classes of motors covered by EPAct. The CEE efficiency levels specified were generally two NEMA efficiency bands (Table 12-10, NEMA MG-1-2011) above those required by EPAct.

- In 2001, the NEMA Premium Efficiency Electric Motor specification was developed to address confusion with respect to what constituted the most efficient motors available in the market. This specification was developed by NEMA, CEE, and other stakeholders, and was adapted from the CEE 1996 criteria. It currently serves as the benchmark for premium energy efficient motors. NEMA Premium[R] also denotes a brand name for motors which meet this specification. Specifically, this specification covers motors with the following attributes:

    - Speed: 2, 4, and 6 pole
    - Size: 1-500 horsepower (hp)
    - Design: NEMA A and B
    - Enclosure type: open and closed
    - Voltage: low and medium voltage
    - Class: general, definite, and special purpose

The choice of installing a premium efficiency motor strongly depends on motor operating conditions and the life cycle costs associated with the investment. In general, premium efficiency motors are most economically attractive when replacing motors with annual operation exceeding 2,000 hours/year. However, software tools such as MotorMaster+ (see Appendix D) can help identify attractive applications of premium efficiency motors based on the specific conditions at a given plant.

Sometimes, even replacing an operating motor with a premium efficiency model may have a low payback period. According to data from the Copper Development Association, the upgrade to high-efficiency motors, as compared to motors that achieve the minimum efficiency as specified by EPACT, can have paybacks of less than 15 months for 50 hp motors (CDA, 2001). Payback times will vary based on size, load factor, running time, local energy costs, and available rebates and/or incentives (see Appendix D). Given the quick payback time, it usually makes sense to by the most efficient motor available (U.S. DOE and CAC, 2003).

NEMA and other organizations have created the Motor Decisions Matter^{SM} campaign to help industrial and commercial customers evaluate their motor repair and replacement options, promote cost-effective applications of NEMA Premium^{R} motors and “best practice” repair, and support the development of motor management plans before motors fail.

In 2004, CEMEX (formerly RMC Pacific Materials) in Davenport, California, retrofitted the motors on cement blowers and silo pumps. With the use of DOE’s MotorMaster+software tool, plant personnel identified that 13 motors with an aggregate horsepower of 2,350 hp, were less than 80% efficient, of the wrong type, and required replacement. The specific motors were retrofitted with high efficiency (95%) totally enclosed fan cooled (TEFC) motors of similar capacity. Because of the motor retrofit, the plant managed to reduce electricity use by more than 2 million kWh, energy costs by $168,000 and annual maintenance costs by $30,000 (U.S. DOE, 2005a).

In some cases, it may be cost-effective to rewind an existing energy-efficient motor, instead of purchasing a new motor. As a rule of thumb, when rewinding costs exceed 60% of the costs of a new motor, purchasing the new motor may be a better choice (MDM, 2012). When rewinding a motor, it is important to choose a motor service center that follows best practice motor rewinding standards in order to minimize potential efficiency losses. An ANSI-approved recommended best practice standard has been offered by the Electric Apparatus Service Association (EASA) for the repair and rewinding of motors (EASA, 2006). When best rewinding practices are implemented, efficiency losses are typically less than 0.5% to 1% (EASA, 2003). However, poor quality rewinds may result in larger efficiency losses. It is therefore important to inquire whether the motor service center follows EASA best practice standards (EASA, 2006).

Maintenance. The purposes of motor maintenance are to prolong motor life and to foresee a motor failure. Motor maintenance measures can be categorized as either preventative or predictive. Preventative measures, the purpose of which is to prevent unexpected downtime of motors, include electrical consideration, voltage imbalance minimization, load consideration, and motor ventilation, alignment, and lubrication. The purpose of predictive motor maintenance is to observe ongoing motor temperature, vibration, and other operating data to identify when it becomes necessary to overhaul or replace a motor before failure occurs (Barnish et al., 1997). The savings associated with an ongoing motor maintenance program are significant, and could range from 2% to 30% of total motor system energy use (Efficiency Partnership, 2004).

Properly Sized Motors. Motors that are sized inappropriately result in unnecessary energy losses. Where peak loads on driven equipment can be reduced, motor size can also be reduced. Replacing oversized motors with properly sized motors saves, on average for U.S. industry, 1.2% of total motor system electricity consumption (Xenergy, 1998). Higher savings can often be realized for smaller motors and individual motor systems.

To determine the proper motor size, the following data are needed: load on the motor, operating efficiency of the motor at that load point, the full-load speed of the motor to be replaced, and the full-load speed of the replacement motor. The U.S. DOE's BestPractices program provides a fact sheet that can assist in decisions regarding replacement of oversized and under loaded motors (U.S. DOE, 1996a). Additionally, software packages such as MotorMaster+ (see Appendix D) can aid in proper motor selection.

Motor Automation. Motors should only run when needed. A 10% reduction in motor operating time can save more energy than replacing a conventional motor with a NEMA Premium® efficiency motor (U.S. DOE, 2008). Therefore, automatic shutdown of motors that would otherwise be left idling can reduce energy costs without requiring high investment. A 25 hp non-automated motor running unloaded for 5 hours per day, costs about $1,000 annually (Bayne, 2011).

Although there is a concern that often motor start-ups will negatively affect the motor's lifetime, as long as the frequency of motor start-ups is not excessive, the lifetime will not be significantly affected (U.S. DOE, 2008). NEMA (2001) gives the maximum number of allowable motor start-ups per hour and the duration of rest time between start-ups, for various horsepower motors and synchronous speed ratings.

Adjustable Speed Drives (ASDs).[14] Adjustable-speed drives better match speed to load requirements for motor operations, and therefore ensure that motor energy use is optimized to a given application. Adjustable-speed drive systems are offered by many suppliers and are available worldwide. Worrell et al. (1997) provide an overview of savings achieved with ASDs in a wide array of applications; typical energy savings are shown to vary between 7% and 60%. Also, in cement plants large variations in load occur (Bösche, 1993). 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.

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%,

[14] Several terms are used in practice to describe a motor system that permits a mechanical load to be driven at variable speeds, including adjustable speed drives (ASDs), variable speed drives (VSDs), adjustable frequency drives (AFDs), and variable frequency drives (VFDs). The term ASD is used throughout this Energy Guide for consistency.

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. ECRA (2009) estimated electricity savings to range between 3 and 9 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). When the kiln is mostly operated at full capacity, electricity savings can be limited (ECRA, 2009).

Power Factor Correction. Inductive loads like transformers, electric motors, and HID lighting may cause a low power factor. A low power factor may result in increased power consumption, and hence increased electricity costs. In cement plants where a big number of electric motors are used the inductive power consumption can be significant (Pulkki, 2004). The power factor can be corrected by minimizing idling of electric motors (a motor that is turned off consumes no energy), replacing motors with Premium Efficiency motors (see above), and installing capacitors in the AC circuit to reduce the magnitude of reactive power in the system.

Minimizing Voltage Unbalances. A voltage unbalance degrades the performance and shortens the life of three-phase motors. A voltage unbalance causes a current unbalance, which will result in torque pulsations, increased vibration and mechanical stress, increased losses, and motor overheating, which can reduce the life of a motor's winding insulation. Voltage unbalances may be caused by faulty operation of power factor correction equipment, an unbalanced transformer bank, or an open circuit. A rule of thumb is that the voltage unbalance at the motor terminals should not exceed 1%. Even a 1% unbalance will reduce motor efficiency at part load operation, while a 2.5% unbalance will reduce motor efficiency at full load operation.

For a 100 hp motor operating 8,000 hours per year, a correction of the voltage unbalance from 2.5% to 1% will result in electricity savings of 9,500 kWh or almost $500 at an electricity rate of $0.05/kWh (U.S. DOE, 2005b).

By regularly monitoring the voltages at the motor terminal and through regular thermographic inspections of motors, voltage unbalances may be identified. It is also recommended to verify that single-phase loads are uniformly distributed and to install ground fault indicators as required. Another indicator that a voltage unbalance may be a problem is 120 Hz vibration, which should prompt an immediate check of voltage balance (U.S. DOE, 2005b). The typical payback period for voltage controller installation on lightly loaded motors in the United States is about 2 years (IAC, 2012).

Soft Starters. Soft starters are special devices which allow the gradual speed acceleration of the motor, and limit the electrical stresses associated with motor start-up (U.S. DOE, 2003). With the use of soft starters power use during motor start-up can be reduced. Investment costs are estimated at $0.40/ton clinker while electricity use can be reduced by 2.5 kWh/ton clinker (Hollingshead and Venta, 2009).

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 (U.S. DOE and CAC, 2003). 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.

Compressed air systems consist of a supply side, which includes compressors and air treatment, and a demand side, which includes distribution and storage systems and end-use equipment. According to the U.S. DOE, a properly managed supply side will result in clean, dry, stable air being delivered at the appropriate pressure in a dependable, cost-effective manner. A properly managed demand side minimizes waste air and uses compressed air for appropriate applications (U.S. DOE, 2003).

System Improvements. Adding additional compressors should be considered only after a complete system evaluation. In many cases, compressed air system efficiency can be managed and reconfigured to operate more efficiently without purchasing additional compressors. System improvements utilize many of the energy efficiency measures for compressors discussed below. Compressed air system service providers offer integrated services both for system assessments and for ongoing system maintenance needs, alleviating the need to contact several separate firms. The Compressed Air Challenge® (http://www.compressedairchallenge.org) offers extensive training on the systems approach, technical publications, and free web-based guidance for selecting the right integrated service provider. Also provided are guidelines for walk-through evaluations, system assessments, and fully instrumented system audits (U.S. DOE and CAC, 2003). Even in recently commissioned plants, energy savings of up to 30% can be achieved (Aller et al., 2006).

Rinker Materials cement plant, after performing a system evaluation, identified that the load out pressure problems were unrelated to capacity and that with an investment of $10,000 in piping changes, air pressure problems could be solved without any increase in operational costs (Aller et al., 2006). The evaluation discovered that a number of compressors were not operating at full capacity, compressor controls were far from optimized (even when leaks were repaired controls would not respond), several applications were using more compressed air than needed while other applications were not necessary. Also, instead of raising overall plant air pressure, several issues could be solved with a number of changes in the distribution system, resulting in significant savings in operational costs. All of the above problems were solved, while reducing operational costs by 30%. The payback period was significantly less than 2 years (Aller et al., 2006).

A Lafarge cement plant, after a system evaluation project, decreased operational costs by $190,000 per year with a payback period of 13 months (Aller et al., 2006). Initially the compressed air system was composed of five compressors (total of 1,325 hp) while in the next five years, six more compressors (470 hp) were added. The study showed that the capital and operational costs of the six new compressors could have been avoided as the average operational capacity could have been roughly satisfied with the existing compressors (Aller et al., 2006). Some of the actions that took place were a leak reduction and repair project, the installation of a more efficient bag cleaning system, the permanent shut down of a 250 hp compressor and the part-time use of two more compressors.

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 (U.S. DOE and CAC, 2003; Scales and McCulloch, 2007):

- *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). In an energy assessment at a Cemex cement plant, a high differential pressure in two in-line filters negatively affected air compressor control. The high pressure drop of more than 15 psid increased energy costs, tear and wear. The replacement of filter elements would result in annual energy savings of 69,000 kWh (U.S. DOE, 2007).

- *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 (U.S. DOE, 2004a).

- *Maintain the coolers* on the compressor to ensure that the dryer gets the lowest possible inlet temperature (U.S. DOE and CAC, 2003).

- *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 (U.S. DOE and CAC, 2003).

- *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.

- Applications requiring compressed air should be *checked for excessive pressure, duration, or volume*. Applications not requiring maximum system pressure should be regulated, either by production line sectioning or by pressure regulators on the equipment itself. Using more pressure than required wastes energy and can also result in shorter equipment life and higher maintenance costs. Case studies have demonstrated that the payback period for this measure can be shorter than half a year (IAC, 2012).

Monitoring. In addition to proper maintenance, a continuous monitoring system can save significant energy and operating costs in compressed air systems. Effective monitoring systems typically include the following (CADDET, 1997b):

- Pressure gauges on each receiver or main branch line and differential gauges across dryers, filters, etc.

- Temperature gauges across the compressor and its cooling system to detect fouling and blockages.

- Flow meters to measure the quantity of air used.

- Dew point temperature gauges to monitor the effectiveness of air dryers.

- Kilowatt-hour meters and hours run meters on the compressor drive.

- Checking of compressed air distribution systems after equipment has been reconfigured to be sure that no air is flowing to unused equipment or to obsolete parts of the compressed air distribution system.

- Checking for flow restrictions of any type in a system, such as an obstruction or roughness, which can unnecessarily raise system operating pressures. As a rule of thumb, every 2 psi pressure rise resulting from resistance to flow can increase compressor energy use by 1% (U.S. DOE and CAC, 2003). The highest pressure drops are usually found at the points of use, including undersized or leaking hoses, tubes, disconnects, filters, regulators, valves, nozzles and lubricators (demand side), as well as air/lubricant separators, after-coolers, moisture separators, dryers and filters.

- Checking for compressed air use outside production hours.

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 (U.S. DOE and CAC, 2003). 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. A compressor operating 2,500 hours per year at 87 psi with a leak diameter of 0.02 inches (½ mm) is estimated to lose 250 kWh per year; 0.04 inches (1 mm) to lose 1,100 kWh per year; 0.08 inches (2 mm) to lose 4,500 kWh per year; and 0.16 in. (4 mm) to lose 11,250 kWh per year (CADDET, 1997b). Several cement case studies suggest that the payback period for leak reduction efforts is generally shorter than four months (IAC, 2012).

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. Another simple way is a bleed down test (Bayne, 2011). In a bleed down test the plant air system is brought to full pressure and then shut down. By recording the system pressure while compressed air is not used anywhere in the plant, any pressure losses can be attributed to existing leaks. 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.

Turning Off Unnecessary Compressed Air. Equipment that is no longer using compressed air should have the air turned off completely. This can be done using a simple solenoid valve. Compressed air distribution systems should be checked when equipment has been reconfigured to ensure that no air is flowing to unused equipment or to obsolete parts of the compressed air distribution system. In Rinker Materials cement plant, the permanent shut down of two out of nine compressors and the part time operation of two more air compressors achieved $120,000 annual savings in electricity costs (Aller et al., 2006).

Modification of System in Lieu of Increased Pressure. For individual applications that require a higher pressure, instead of raising the operating pressure of the whole system, special equipment modifications should be considered, such as employing a booster, increasing a cylinder bore, changing gear ratios, or changing operation to off peak hours.

Replacement of Compressed Air by Alternative Sources. Many operations can be accomplished more economically and efficiently using energy sources other than compressed air (U.S. DOE 2004b, 2004c). Various options exist to replace compressed air use, including:

- Cooling electrical cabinets: air conditioning fans should be used instead of using compressed air vortex tubes.
- Flowing high-pressure air past an orifice to create a vacuum: a vacuum pump system should be applied instead of compressed air venturi methods.
- Cooling, aspirating, agitating, mixing, or package inflating: use blowers instead of compressed air.
- Cleaning parts or removing debris: brushes, blowers, or vacuum pump systems should be used instead of compressed air.
- Moving parts: blowers, electric actuators, or hydraulics should be used instead of compressed air.
- Tools or actuators: electric motors should be considered because they are more efficient than using compressed air (Howe and Scales, 1995). However, it has been reported that motors can have less precision, shorter lives, and lack safety compared to compressed air. In these cases, using compressed air may be a better choice.

Based on numerous industrial case studies, the average payback period for replacing compressed air with other applications is about 1 year (IAC, 2012).

Pressure Drop Minimization. An excessive pressure drop will result in poor system performance and excessive energy consumption. Flow restrictions of any type in a system, such as an obstruction or roughness, results in higher operating pressures than is truly needed. Resistance to flow increases the drive energy on positive displacement compressors by 1% of connected power for each 2 psi of differential (U.S. DOE and CAC, 2003). The highest pressure drops are usually found at the points of use, including undersized or leaking hoses, tubes, disconnects, filters, regulators, valves, nozzles, and lubricators (demand side), as well as air/lubricant separators on lubricated rotary compressors and after-coolers, moisture separators, dryers, and filters (supply side).

Minimizing pressure drop requires a systems approach in design and maintenance. Air treatment components should be selected with the lowest possible pressure drop at specified maximum operating conditions and best performance. Manufacturers' recommendations for maintenance should be followed, particularly in air filtering and drying equipment, which can have damaging moisture effects like pipe corrosion. Finally, the distance the air travels through the distribution system should be minimized. Audits of U.S. cement plants found that the payback period is typically shorter than three months for this measure (IAC, 2012).

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.

Improved Load Management. Because of the large amount of energy consumed by compressors, whether in full operation or not, partial load operation should be avoided. For example, unloaded rotary screw compressors still consume 15% to 35% of full-load power while delivering no useful work (U.S. DOE and CAC, 2003).

Air receivers can be employed near high demand areas to provide a supply buffer to meet short-term demand spikes that can exceed normal compressor capacity. In this way, the number of required online compressors may be reduced. Multi-stage compressors theoretically operate more efficiently than single-stage compressors. Multi-stage compressors save energy by cooling the air between stages, reducing the volume and work required to compress the air. Replacing single-stage compressors with two-stage compressors typically provides a payback period of two years or less (Ingersoll-Rand, 2001). Using multiple smaller compressors instead of one large compressor can save energy as well. Large compressors consume more electricity when they are unloaded than do multiple smaller compressors with similar overall capacity. An analysis of U.S. case studies shows an average payback period for optimally sizing compressors of about 1.4 years (IAC, 2012).

In June 2004, the Canandaigua Wine Company upgraded the compressed air system at its winery in Lodi, California. Before the project began, the winery was served by two 125 hp rotary screw compressors that operated at full load only during the 3-month fall grape crushing season. During the rest of the year, however, the compressors were operated at part-load, which wasted energy. The company opted to install a 75 hp variable-speed compressor, which could be used to satisfy facility demand during the off-season while also providing supplemental power to the two 125 hp units during the fall crush season. Additionally, the company installed a new compressor control system, additional storage, and started a leak reduction campaign. The total energy savings attributable to the upgrade were estimated at 218,000 kWh per year, saving the company $27,000 annually (U.S. DOE, 2005c). The simple payback period was estimated at 1.2 years.

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). In addition to energy savings, compressor capacity is increased when cold air from outside is used. Industrial case studies have found an average payback period for importing outside air of less than 1.4 years (IAC, 2012), but costs can vary significantly depending on facility layout.

Controls. The primary objectives of compressor control strategies are to shut off unneeded compressors and to delay bringing on additional compressors until needed. Energy savings for sophisticated compressor controls have been reported at around 12% annually (Radgen and Blaustein, 2001). An excellent review of compressor controls can be found in Compressed Air Challenge® *Best Practices for Compressed Air Systems* (Second Edition) (Scales and McCulloch, 2007). Common control strategies for compressed air systems include:

- *Start/stop (on/off) controls*, in which the compressor motor is turned on or off in response to the discharge pressure of the machine. Start/stop controls can be used for applications with very low duty cycles and are applicable to reciprocating or rotary screw compressors. The typical payback for start/stop controls is one to two years (CADDET, 1997b).

- *Load/unload controls*, or constant speed controls, which allow 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 (U.S. DOE and CAC, 2003). Hence, load/unload controls can be inefficient.

- *Modulating or throttling controls*, which 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.

- *Single master sequencing system controls*, which take individual compressor capacities on-line and off-line in response to monitored system pressure demand and shut down any compressors running unnecessarily. System controls for multiple compressors typically offer a higher efficiency than individual compressor controls.

- *Multi-master controls*, which are the latest technology in compressed air system control. Multi-master controls are capable of handling four or more compressors and provide both individual compressor control and system regulation by means of a network of individual controllers (Martin et al., 2000). The controllers share information, allowing the system to respond more quickly and accurately to demand changes. One controller acts as the lead, regulating the whole operation. This strategy allows each compressor to function at a level that produces the most efficient overall operation. The result is a highly controlled system pressure that can be reduced close to the minimum level required (U.S. DOE and CAC, 2003). According to Nadel et al. (2002), such advanced compressor controls are expected to deliver energy savings of about 3.5% where applied.

In addition to energy savings, the application of controls can sometimes eliminate the need for some existing compressors, allowing extra compressors to be sold or kept for backup. Alternatively, capacity can be expanded without the purchase of additional compressors. Reduced operating pressures will also help reduce system maintenance requirements (U.S. DOE and CAC, 2003).

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). Further savings can be realized by ensuring other system components (e.g., filters, fittings, and hoses) are properly sized.

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) (U.S. DOE and CAC, 2003). Paybacks are typically less than one year (Galitsky et al., 2005).

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 (U.S. DOE and CAC, 2003). Implementing this measure saves up to 20% of the energy used in compressed air systems annually for space heating (Radgen and Blaustein, 2001).

Natural Gas Engine-Driven Air Compressors. Gas engine-driven air compressors can replace electric compressors with some advantages and disadvantages. Gas engine-driven compressors are more expensive and can have higher maintenance costs, but may have lower overall operating costs depending on the relative costs of electricity and gas. Variable-speed capability is standard for gas-fired compressors, offering a high efficiency over a wide range of loads. Heat can be recovered from the engine jacket and exhaust system. However, gas engine-driven compressors have some drawbacks: they need more maintenance, have a shorter useful life, and sustain a greater likelihood of downtime. According to Galitsky et al. (2005), gas engine-driven compressors currently account for less than 1% of the total air compressor market.

Ultra Creative Corporation, a U.S. manufacturer of specialty plastic bags, installed gas engine-driven compressors in its plant in Brooklyn, New York. The initial costs were

$85,000 each for two 220 hp units and $65,000 for one 95 hp unit. The company reported savings of $9,000 in monthly utilities (averaging $108,000 annually) (Audin, 1996).

Similarly, Nestlé Canada found that its gas engine-driven air compressor system was a cost effective option when it was operated properly. The company's projected payback period was estimated as low as 2.6 years with a 75% efficient heat recovery system, and as high as 4.2 years without heat recovery (Audin, 1996).

Fan Systems

As in other motor applications, considerable opportunities exist to upgrade the performance and improve the energy efficiency of fan systems. For fans in particular, concern about failure or underperformance have led to many fans being oversized for their particular application (U.S. DOE 2003c). Oversized fans do not operate at optimal efficiency and therefore waste energy. However, the efficiencies of fan systems vary considerably across impeller types.

High Efficiency Fans. Many old cement plants are equipped with older technology fans. Older fans have a typical efficiency of 60-65%, while new design fans can operate at 80% efficiency. We assume a decrease in electricity use of 1 kWh/ton clinker. The investment cost is estimated at $0.50/ton clinker (Hollingshead and Venta, 2009).

Maintenance. As for most energy using systems, a proper maintenance program for fans can improve system performance, reduce downtime, minimize repair costs, and increase system reliability. The U.S. DOE recommends establishing a regular maintenance program for fan systems, with intervals based on manufacturer recommendations and experience with fans in similar applications (U.S. DOE, 2003). Additionally, the U.S. DOE recommends the following important elements of an effective fan system maintenance program (U.S. DOE, 2003):

- *Belt inspection*. In belt-driven fans, belts are usually the most maintenance-intensive part of the fan assembly. Belts wear over time and can lose tension, which reduces their ability to transmit power efficiently. Belt inspection and tightening should be performed on a regular basis, especially for large fans because the potential size of the power loss.

- *Fan cleaning*. Many fans experience a significant loss in energy efficiency due to the buildup of contaminants on blade surfaces. Such build up can create imbalance problems that can reduce performance and contribute to premature wear of system components. Fans that operate in particulate-laden or high-moisture airstreams are particularly vulnerable and are therefore recommended to be cleaned regularly.

- *Leak inspection and repair.* Leakage in a fan duct system will decrease the amount of air that is delivered to the desired end use, which can significantly reduce the efficiency of the fan system. Ductwork should be inspected on a regular basis and leaks should be repaired as soon as possible. In systems with inaccessible ductwork, the use of temporary pressurization equipment can determine if the integrity of the system is adequate.

- *Bearing lubrication.* Worn bearings can lead to premature fan failure, as well as create unsatisfactory noise levels. Fan bearings should be monitored and lubricated frequently based on manufacturer recommendations.

- *Motor replacement.* Eventually, all fan motors will wear and will require repair or replacement. The decision to repair or replace a fan motor should be based on a life cycle costs analysis, as described in the motor's system section.

Properly Sized Fans. Conservative engineering practices often result in the installation of fans that exceed system requirements. Such oversized fans lead to higher capital costs, higher maintenance costs, and higher energy costs than fans that are properly sized for the job (U.S. DOE, 2003). However, other options may be more cost effective than replacing an oversized fan with a smaller fan (U.S. DOE, 2002). Other options include (U.S. DOE, 2003):

- Decreasing fan speed using different motor and fan sheave sizes (may require downsizing the motor)

- Installing an ASD or multiple-speed motor (see below)

- Using an axial fan with controllable pitch blades

At a Louisiana Pacific Corporation board mill in Tomahawk, Wisconsin, a fan system optimization project was pursued to resize and replace fans to better meet airflow and pressure requirements. The previous system was originally relocated from Colorado, where thinner high elevation air required greater fan speed. This system had to be modified with dampers on the combustion air, dryer, and scrubber fans when it was installed in Wisconsin. The new fan system led to electricity savings of about 2.5 million kWh per year, with annual cost savings of around $85,000. With investment costs of $44,000, the payback period was only around 6 months (U.S. DOE, 1999).

The Roanoke Cement plant upgraded a fan after a bypass precipitator to baghouse conversion. A 500 horse power fan is required to make cold starts but once the process is up to temperature, the power on the fan drops of to 300 hp utilizing a damper. In 2008, a medium voltage variable speed drive was installed and under normal running conditions the fan pulls around 80 hp. The project exceeded the estimated 2 year payback period by 15 months (Drzymala, 2012).

Adjustable Speed Drives (ASDs) and Improved Controls. Significant energy savings can be achieved by installing adjustable speed drives on fans. Savings may vary between 14% and 49% when retrofitting fans with ASDs (U.S. DOE, 2002).

High Efficiency Belts (cog belts). Belts make up a variable, but significant portion of the fan system in many plants. It is estimated that about half of the fan systems use standard V-belts, and about two-thirds of these could be replaced by more efficient cog belts (U.S. DOE, 2002). Standard V-belts tend to stretch, slip, bend and compress, which lead to a loss of efficiency.

Replacing standard V-belts with cog belts can save energy and money, even as a retrofit. Cog belts run cooler, last longer, require less maintenance and have an efficiency that is about 2% higher than standard V-belts. Typical payback periods will vary from less than one year to three years.

Duct Leakage Repair. Duct leakage can waste significant amounts of energy in fan and ventilation systems. Measures for reducing duct leakage include installing duct insulation and performing regular duct inspection and maintenance, including ongoing leak detection and repair. For example, according to studies by Lawrence Berkeley National Laboratory, repairing duct leaks in industrial and commercial spaces could reduce HVAC energy consumption by up to 30% (Galitsky et al., 2005).

Because system leakage can have a significant impact on fan system operating costs, the U.S. DOE recommends considering the type of duct, the tightness and quality of the fittings, joints assembly techniques, and the sealing requirements for duct installation as part of the fan system design process as proactive leak prevention measures (U.S. DOE, 2003).

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.

Table 6 provides an overview of the typical performance and applications of various lamp types.

Table 6. Performance comparison of lighting sources

Lamp	Efficacy (Lumen/watt)	Typical Lifetime (Hours)	Applications
Incandescent	5–20	1,000	Task
Halogen	<24	1,000	Task
CFL	20–70	8,000–15,000	Task

Fluorescent T-12	60	20,000	Any
Fluorescent T-8	80–100	20,000	Any
Fluorescent T-5	80–105	20,000	Any
Mercury Vapor	30-50	60,000	Hi-Bay
Induction	80	100,000	Exterior, Hi-Bay
High Pressure Sodium	85–150	10,000–50,000	Exterior, Hi-Bay
Metal Halide	70–115	20,000	Hi-Bay
LED	10–120	50,000	Task

Note: Values are typical performance. Performance of individual products may vary. The performance of fluorescent lamps assumes the use of an electronic ballast. Technology development may change the future performance of specific lighting technologies.

Turning Off Lights in Unoccupied Areas. An easy and effective measure is to encourage personnel to turn off lights in unoccupied building spaces. An energy management program that aims to improve the awareness of personnel with regard to energy use can help staff get in the habit of switching off lights and other equipment when not in use.

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. Numerous case studies throughout the United States suggest that the average payback period for occupancy sensors is approximately 1 year (IAC, 2012). In a case study from the pharmaceutical industry, at the Merck office and storage building in Rahway, New Jersey, lighting panels were programmed to turn off automatically during expected periods of building non-use (override switches in entrance hallways allowed lights to be turned on manually during these times, if needed). Annual savings amounted to 1,310 MBtu per year, which corresponded to avoided energy-related carbon dioxide (CO_2) emissions of nearly 260 tons per year (Merck, 2005).

Manual controls can be used in conjunction with automatic controls to save additional energy in smaller areas. One of the easiest measures is to install switches to allow occupants to control lights. Other lighting controls include daylight controls for indoor and outdoor lights, which adjust the intensity of electrical lighting based on the availability of daylight.

An example of energy efficient lighting control is illustrated by Figure 10, which depicts five rows of overhead lights in a workspace. During the brightest part of the day, ample daylight is provided by the window and thus only row C would need to be turned on. At times when daylight levels drop, all B rows would be turned on and row C would be turned off. Only at night or on very dark days would it be necessary to have both rows A and B turned on (Cayless and Marsden, 1983). These methods can also be used as a control strategy on a retrofit by adapting the luminaries already present (for example, turning on the lighting in rows farthest away from the windows during the brightest parts of the day, then turning on additional rows as needed later).

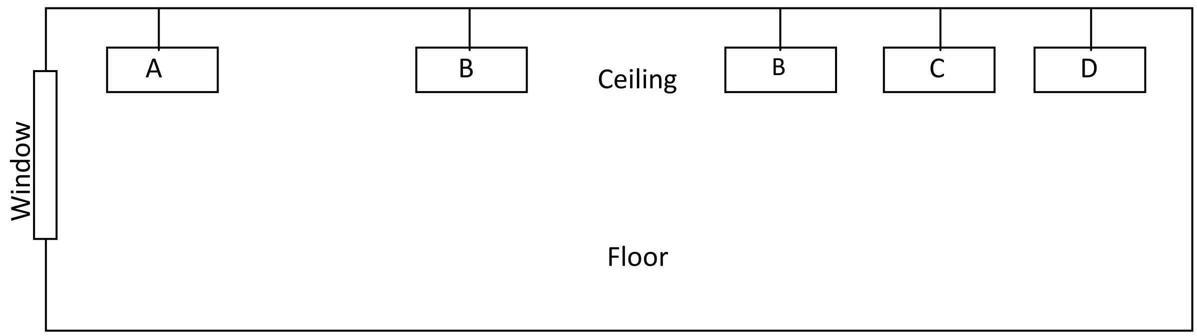

Figure 10. Lighting placement and controls.

Exit Signs. Energy costs can be reduced by switching from incandescent lamps to light emitting diodes (LEDs) or radium strips in exit sign lighting. An incandescent exit sign uses about 40 W, while LED signs may use only about 4W to 8 W, reducing electricity use by 80% to 90%. A 1998 Lighting Research Center survey found that about 80% of exit signs being sold use LEDs (LRC, 2001). The lifetime of an LED exit sign is about 10 years, compared to 1 year for incandescent signs, which can reduce exit sign maintenance costs considerably. In addition to exit signs, LEDs are increasingly being used for path marking and emergency way finding systems. Their long life and cool operation allows them to be embedded in plastic materials, which makes them well suited for such applications (LRC, 2001).

New LED exit signs are inexpensive, with prices typically starting at around $20. The U.S. EPA's ENERGY STAR program website (http://www.energystar.gov) provides a list of suppliers of LED exit signs.

Tritium exit signs are an alternative to LED exit signs. Tritium signs are self-luminous and thus do not require an external power supply. The advertised lifetime of these signs is around 10 years and prices typically start at around $150 per sign.

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 can require 12% to 30% less power than their magnetic predecessors (Cook, 1998; Galitsky et al., 2005). New electronic ballasts have smooth and silent dimming capabilities, in addition to longer lives (up to 50% longer), faster run-up times, and cooler operation than magnetic ballasts (Eley et al., 1993; Cook, 1998). New electronic ballasts also have automatic switch-off capabilities for faulty or end-of-life lamps.

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. Typical energy savings from the replacement of a T-12 lamp by a T-8 lamp are around 30% (Galitsky et al., 2005).

High-Intensity Discharge (HID) Voltage Reduction. Reducing lighting system voltage can also save energy. A Toyota production facility installed reduced-voltage HID lights and realized a 30% reduction in lighting energy consumption (Galitsky et al., 2005). Commercial products are available that attach to a central panel switch (controllable by computer) and constrict the flow of electricity to lighting fixtures, thereby reducing voltage and saving energy, with an imperceptible loss of light. Voltage controllers work with both HID and fluorescent lighting systems and are available from multiple vendors.

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.

Daylighting. Daylighting involves the efficient use of natural light in order to minimize the need for artificial lighting in buildings. Increasing levels of daylight within rooms can reduce electrical lighting loads by up to 70% (CADDET, 2001; IEA, 2000). Unlike conventional skylights, an efficient daylighting system may provide evenly dispersed light without creating heat gains, which can reduce the need for cooling compared to skylights. Daylighting differs from other energy efficiency measures because its features are integral to the architecture of a building; therefore, it is applied primarily to new buildings and incorporated at the design stage. However, existing buildings can sometimes be cost-effectively refitted with daylighting systems.

Daylighting can be combined with lighting controls to maximize its benefits. Because of its variability, daylighting is almost always combined with artificial lighting to provide the necessary illumination on cloudy days or after dark (see also Figure 10). Daylighting technologies include properly placed and shaded windows, atria, clerestories, light shelves, and light ducts. Clerestories, light shelves, and light ducts can accommodate various angles of the sun and redirect daylight using walls or reflectors.

More information on daylighting can be found at the website of the Daylighting Collaborative led by the Energy Center of Wisconsin (http://www.daylighting.org/).

LED Lighting. Light Emitting Diode (LED) lights have been receiving a lot of attention as the next generation of energy efficient lighting. In typical florescent lighting, electrical arcs are used to excite mercury and phosphorous compounds, which then emit light. On the other hand, LED lights are semiconductor diodes that use far less energy to emit the same lumens of light. Several new LED light products that are compatible with current light fixtures, such as T-8 light fixtures are emerging on the market (Myer et al. 2009).

Dust Control

Main sources of dust emissions in the cement industry are the kiln systems, clinker coolers, cement mills and the conveying systems. In new cement plants only bag filters (BF) or electrostatic precipitators (EPs) are installed (CEMBUREAU, 1997). To ensure the proper operation of dust collectors, pulse air jets, mechanical shakers, bags and cartridges need to be inspected regularly, fabric bags need to be sized correctly and fitted properly, and all the worn fabrics should be replaced (MEMS, 2010).

Significant energy savings are expected when the motors used to drive the dust collectors shut down when not needed; see also the Motor Automation Section. Best practices for dust collectors according to Bayne (2011) can ensure efficient operation of baghouse filters at the minimum energy consumption:

- *Seal areas,* as the existence of leaks will increase draft requirements.
- Employ the *minimum effective draft*. Extra draft employment will accumulate more dust on the filters resulting in increased wear of ducts and bags. Use dampers and/or variable speed fans to control the draft.
- *Automate dust collectors* so that they don't operate when not needed.
- Resizing and slowing down fans that are too big will result in energy savings. Installing a variable frequency driver (VFD) will require higher capital investment but will result in more energy savings.
- *Maintain the differential pressure* across the dust collector (pressure difference between the dirty and clean side of the bags) between 4 to 5 inches of water. For the

efficient operation of dust collectors filters should be relatively dirty or have a dust cake.

- Use a *differential pressure control system* on your cleaning system. Differential pressure should range between 4 and 5 inches of water when a fan driven dust collector is used.

- When a compressed air jet pulse cleaning system is used employ the *minimum effective pressure* which usually ranges between 60 and 70 psi, and not more than the manufacturer's recommended pressure when a pneumatic shaker is used.

- Employ a *rather short pulse* to shake the extra dust off in the case of compressed air blow down systems.

6.9 Product 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. Savings of 2-5 kcal/kg per percent bypass are assumed (Alsop and Post, 1995). For illustrative purposes, assume a 20%-point reduction in bypass volume, resulting in energy savings of 0.1-0.2 MBtu/ton clinker. According to Bolwerk et al. (2006), low alkali cement production leads to higher energy consumption of about 5-10 kBtu/ton clinker per percent bypass. Typically, the bypass rates are 15% for chlorine bypass and 70% for sulphur bypass (IPPC, 2010). Additionally, electricity is saved due to the increased cement production, as the CKD would otherwise end up as 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, and 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. The intergrinding of one ton of additives will offset the environmental impact (NOx, SO_2, CO_2, PM and other emissions) of producing one ton of Portland cement (about 0.95 tons of clinker) (Staudt, 2009b). 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 59% (IPPC, 2010). 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. Cement companies use only limited amounts of additives as grinding and flow aids. In the U.S., the concrete companies usually are the ones that add high amounts of additives. As explained by Staudt (2009b), this is probably due to the U.S. market structure, as concrete companies can be situated closer to the additive sources, thus making it more cost-effective to add SCMs (Supplementary Cementitious Materials) and pozzolans during concrete blending instead of cement blending (Staudt, 2009b). Another reason is that concrete companies can adjust their products according to the specific needs of the local markets (Staudt, 2009b). In 2010, 95% of granulated blast furnace slag produced (2.5 million metric tonnes), was sold for cementitious purposes (USGS, 2012c). Of which, 70,000 metric tonnes were used in clinker production and 235,000 metric tonnes were used in blended cement production (USGS, 2012a). The remaining 2.2 million metric tonnes were used by the concrete industry.

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 fly ash in the U.S. conforms to ASTM C618 (VDZ and PENTA, 2008). 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.

An 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 0.9 MBtu/ton (the calculation was based on the clinker content (88%) and average fuel use (3.3 MBtu/ton cement) in 2009, in the U.S. 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 have 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 results in total fuel savings of 1.0 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 additives[15], 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, 1997) 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. According to another study, the investment cost for receiving, metering and storing the additives is estimated at $4.1/ton clinker (Hollingshead and Venta, 2009).

ECRA (2009) estimated the reduction in energy use from using 30-70% by mass granulated blast furnace slag (GBFS), at 0.4-1.6 MBtu/ton cement (the average European clinker to cement ratio at the time of the study was 75%). Electricity was not estimated to be significantly influenced. The U.S. clinker to cement ratio (88%) is higher than the European. Therefore, the use of 70% (by mass) GBFS in the U.S cement industry would result in even

[15] The average cost of granulated blast furnace slag is about $75/ton (in 2010 dollars) (USGS, 2012c). This figure may not include shipping costs, which in case the slag source is not close to the facility, operational costs can increase to prohibitive levels (Staudt, 2009b). The price for high-quality fly ash in 1997 was about $25-30/ton, excluding transportation costs which can range between $0.10-0.13/ton-mile (1997 prices) (Robl et al., 1997). In 2010, the price of natural pozzolans for cement manufacture like diatomite was less than $9/ton (fob plant), and for common clays about $13/ton (fob plant) (USGS, 2011c; USGS, 2011b).

higher energy savings, estimated at 2.3 MBtu/ton cement. ECRA (2009) estimated the investment cost for a new silo for storing the new cements (blast furnace slag can be stored outside) and for the slag handling and drying equipment to range between $7-14 million. When fly ash or pozzolans are used the investment costs are estimated at about $11-17 millions, since extra investment is required for storing (ECRA, 2009). The above investments were based on a 2 million tonne per year clinker capacity facility. The availability of blast furnace slag and fly ash can be limited for cement companies situated away from the generation sources of these materials.

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 CO_2 emissions from calcination and energy use. According to the ASTM C150 standard specification for Portland cement, the limestone content cannot be higher than 5%. In European and other countries the limestone content in cement can be much higher. 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 0.2 MBtu/ton clinker), power consumption for grinding by 3.0 kWh/ton cement, and CO_2 emissions by almost 5%. Limestone is an easily available material for cement producers. The additional costs would be minimal, limited to material storage and distribution, while reducing kiln operation costs by 5%.

Reducing the Fineness for Particular Applications. Cement is normally ground to a uniform fineness. However, the applications of cement vary widely, and so does the optimal fineness. The grinding of the cement to the desired fineness could reduce the energy demand for grinding. Holderbank (1993) suggests that cement in Canada and the U.S. is ground finer (on average) than in Western Europe, which suggests that energy savings could be achieved. 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.

6.10 Feedstock Changes

The use of decarbonated feedstock material (i.e. electric arc furnace slag, granulated blast furnace slag, fly ash, and cement kiln dust) as kiln feedstock instead of limestone will reduce the energy use and the CO_2 emissions from calcination and from the reduced fuel use (Bhatty and Gajda, 2004).

Steel Slag, 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 contains C_3S, 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 54 million tons (2010) (49 million tonnes). EAF-slag production is estimated at 8.2 million tons, potentially replacing an equal amount of clinker (USGS, 2012b; USGS, 2012c). The CemStar® process allows replacing 10-15% of the clinker by EAF-slags, 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 CO_2 emissions from calcination, while the reduced combustion energy and lower flame temperatures lead to reduced NOx emissions (Battye et al., 2000; Staudt, 2009b). For illustrative purposes alone, using a 10% injection of slags would reduce energy consumption by 0.16 MBtu/ton of clinker, while reducing CO_2 emissions by roughly 11%. Energy savings can be higher in wet kilns due to the reduced evaporation needs. Reductions in NOx emissions vary by kiln type and may be between 9 and 60%, based on several measurements (Battye et al., 2000; Staudt, 2009b). 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. The total capital investment for a 45 ton/hr wet kiln was estimated by Staudt (2009b) at $1.5 million (2005 dollars). Hollingshead and Venta (2009) estimated the investment cost for a slag hopper with a regulated withdrawal system and conveyors to feed the kiln at $0.9/ton clinker, while the additional operating costs were estimated at $0.1/ton clinker. According to the same study, with the addition of steel slag, production can increase by 5%, with corresponding energy savings of 0.05 MBtu/ton clinker and electricity savings of 3 kWh/ton clinker. Energy and CO_2 savings depend on the CemStar® royalty fee charges (Battye et al., 2000). Costs savings consist of increased income from additional clinker produced (steel slag ($5-15/ton) costs less than clinker ($73/ton) (Staudt, 2009b)) without increase in operation and energy costs, as well as reduced iron ore purchases ($0.5-1.0/ton clinker) (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. U.S. EPA awarded the CemStar® process special recognition in 1999 as part of the ClimateWise program.

The Davenport cement plant in California, introduces 2-5% steel slag directly into the kiln in a patented process. Energy savings of 2-5% reduction and a small reduction in NOx emissions have been reported (Renfrew et al., 2004). The Davenport plant has been closed since 2010.

Fly Ash and Blast Furnace Slag. Other sources of calcium that do not require calcination are fly ash and blast furnace slag. Class F and Class C are the two main fly ash classes specified in the ASTM C 168. Class F fly ash is usually produced from burning anthracite or bituminous coal while Class C fly ash is usually produced from burning coal and lignite. In

2009, 63 million tonnes of fly ash where produced in the U.S., of which about 10 million tonnes were used in concrete facilities to replace Portland cement and 2.4 million tonnes were used in the cement industry either as kiln feed or as substitute for clinker in the production of blended cements (ACAA, 2011). The capital required is for material handling equipment. According to Staudt (2009a), the price of fly ash for limestone substitution is significantly lower than the fly ash price for use in the production of blended cements, and it is estimated to range between $5-10/ton and less. As can be seen in Table 7, the use of 1 ton of Class C fly ash in the kiln will substitute 0.45 tons of limestone, it will reduce CO_2 emissions from calcination by 0.2 tons, while energy use will be reduced by 0.6 MBtu (Staudt, 2009a). According to USGS (2012a), in 2010, 2.4% of raw materials used to produce clinker was fly ash. A 10% kiln feed substitution (based on Cao content) will result in 0.16 MBtu/ton clinker energy savings, while at the same time reduce CO_2 emissions by roughly the same percentage.

The energy savings from replacing one ton of kiln feed with blast furnace slag, as can be seen in Table 7, are 1.10 MBtu while the CO_2 emission savings from calcination are 0.35 tons. The price of blast furnace slag used as kiln feed is lower compared to when used in blended cement production. According to USGS (2012c), the 2010 average price for air-cooled blast furnace slag was $7.5/ton, while for granulated blast furnace slag ranged between $17-103/ton. For use as a kiln feed the lower end of the price range is probably more representative (Staudt, 2009a).

For illustration purposes, a 15% kiln feed substitution (based on CaO content) will result in energy savings of 0.24 MBtu/ton clinker. According to ECRA (2009) 15% replacement of kiln feed with Granulated Blast Furnace Slag (GBFS) will result in energy savings of 0.09-0.34 MBtu/ton clinker. A cement plant, in order to meet the extra demand, replaced 7% of kiln feed with Blast Furnace Slag (BFS) and as a result, energy use decreased by nearly the same amount (Lesniak, 2009). Investment costs for handling and storing BFS are estimated at $0-3.5/ton cement (ECRA, 2009).

Table 7. Energy savings and CO2 emission savings by using different decarbonated kiln feedstock

Kiln Feed Substitutes	% CaO	Limestone equivalence ratio[1]	Clinker equivalence ratio[2]	Calcination CO_2 avoided/ton material	MBtu fuel saved/ton material
Blast Furnace	45%	0.80	0.69	0.35	1.10

Slag (BFS)					
Steel Slag	65%	1.16	1.00	0.51	1.59
Class C Fly Ash	25%	0.45	0.38	0.20	0.61
Class F Fly Ash	3%	0.05	0.05	0.02	0.07

1. tons of limestone that provide same CaO as one ton of decarbonated material.
2. clinker produced per ton of material used based on CaO content.

Source: Staudt, 2009a

Cement Kiln Dust. Cement Kiln Dust (CKD) produced during calcination is collected by baghouses and electrostatic precipitators. CKD is a partially calcined material with a high $CaCO_3$ content (55.5%) that can be used to substitute kiln feed and at the same time reduce CO_2 emissions from calcination. Cement plants that do not recycle CKD have a higher raw material to clinker ratio. CKD disposal decreased dramatically from 54 kg CKD/ton clinker in 1990, to 15 kg CKD/tonne clinker in 2006 (Adaska and Taubert, 2008). In dry process plants, when the kiln dust does not contain compounds in levels that could affect kiln operation and product quality, CKD is usually returned to the kiln (VDZ and PENTA, 2008). In wet kilns, kiln dust recirculation may not be possible, as partially calcined CKD tends to cause blockages. A few wet plants have solved this problem with the insufflation[16] of kiln dust into the burning zone (VDZ and PENTA, 2008). When the insufflation method is adopted, the CKD content of the kiln feed is limited to about 15%, as it decreases the flame temperature (U.S. EPA, 1994). Ash Grove Cement Company invested $100,000 (in 1993 dollars) in a CKD returning system in order to recycle 80-90 tons of CKD per day that otherwise would have required disposal (U.S. EPA, 1994). According to Hollingshead and Venta (2009), the investment cost for CKD returning equipment is estimated at $0.10/ton clinker. Clinker production is expected to increase by 2% while electricity and fuel use will increase by 1 kWh/ton clinker and 0.018 MBtu/ton clinker respectively (Hollingshead and Venta, 2009). Assuming that a 2% increase in throughput translates into 2% less fuel use per ton of product, and taking into account that 0.018 MBtu/ton clinker extra fuel is required, we estimate the energy savings for a dry kiln plant at 0.05 MBtu/ton clinker.

CKD contains alkali compounds that can negatively affect the operation of the kiln. The Fuller fluidized process and the Passamaquoddy Recovery Scrubber™ technology have been developed for CKD treatment. Both technologies are capital intensive with a payback period estimated to be 6 and 3 years respectively (U.S. DOE-NETL, 2001; U.S. EPA, 1994).

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[16] Insufflation is the practice of injecting cement kiln dust into the kiln flame. In this way, cement kiln dust can be returned to the kiln with a maximum chance of incorporation into the clinker (Alsop et al., 2007), avoiding fine dust recirculation and blockages.

A cement plant in Thomaston, Maine, installed a recovery scrubber technology, and it not only recovers 100% of the generated CKD but it also recycles the CKD produced during the last 100 years of the plant's operation that was stored at its on-site stockpile (Adaska and Taubert, 2008). The quantity and quality of CKD that can be recycled to the kiln is limited by product specifications and local market demands. In some markets, only CKD with alkali levels within specified limits can be directly returned to the kiln.

Calcareous Oil Shale. Some oil shale deposits contain calcareous material that is partially decarbonated. Calcareous oil shale can serve as kiln feed substitute in clinker production and reduce CO_2 emissions from calcination. Calcareous oil shale may also have a calorific value that can be utilized either in the calcination process or in a furnace for power generation (VDZ and Penta, 2008). In case the oil shale is burned separately in a calciner or furnace, the generated ash could then be used in the kiln. Kiln feed with an oil shale content of 8% has an energy contribution of about 72 kBtu/ton clinker (Hollingshead and Venta, 2009). The investment costs for a new feeding system are estimated at $1/ton clinker with additional operational costs of $0.10/ton clinker (Hollingshead and Venta, 2009). The CO_2 reduction potential is estimated at 0.011 lb CO_2/ton clinker (0.005 kg CO_2/ton clinker) (Hollingshead and Venta, 2009). CO_2 reduction will be lower if the oil shale needs to be processed.

Calcareous oil shale has been used as kiln feed substitute in cement plants in Russia and Germany (Bhatty and Gajda, 2004). At Rohrbach Zement, Germany, oil shale with $CaCO_3$ content of 43% has been used successfully for more than 60 years (Hilger, 2003). Oil shale is used in the precalciner, providing approximately 20% of energy and 10% of raw mineral requirements. However, the majority of oil shale is used in fluidized bed for the production of burnt shale which is then used in the manufacture of blended cements. Finely ground burnt shale is characterized by hydraulic properties similar to that of Portland cement. Rohrbach Zement manufactures blended cements with a burnt shale content of up to 35%. Waste heat from fluidized beds is used to generate electricity which exceeds the plant's power requirements (Hilger, 2003). The electricity use for grinding blended_cement with a 27% burnt shale content, is 50% lower than the electricity use for grinding Portland cement (Hilger, 2003).

Reduce the Lime Saturation Factor (LSF). Lime Saturation Factor (LSF) is the ratio of calcium oxide (CaO) to the other oxides (SiO_2, Al_2O_3 and Fe_2O_3) and it determines the maximum amount of lime that can be combined with the various oxides (Lawrence, 1998; Taylor, 1997). For Ordinary Portland Cement (OPC) the LSF ranges between 90 and 102 (ECRA, 2009). Cements with low LSFs are produced with less limestone in the raw meal. Change in the LSF of 1 is translated into a 0.2-0.4% by mass change of the clinker CaO content. The use of less limestone in the kiln will reduce CO_2 emissions from calcination. Also, due to better raw meal burnability, clinker can be burned at lower temperatures, reducing fuel consumption and CO_2 emissions. The production of low LSF cements allows the use of raw materials with lower limestone content. However, low LSF cements have a reduced alite content which results in slow setting times and low early strength development. Finer ground cement can outweigh these drawbacks but only to a limited extend. The strength development of finely ground low LSF cements, composed of more than one constituent can be unpredictable (ECRA, 2009). A decrease of the LSF by 10 will result in fuel savings of 86 kBtu/ton clinker while electricity use will increase by 10-20 kWh/ton clinker due to finer cement grinding (ECRA, 2009). The overall CO_2 emissions are expected to decrease by 35-26 kg CO_2/tonne clinker. No capital investment is required. The Golden Bay Cement plant, in New Zealand, used additives (CBA® quality improver) and reduced the LSF from 98 to 95 without affecting the cement performance (Wray et al., 1999). This allowed the plant to use locally mined lower cost raw materials. Fuel use was reported to decrease by 90-108 kBtu/ton clinker (Wray et al., 1999).

6.11 Alternative Fuels

Fuel Switching. CO_2 emissions from combustion account for about one third of the overall CO_2 emissions from cement manufacture. The switch from more carbon intensive to less carbon intensive fossil fuels can have a substantial effect on the abatement of greenhouse gases. The CO_2 abatement potential for switching from coal 0.22 lb CO_2/kBtu (95 kg CO_2/GJ) to heavy oil 0.18 lb CO_2/kBtu (78 kg CO_2/GJ) is 18%, while for switching to natural gas 0.13 lb CO_2/kBtu (56 kg CO_2/GJ) is 40%. Based on the GNR data, in 2009, the U.S. cement industry covered 86% of its fuel demand with fossils fuels, mainly coal and petcoke, 13% with fossil fuels and waste, and 1.3% with biomass (CSI, 2011). From a technical point of view, cement kilns can operate on 100% oil or natural gas, Currently, the cement industry burns coal and petcoke, fuels that are rich in coal ash which becomes a part of the product and provides an additional benefit to cement manufacturers. According to ECRA (2009), the capital cost for fuel switching is estimated at $1.5-4.5/ton clinker. Fuel use can change from an increase of 0.26 to a decrease of 0.17 MBtu/ton clinker. Electricity use can increase by 0-2.5 kWh/ton clinker (ECRA, 2009). Any fuel switch scenario needs to take into account whether other pollutants, such as NOx emissions, will increase as a result of the switch. Whether it is economically attractive or not to switch from coal and petcoke to oil and natural gas, will depend on the fuel prices.

Alternative Fuels – Biomass and Waste. A wide range of alternative fuels can be used in cement kilns. Alternative fuels usually derive from various waste sources and cost less than conventional fuels. The revenues from waste intake have helped to reduce the production costs of all waste burning cement kilns, and especially of wet process kilns. The use results in reduced waste disposal in landfills, conservation of natural resources, and greenhouse gas emission abatement. The CO_2 emission reduction from switching to alternative fuels will depend on the carbon intensity of the alternative fuel related to its calorific value. Biomass fuels include animal meal, waste wood products, sawdust and waste sewage sludge, but it can also be biofuel cultivated specifically for fuel use, such as wood, and grass. The latter will generally be more expensive than coal. Other alternative fuels that have been used in cement kilns are: automobile shredder residue (ASR), plastics, refinery spent catalyst, clarified soil oil sediments (CSOS), scrap carpet, scrap paper and wood, and scrap tires (U.S. EPA, 2008). High raw material temperatures (about 1,450^{o}C), high kiln gas temperatures (about 2,000^{o}C) and long retention periods (8 seconds or more), can insure the complete breakdown of organic waste (WBCSD/SINTEF, 2006) and efficient dust filters may reduce any potential emissions to safe levels (Holderbank et al., 1999; Cembureau, 1997).

In theory, cement kilns can operate on 100% biomass, but there are certain limitations such as the calorific and moisture content but also the content in trace compounds (i.e. chlorine) of the specific fuel. Most organic materials have low calorific values of about 9-16 MBtu/ton. Cement kilns require fuels with high calorific values (19-21 MBtu/ton), thus the use of biomass should be in combination with other fuels. Up to 60% of the precalciner fuel can be of low calorific value (ECRA, 2009; Tokheim, 2006). When low calorific value fuels with high chlorine compounds (requiring chlorine by-pass system) are used in a kiln, the fuel energy consumption will increase. When utilizing high waste fuel rates, clinker capacity may be reduced, as cement kiln operation with a 60-80% waste substitution rate differs drastically from the operation with 100% fossil fuels. Fuel use for using biomass may increase by 0-260 kBtu/ton clinker while electricity use may also increase by 0-2.7 kWh/ton clinker (ECRA, 2009). The capital cost investment was estimated at $1.6-4.9/ton clinker, while operational costs (based only on fuel costs) will decrease by $2.5-10/ton clinker (ECRA, 2009). According to another study (Hollingshead and Venta; 2009), when a low substitution rate is employed, major firing system conversions are not required and were estimated at $1.60/ton clinker. Operational costs will increase by $0.10/ton clinker (Hollingshead and Venta, 2009), power use will not change while fuel use may increase by 0-72 kBtu/ton clinker (Hollingshead and Venta, 2009; Kääntee et al., 2004). Investment costs can vary drastically depending on the chemical composition and trace contents of various fuels (ECRA, 2009).

A cement plant in Norway, Norcem Brevik, installed a so called “hot combustion chamber” in order to ensure sufficient residence time, a chlorine by-pass system, and a bigger capacity fuel feeding system (Skjeggerud et al., 2009; Tokheim, 2006). As a result, it achieved a traditional fuel substitution rate of 60%, and maintained clinker capacity at previous levels. Energy costs decreased substantially while energy use increased by 0.32 MBtu/ton clinker (Skjeggerud et al., 2009).

Any future increase in alternative fuel prices will limit the savings in operational costs. In addition to the capital required for equipment modifications, performance testing poses another significant cost, ranging from $50,000 per kiln for the co-processing of non-hazardous alternative fuels (i.e. biosolids) to up to $500,000 in the case of hazardous fuel (i.e. CSOS) (U.S. EPA, 2008). In case a cement plant does not have CEMS (Continuous Emissions Monitoring Systems) and is planning to initiate the use of alternative fuels, it will have to install it. Increasing fuel prices offer a big incentive to cement producers to move towards alternative fuels while even with loss in clinker capacity, this measure is often financially attractive (Shenk and Jensen, 2009). However, in order to be able to justify the high capital investment, stable kiln operation and long-term alternative fuel supply needs to be assured.

Tire Derived Fuel (TDF). The use of scrap tires has increased drastically over the past years. In 2005, 47 cement plants used TDF (U.S. EPA, 2008). Scrap tires have a high calorific value (14,000 Btu/ton) and provide raw materials which are necessary in cement manufacturing. When one ton of TDF is used, approximately 770 lb Fe (350 kg) are recovered (U.S. EPA, 2008). Coal can be substituted by whole tires with an average rate of 15%. According to U.S. EPA (2007b) kilns cannot use more than 25% TDF as the zinc content slows down the setting time. Some cement kilns however, use as much as 30% (Hollingshead and Venta, 2009). The TDF emission factor is 0.19 lb CO_2/kBtu while for coal it is 0.22 lb CO_2/kBtu. Typically, 1.05-1.10 tons of TDF can replace one ton of coal (Hollingshead and Venta, 2009). When TDF is used, net CO_2 emissions will increase as TDF is not considered a CO_2 neutral fuel and electricity use will also increase. 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, 1996). 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). For a 15% substitution rate, power use will increase by 1.5 kWh/ton clinker and there will be additional operating costs of $0.10/ton clinker (Hollingshead and Venta, 2009). In a Lafarge plant, a disruption in the chipped tire supply forced them to install a kiln chute in order to be able to use whole tires. The investment cost was $4 million, excluding performance testing and permitting (U.S. EPA, 2008). Depending on which part of the kiln the tires will be fed (Cembureau, 2009) their use can lead to NOx emission reduction (U.S. EPA, 2008). The ongoing conversion of wet to dry kilns may reduce the number of facilities utilizing whole tires, as short dry kilns cannot process whole tires as easily as other types of kilns (i.e. long wet kilns) (U.S. EPA, 2008).

6.12 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 discusses for completeness of the technical analysis.

Fluidized Bed Kiln. The Fluidized Bed Kiln (FBK) is a newer 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 NOx-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), and 10-12% lower compared to suspension preheater kilns equipped with grate cooler (IPPC, 2010). 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 NOx 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). Currently, a plant is being constructed in China with a capacity of 1,000 tpd, but it is not yet in operation (ECRA, 2009). The future fuel consumption is estimated at 2.52-2.9 MBtu/ton clinker (Cohen, 1995). ECRA (2009) estimated energy savings of up to 0.26 MBtu/ton clinker. 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.

Geopolymers. Clinker is made by calcining calcium carbonate (limestone), which releases CO_2 into the atmosphere. Geopolymers, or else called inorganic polymers, can be made from inorganic alumino-silicate compounds. An inorganic polycondensation reaction results in a three-dimensional structure, like that of zeolites. It can be produced by blending three elements, i.e. calcined alumino-silicates (from clay), alkali-disilicates and granulated blast furnace slag or fly-ash (Davidovits, 1994a). Geopolymer cements harden at room temperatures and provide compressive strengths of 20 MPa after 4 hours and up to 70-100 MPa after 28 days, while they also have high fire resistance (Davidovits, 1994a; Zongrijn et al., 2004). The zeolite-like matrix results in the immobilization of materials, e.g. wastes. Despite the high alkali content, geopolymers do not show alkali aggregate reactions (Davidovits, 1993). Research on geopolymers was already going on in Eastern Europe and the U.S in the early 1980s. Geopolymer cements use hydroxide or sodium silicates as activators instead of lime, therefore eliminating process CO_2 emissions, and require lower kiln temperatures of about 1,400°F (750^{o}C) when compared to ordinary cements (Davidovits, 1994a; Davidovits, 2002; Müller and Harnisch, 2008). Davidovits et al. (1994b) estimated that geopolymer production will consume 3/5 less energy than the production of Portland cement. The first industrial geopolymer plant is currently being built in Australia, Zeobond Pty Ltd. Production costs are expected to be 20% higher than OPC cement (von Weizsäcker et al, 2009). The production of Zeobond geopolymer binder does not require big amounts of energy intensive activators, and it relies on waste products from other manufacturing industries; CO_2 emissions can be as low as 10-20% of those of Portland cement binders (Duxson et al., 2007; Net Balance Foundation, 2007). The CO_2 emissions from geopolymer production are estimated at 300 kg CO_2/tonne of product (ECRA, 2009; IEA, 2009). However, the above figure does not take into account emissions from the production of activators. Water consumption in the manufacture and use of geopolymers is similar to OPC (von Weizsäcker et al, 2009). The use of geopolymers results in the immobilization of solid wastes in the matrix (Davidovits, 1991). The availability of raw materials, such as fly ash and blast furnace slag, is limited and in some cases expensive (e.g. natural alumino-silicate metakaolin), therefore it is more likely that geopolymer cement production will not be widely practiced. In regard to capital investment, geopolymer facilities will require lower capital investment than conventional cement plants (IEA, 2009).

Belite and Other Low Energy Clinker. Ordinary Portland Cement (OPC) has an alite (C_3S) content of 40-80%. Belite clinkers contain up to 90% belite (C_2S) and no to small quantities of alite. The production of belite clinkers has the potential to decrease CO_2 emissions from both calcination and fuel combustion (Lawrence, 1998). This is achieved due to the low lime content in the raw meal (Lime Saturation Factor LSF of about 0.80) and due to the lower kiln temperatures (1,350^oC) (belite clinkers have better burnability than alite clinkers). Belite clinkers with 0.80-0.85 LSF, have 10% less energy demand and require 300^oF (150^oC) lower kiln temperature than conventional alite clinkers (Lawrence, 1998). The production of low LSF cements can limit the use of materials with high lime content and enhance the use of supplementary cementitious materials (i.e. slags and fly ash). Major drawback is the low hydraulic reactivity. Cements with LSFs below 0.84 are characterized by low strength development which cannot be compensated by increased cement fineness or increased sulphate levels (Lawrence, 1998). In order to improve belite cement performance, ground alite or OPC should be added; minimum alite content of 15% (Lawrence, 1998). Belite cement reactivity and strength development can be enhanced by i) rapid clinker quenching ii) the addition of impurity ions (i.e. sulphates) and iii) the addition of OPC clinker (Lawrence, 1998). Rapid cooling of belite clinkers has shown to improve the hydraulic activity considerably. However, this method will increase heat losses and limit energy savings. According to ECRA (2009), fuel savings are limited to 5%. In addition, belite clinkers are harder to grind (Hills, 2007), increasing electricity use by 20-40 kWh/ton of clinker (ECRA, 2009). Investment costs for storage, handling and drying of the new materials were estimated by ECRA (2009) at $5-7.6/ton clinker.

Other promising alternatives to regular cements are belite cements that contain hydraulically active sulfoaluminate or ferrite phases. These types of cements have shown to have low setting times and develop good early and late strengths. However, several problems have been indicated due to strength loss after a number of years (Lawrence, 1998). Nowadays, their application is limited to Japan and China (ECRA, 2009; Lawrence, 1998). An innovative cement, Aether™, which is being developed, is composed of 40-75% belite, 15-35% calcium sulfoaluminate (yeelemite), and 5-25% ferrite, is expected to reduce energy consumption of cement manufacture by 15% and CO_2 emissions by 25-30% (Morin et al., 2011). Aether^{TM} could be produced in a traditional cement plant after a few modifications. Research is still ongoing on the manufacturing process, hydration and durability.

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, ranging from 20-40%, 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. A variety of waste fuels, including tires, steadily increase their share in fuel use. Between 1970 and 2010, primary physical energy intensity for cement production dropped 1.2% per year from 7.3 MBtu/short ton to 4.5 MBtu/short ton. Carbon dioxide intensity due to fuel consumption and raw material calcination dropped 24%, from 610 lb. C/ton of cement (0.31 tC/tonne) to 469 lb. C/ton cement (0.23 tC/tonne).

Despite the historic progress, there is ample room for energy efficiency improvement. Over 50 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 Table 8 and Table 9, 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 8. 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	Estimated Payback Period (1) (2)
Raw Materials Preparation			
Mechanical Transport Systems	-	1.0 - 3.0	>3 (1)
Improved Pneumatic Systems	-	1.6	N/A (1)
Improved Raw Mill Blending	0.00-0.02	0.7-2.3	>10

Use of Vertical Roller Mills	-	9.2-10.9	>10
Use of High-Pressure Roller Presses	-	16.9-17.5	7-8 (1)
High Efficiency Classifiers	-	3.9-5.3	>10 (1)
Separate Raw Material Grinding	-	0.8-1.2	>10 (1)
Raw Meal Process Control	-	1.2-1.6	1
Fuel Preparation	-	0.6-1.9	N/A (1)
Clinker Making			
Energy Management and Control Systems	0.08-0.16	0-3.9	<2
Kiln Combustion System Improvements	0.06-0.32	-	<1
Mineralized Clinker	0.00-0.14	0- -0.8	N/A
Indirect Firing	0.12-0.18	0- -0.5	>10 (1)
Oxygen Enrichment	0.0-0.16	-9- -32	N/A(1)
Mixing Air Technology (PH kilns)	0.16	0.02	2 (1)
Seal Replacement	0.01	-	<1
Kiln Shell Heat Loss Reduction	0.09-0.50	-	<1
Preheater Shell Heat Loss Reduction	0.02	-	6
Refractories	0.05	-	4
Conversion to Grate Cooler	0.25	-3.0- -5.0	>18
Optimize Grate Cooler	0.04-0.13	0.0- -1.7	2-7
Low-Pressure Drop Suspension Preheaters	-	0.5-3.7	>10 (1)
Heat Recovery for Power Generation	-	18.0	2-14 (1)
Conversion of Long Dry to Preheater	0.60-1.30	-	>10
Increase Preheater Stages (from 5 to6)	0.10	-	>7 (1)
Addition of Precalciner or Upgrade	0.12-0.54	-	>10 (1)
Conversion of Long Dry Kiln to Preheater Precalciner	0.84-1.11	-	>10 (1)
Efficient Mill Drives	-	0.8-3.2	1
Finish Grinding			
Energy Management and Process Control	-	1.6-8.5	<2
Vertical Roller Mills	-	9.0-20	>8 (1)
Horizontal Roller Mills	-	15.6	>10 (1)
High-Pressure Roller Presses – pre-grinding	-	5.0-10.0	>10 (1)
High-Pressure Roller Presses – finish grinding	-	11.0-25.0	>10 (1)
Improved Grinding Media	-	1.8	>10 (1)
High-Efficiency Classifiers	-	1.7-6.0	>10 (1)
Plant Wide Measures			
Preventative Maintenance	0.04	0.0-5.0	<1
High Efficiency Motors	-	0.0-5.0	<1
Adjustable Speed Drives	-	5.5-9.0	1-3
Optimization of Compressed Air Systems	-	0.0-2.0	<3
High Efficiency Fans	-	0.9	N/A
Efficient Lighting	-	0.0-0.5	N/A
Product Change			
Higher Alkali Cement	0.10-0.33	N/A	Immediate
Blended Cement	0.90	-15.00	1-3
Limestone Portland Cement	0.17	3.0	<1
Reducing Fineness	-	0.0-14.0	Immediate
Feedstock Change			
Use of Steel Slag in Clinker (CemStar) (10% substitution)	0.15	-	1-2
Use of Fly Ash, Blast Furnace Slag in Clinker (15%	0.24	0.0- -1.7	<7 (1)
Use of Cement Kiln Dust in Clinker	0.05	-0.9	<2
Use of Calcareous Oil Shale in Clinker (8% oil shale)	0.07	-	10 (1)
Reduce the Lime Saturation Factor	0.08-0.10	-9- -18	N/A
Alternative Fuels			
Fuel Switching	0.16- -0.28	0.0- -2.5	N/A
Biomass and Waste	0.00- -0.43	0.0- -2.5	<4
Tire Derived Fuel	-	-1.50	N/A

(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.

(2) Fuel and electricity costs used in the calculation of the payback periods are based on the U.S. cement industry's energy expenditures as reported by the U.S. Energy Information Administration in the 2006 Manufacturers Energy Consumption Survey. The cost of electricity is $0.058/kWh and the cost of fuel is $2.61/MBtu.

Table 9. 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	Specific Electricity Savings (kWh/ton cement)	Estimated Payback Period (3) (4)
Raw Materials Preparation			
Slurry Blending and Homogenizing	-	0.1-0.6	<3
Wash Mills with Closed Circuit Classifier	-	8.0-11.0	>10 (1)
High Efficiency Classifiers	-	3.9-5.3	>10 (1)
Fuel Preparation	-	0.8-2.4	N/A (1)
Clinker Making			
Energy Management and Control Systems	0.14-0.27	0.0-3.9	<1
Kiln Combustion System Improvements	0.11-0.54	-	<1
Mineralized Clinker	0.00-0.14	0.0- -0.8	N/A
Indirect Firing	0.12-0.18	0.0- -0.5	>10 (1)
Oxygen Enrichment	0.0-0.27	-9.0- -32.0	N/A(1)
Mixing Air Technology	0.27	0.02	1 (1)
Seal Replacement	0.02	-	<1
Kiln Shell Heat Loss Reduction	0.09-0.50	-	<1
Refractories	0.05	-	4
Conversion to Grate Cooler	0.43	-3.0- -5.0	9-12
Optimize Grate Cooler	0.04-0.13	0.0- -1.7	2-7
Conversion to Semi-Dry Process Kiln	0.93-1.30	-4.7- - 6.5	>10 (1)
Conversion to Semi-Wet Process Kiln	0.60-0.90	-3.7	1-3
Conversion to Dry precalciner Kiln	1.70-2.70	-8.4	>7 (1)
Efficient Mill Drives	-	0.8-3.2	1
Finish Grinding			
Energy Management and Process Control	-	1.6-8.5	<2
Vertical Roller Mills	-	9.0-20	>8 (1)
Horizontal Roller Mills	-	15.6	>10 (1)
High-Pressure Roller Presses – pre-grinding	-	5.0-10.0	>10 (1)
High-Pressure Roller Presses – finish grinding	-	11.0-25.0	>10 (1)
Improved Grinding Media	-	1.8	>10 (1)
High-Efficiency Classifiers	-	1.7-6.0	>10 (1)
Plant Wide Measures			
Preventative Maintenance	0.04	0.0-5.0	<1
High Efficiency Motors	-	0.0-5.0	<1
Adjustable Speed Drives	-	5.5-9.0	1-3
Optimization of Compressed Air Systems	-	0.0-5.0	<3
High Efficiency Fans	-	0.9	N/A
Efficient Lighting	-	0.0-0.5	N/A
Product Change			
Higher Alkali Cement	0.10-0.33	N/A	Immediate
Blended Cement	1.39	-15.0	1-2
Limestone Portland Cement	0.29	3.0	<1
Reducing Fineness	-	0.0-14.0	Immediate
Feedstock Change			
Use of Steel Slag in Clinker (CemStar)	0.15	-	1-2
Use of Fly Ash, Blast Furnace Slag in Clinker	0.24	0.0- -1.7	<7 (1)
Use of Calcareous Oil Shale in Clinker	0.07	-	10 (1)
Reduce the Lime Saturation Factor	0.08-0.10	-9- -18	N/A
Alternative Fuels			
Fuel Switching	0.16- -0.28	0.0- -2.5	N/A
Biomass and Waste	0.00- -0.43	0.0- -2.5	<4
Tire Derived Fuel	-	-1.50	N/A

(3) 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.

(4) Fuel and electricity costs used in the calculation of the payback periods are based on the U.S. cement industry's energy expenditures as reported by the U.S. Energy Information Administration in the 2006 Manufacturers Energy Consumption Survey. The cost of electricity is $0.058/kWh and the cost of fuel is $2.61/MBtu.

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8. Glossary

AAGC	Air Activated Gas Conveyor
AC	Alternating Current
ACAA	American Coal Ash association
Al_2O_3	Aluminium Oxide
APC	Advanced Process Control
ASDs	Adjustable speed drives
ASR	Alkali-Silica Reactivity
ASR	Automobile Shredder Residue
ASTM	American Society for Standards and Materials
BBBP	Better Buildings, Better Plants
BF	Bag Filter
BFS	Blast Furnace Slag
Btu	British Thermal Unit
C	Carbon
C_2S	Belite
C_3S	Alite
CAC	Compressed Air Challenge®
$CaCO_3$	Calcium Carbonate
CAF	Cement Advanced Furnace
CaF_2	Calcium Fluoride
CADDET	Centre for the Analysis and Dissemination of Demonstrated Technologies
CaO	Calcium oxide (lime)
CDA	Copper Development Association
CEE	Consortium of Energy Efficiency
CEMS	Continuous Emissions Monitoring Systems
CFL	Compact fluorescent lamp
CIM	Computer Integrated Manufacturing
CIPEC	Canadian Industry Program for Energy Conservation
CKD	Cement Kiln Dust

cm	centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
CSI	Cement Sustainability Initiative
CSOS	Clarified Soil Oil Sediments
DC	Direct Current
EAF	Electric Arc Furnace
EASA	Electric Apparatus Service Association
ECRA	European Cement Research Academy
ECU	European Currency Unit
EIA	Energy Information Administration (U.S. Department of Energy)
EP	Electrostatic Precipitator
EPAct	Energy Policy Act
FBK	Fluidized Bed Kiln
Fe	Iron
Fe_2O_3	Iron Oxide
FLC	Fluidized Conveying
fob	Free on Board or Freight on Board
GBFS	Granulated Blast Furnace Slag
GJ	Gigajoule
GNR	Getting the Numbers Right
GWh	Gigawatt-hour
HHV	High Heating Value
HID	High Intensity-discharge
hp	horsepower
HPGR	High-Pressure Grinding Rolls
HVAC	Heating, ventilation, and air-conditioning
Hz	Hertz
IAC	Industrial Assessment Center
IEA	International Energy Agency
IEA-ETSAP	International Energy Agency-Energy Technology Systems Analysis Program

IPPC	Integrated Pollution Prevention Control
ISO	International Organization for Standardization
ITIBMIC	Institute of Technical Information for the Building Materials Industry of China
KBS	Knowledge Based Systems
kBtu	Thousand British Thermal Unit
kcal	kilocalorie
KD	Kiln Dust
kg	kilogram
kWh	kilowatt-hour
lb	pound
LBNL	Lawrence Berkeley National Laboratory
LCC	Life Cycle Costing
LED	Light-emitting diode
LHV	Low Heating Value
LRC	Lighting Research Center
LSF	Lime Saturation Factor
MAT	Mixing Air Technology
MBtu	Million British Thermal Unit
MDM	Motor Decisions Matter^{SM}
MECS	Manufacturing Energy Consumption Survey
mm	millimeter
MPa	Mega Pascal
MPC	Model-Predictive Control
MtC	Million tonnes Carbon
Mtph	million tonnes per hour
NEMA	National Electrical Manufacturers Association
NEMA EE	National Electrical Manufacturers Association Energy Efficiency
NOx	Nitrogen Oxides
O_2	Oxygen
OEC	ORMAT Energy Converter
OPC	Ordinary Portland Cement

ORC	Organic Rankine Cycle
PCA	Portland Cement Association
pH	potential of Hydrogen
PJ	Petajoule
PM	Particulate Matter
psi	pound per square inch
psid	pound per square inch (differential)
psig	pound per square inch (gauge)
RCRA	Resource Conservation and Recovery Act
RMB	Renminbi (Chinese currency)
scf	standard cubic feet
SCMs	Supplementary Cementitious Materials
SEC	Specific Energy Consumption
SiO_2	Silicon Dioxide
SO_2	Sulfur Dioxide
tpd	tonnes per day
TBtu	trillion British Thermal Unit
TDF	Tire Derived Fuel
TEFC	Totally Enclosed Fan Cooled
UNFCCC	United Nations Framework Convention on Climate Change
U.S. DOE	United States Department of Energy
U.S. DOE-OIT	United States Department of Energy-Office of Industrial Technologies
U.S. EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VSDs	Variable speed drives
WBCSD	World Business Council on Sustainable Development
W.C.	Water column
ZKG	Zement Kalk Gips

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Appendix A: Basic Energy Efficiency Actions for Plant Personnel

Personnel at all levels should be aware of energy use and organizational goals for energy 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 below (Caffal, 1995).

- Eliminate unnecessary energy consumption by equipment. 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 air 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.

Reference

Caffal, C., 1995. Energy Management in Industry. Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET), The Netherlands. Analysis Series 17, December.

Appendix B: ENERGY STAR Energy Management Assessment Matrixes

The assessment matrixes on the following pages are designed to help organizations and energy managers compare their energy management practices to those outlined in the Guidelines for Energy Management.

How to use the Assessment Matrixes
The matrixes outline the key activities identified in the ENERGY STAR Guidelines for Energy Management and three levels of implementation:

- ✓ Where there is no evidence
- ✓ Where some elements of a program are in place
- ✓ Where an energy management program is fully implemented

To apply this tool to your organization:

1. Compare your program or facility to the Guidelines by identifying the degree of implementation that most closely matches your organization's program.

2. Use a highlighter to fill in the cell that best characterizes the level of implementation of your program or at your facility. You will now have a visual comparison of your program to the elements of the ENERGY STAR Guidelines for Energy Management.

3. Identify the steps needed to fully implement the energy management elements and record these in the Next Steps column.

In addition to the static Assessment Matrixes printed below, interactive versions are available on the U.S. EPA website by following these links.

ENERGY STAR Energy Program Assessment Matrix

ENERGY STAR Facility Assessment Matrix

ENERGY STAR Small/Medium Manufacturer Energy Management Assessment

ENERGY STAR® Energy Management Assessment Matrix

	Little or no evidence	Some elements	Fully implemented		Next Steps
Make Commitment to Continuous Improvement					
Energy Director	No central or organizational resource Decentralized management	Central or organizational resource not empowered	Empowered central or organizational leader with senior management support	-	
Energy Team	No company energy network	Informal organization	Active cross-functional team guiding energy program	-	
Energy Policy	No formal policy	Referenced in environmental or other policies	Formal stand-alone EE policy endorsed by senior mgmt.	-	
Assess Performance and Opportunities					
Gather and Track Data	Little metering/no tracking	Local or partial metering/tracking/ reporting	All facilities report for central consolidation/analysis	-	
Normalize	Not addressed	Some unit measures or weather adjustments	All meaningful adjustments for organizational analysis	-	
Establish baselines	No baselines	Various facility-established	Standardized organizational base year and metric established	-	
Benchmark	Not addressed or only same site historical comparisons	Some internal comparisons among company sites	Regular internal & external comparisons & analyses	-	
Analyze	Not addressed	Some attempt to identify and correct spikes	Profiles identifying trends, peaks, valleys & causes	-	
Technical assessments and audits	Not conducted	Internal facility reviews	Reviews by multi-functional team of professionals	-	
Set Performance Goals					
Determine scope	No quantifiable goals	Short term facility goals or nominal corporate goals	Short & long term facility and corporate goals	-	
Estimate potential for improvement	No process in place	Specific projects based on limited vendor projections	Facility & organization defined based on experience	-	

Establish goals	Not addressed	Loosely defined or sporadically applied	Specific & quantifiable at various organizational levels	-	
Create Action Plan					
Define technical steps and targets	Not addressed	Facility-level consideration as opportunities occur	Detailed multi-level targets with timelines to close gaps	-	
Determine roles and resources	Not addressed or done on ad hoc basis	Informal interested person competes for funding	Internal/external roles defined & funding identified	-	
Implement Action Plan					
Create a communication plan	Not addressed	Tools targeted for some groups used occasionally	All stakeholders are addressed on regular basis	-	
Raise awareness	No promotion of energy efficiency	Periodic references to energy initiatives	All levels of organization support energy goals	-	
Build capacity	Indirect training only	Some training for key individuals	Broad training/certification in technology & best practices	-	
Motivate	No or occasional contact with energy users and staff	Threats for non-performance or periodic reminders	Recognition, financial & performance incentives	-	
Track and monitor	No system for monitoring progress	Annual reviews by facilities	Regular reviews & updates of centralized system	-	
Evaluate Progress					
Measure results	No reviews	Historical comparisons	Compare usage & costs vs. goals, plans, competitors	-	
Review action plan	No reviews	Informal check on progress	Revise plan based on results, feedback & business factors	-	
Recognize Achievements					
Provide internal recognition	Not addressed	Identify successful projects	Acknowledge contributions of individuals, teams, facilities	-	
Get external recognition	Not sought	Incidental or vendor acknowledgement	Government/third party highlighting achievements	-	

ENERGY STAR® Facility Energy Management Assessment Matrix

Company Name:		Assessment Date:			
	Little or no evidence	**Some elements/degree**	**Fully implemented**		**Next Steps**
Commit to Continuous Improvement					
Site Energy Leader	None assigned.	Assigned responsibilities but not empowered. 20-40% of time is devoted to energy.	Recognized and empowered leader having site manager and senior energy manager support.		
Site Energy Champion	None identified.	Senior manager implicitly supports the energy program.	Senior manager actively supports the energy program and promotes energy efficiency in all aspects of site operations.		
Site Energy Team	No site energy team.	Informal organization with sporadic activity.	Active cross-functional team guiding site energy program.		
Energy Policy	No energy policy or awareness of organizational policy.	Organizational policy in place. Little awareness by site energy team and limited application of policy.	Organizational policy supported at site level. All employees aware of goals and responsibilities.		
Site Energy Plan	No written plan.	Informal plan not widely known.	Written formal plan endorsed, distributed, and verified.		
Accountability	No energy budgeting and accountability.	Estimates used for allocating energy budgets.	Key users are metered separately. Each entity has total accountability for their energy use.		
Participation Levels	No reporting of energy performance data internally or involvement in external organizations.	Some participation, sharing, mentoring, and professional memberships. Annual reporting of performance.	Participates in energy network/organizations. Shares best practices/mentors other sites. Reports usage quarterly.		
Assess Performance and Opportunities					
Track & Analyze Data	Limited metering or tracking. No demand analysis or billing evaluation.	Some metering, tracking, analyzing, and reporting. Energy bills verified for accuracy.	Key loads metered, tracked, analyzed, and reported. Facility peak demand analyzed. Adjusts for real-time demand.		

Documentation	No manuals, plans, designs, drawings, specs, etc. for building and equipment available.	Some documentation and records available. Some review of equipment commissioning specs conducted.	Critical building and equipment documentation available and used for load surveys/recommissioning/efficiency goals.		
Benchmarking	Energy performance of systems and facilities not benchmarked.	Limited comparisons of specific functions, or only same-site historical comparisons.	Key systems/sites benchmarked using comparison tools like Portfolio Manager/Energy Performance Indicators.		
Technical Assessments	No formal or external reviews.	Limited review by vendors, location, or organizational and corporate energy managers.	Extensive regular reviews by multi-functional team of internal and external professionals. Full assessment every 5 years.		
Best Practices	None identified.	Ad hoc or infrequent monitoring of trade journals, internal databases, and other facilities' best practices.	Regular monitoring of trade journals, internal databases, and other facilities. Best practices shared and implemented.		
Set Performance Goals					
Goals/Potential	Energy reduction goals not established.	Loosely defined. Little awareness of energy goals by others outside of site energy team.	Potential defined by experience or assessments. Goals roll up to unit/site/ organization and status posted prominently.		
Career Development	No career development. No opportunities available.	Exposure to other energy programs. Some temporary or project assignments available elsewhere.	Energy professionals have established career paths that are reviewed annually. Opportunities for growth encouraged.		
Energy Team Incentives	No ties between energy efficiency improvement and compensation.	Spot awards or luncheons for employees on a project.	Accountability tied to performance reviews, compensation, and personal and plant bonuses.		
Create Action Plan					
Improvement Planning	No upgrade plan.	Upgrades implemented sporadically. Some compliance with organizational goals and standards.	Upgrade plans established; reflect assessments. Full compliance with organizational EE design guidelines and goals.		
Roles and Resources	Not addressed, or addressed on ad hoc basis only.	Informal interested person competes for funding. Little support from organizational program.	Internal/external roles defined and funding identified. Organizational or corporate program support secured.		
Site Planning Integration	Impact on energy from changes not considered.	Decisions impacting energy considered on first-cost basis only.	Projects/contracts include energy analysis. Energy projects evaluated with other investments. Lifecycle costing applied.		

Implement Action Plan					
Communication Plan	Site plan not developed.	Periodic communications for projects. Some reporting of energy use information.	All stakeholders are addressed on regular basis.		
Energy Awareness	None conducted.	Occasional energy efficiency awareness campaigns. Some communication of energy costs.	Planned outreach and communications. Support organizational initiatives. Employees aware of site energy costs.		
Building Staff Capacity	No training offered.	Some vendor training for key individuals and operators.	Broad training/certification in technology and best practices. Networking opportunities actively pursued.		
Contract Management	Contracts are renewed automatically without review.	Occasional review of supplier contracts.	Energy-efficient procurement policy in place. Vendors for replacements on standby. Regular review of suppliers.		
Incentives and Rebates	Not researched or pursued.	Occasional communication with utility representatives. Limited knowledge of incentive programs.	Researches rebates and incentives offered regionally and nationally. Communicates often with utility representatives.		
Evaluate Progress					
Measuring Results	No reviews.	Historical comparisons. Some reporting of results.	Compare usage & costs vs. goals, plans, other sites. Results reported to site and organizational or corporate management.		
Reviewing Action Plan	No reviews.	Informal check on progress.	Revise plan based on results, feedback and business factors. Best practices shared with other sites / organization or corporate program.		
Recognize Achievements					
Site Recognition	Not addressed.	Occasional recognition of projects and people.	Recognition system in place. Awards for projects pursued by operators.		
Organizational Recognition	Not sought.	Occasionally when prompted by senior management.	Senior management acknowledges site successes.		
External Recognition	Not sought.	Occasional trade magazine and vendor recognition.	Government and third-party recognition highlighting achievements sought. ENERGY STAR awarded annually.		

Appendix C: Teaming Up to Save Energy Checklist

The following checklist can be used as a handy reference to key tasks for establishing and sustaining an effective energy team. For more detailed information on energy teams, consult the U.S. EPA's *Teaming Up to Save Energy* (U.S. EPA, 2006), and other resources available at http://www.energystar.gov/.

ORGANIZE YOUR ENERGY TEAM		√
Energy Director	Able to work with all staff levels from maintenance to engineers to financial officers. Senior-level person empowered by top management support	
Senior Management	Energy director reports to senior executive or to a senior management council. Senior champion or council provides guidance and support	
Energy Team	Members from business units, operations/engineering, facilities, and regions. Energy networks formed. Support services (PR, IT, HR).	
Facility Involvement	Facility managers, electrical personnel. Two-way information flow on goals and opportunities. Facility-based energy teams with technical person as site champion.	
Partner Involvement	Consultants, vendors, customers, and joint venture partners. Energy savings passed on through lower prices.	
Energy Team Structure	Separate division and/or centralized leadership. Integrated into organization's structure and networks established.	
Resources & Responsibilities	Energy projects incorporated into normal budget cycle as line item. Energy director is empowered to make decisions on projects affecting energy use. Energy team members have dedicated time for the energy program.	
STARTING YOUR ENERGY TEAM		√
Management	Senior management briefed on benefits, proposed approach, and	

Briefing	potential energy team members.	
Planning	Energy team met initially to prepare for official launch.	
Strategy	Energy team met initially to prepare for official launch.	
Program Launch	Organizational kickoff announced energy network, introduced energy director, unveiled energy policy, and showcased real-world proof.	
Energy Team Plans	Work plans, responsibilities, and annual action plan established.	
Facility Engagement	Facility audits and reports conducted. Energy efficiency opportunities identified.	
BUILDING CAPACITY		√
Tracking and Monitoring	Systems established for tracking energy performance and best practices implementation.	
Transferring Knowledge	Events for informal knowledge transfer, such as energy summits and energy fairs, implemented.	
Raising Awareness	Awareness of energy efficiency created through posters, intranet, surveys, and competitions.	
Formal Training	Participants identified, needs determined, training held. Involvement in ENERGY STAR Web conferences and meetings encouraged. Professional development objectives for key team members.	
Outsourcing	Use of outside help has been evaluated and policies established.	
Cross-Company Networking	Outside company successes sought and internal successes shared. Information exchanged to learn from experiences of others.	
SUSTAINING THE TEAM		√
Effective Communications	Awareness of energy efficiency created throughout company. Energy performance information is published in company reports and communications.	
Recognition and	Internal awards created and implemented. Senior management is	

Rewards	involved in providing recognition.	
External Recognition	Credibility for your organization's energy program achieved. Awards from other organizations have added to your company's competitive advantage.	
MAINTAINING MOMENTUM		√
Succession	Built-in plan for continuity established. Energy efficiency integrated into organizational culture.	
Measures of Success	Sustainability of program and personnel achieved. Continuous improvement of your organization's energy performance attained.	

Appendix D: Support Programs for Industrial Energy Efficiency Improvement

This appendix provides a list of energy efficiency support 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

URL: http://www1.eere.energy.gov/manufacturing/tech_deployment/software_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

URL: http://www1.eere.energy.gov/manufacturing/tech_deployment/software_ssat.html

3E Plus®: Insulation Thickness Computer Program

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: U.S. Department of Energy

URL: http://www1.eere.energy.gov/manufacturing/tech_deployment/software_ssat.html

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

URL: http://www1.eere.energy.gov/manufacturing/tech_deployment/software_motormaster.html

The 1-2-3 Approach to Motor Management

Description: A step-by-step motor management guide and spreadsheet tool that can help motor service centers, vendors, utilities, energy-efficiency organizations, and others convey the financial benefits of sound motor management.

Target Group: Any industry

Format: Downloadable Microsoft Excel spreadsheet

Contact: Consortium for Energy Efficiency (CEE), (617) 589-3949

URL: http://www.motorsmatter.org/tools/123approach.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

URL: http://www1.eere.energy.gov/manufacturing/tech_deployment/software_airmaster.html

Fan System Assessment Tool (FSAT)

Description: The Fan System Assessment Tool (FSAT) helps to quantify the potential benefits of optimizing a fan system. FSAT calculates the amount of energy used by a fan system, determines system efficiency, and quantifies the savings potential of an upgraded system.

Target Group: Any user of fans

Format: Downloadable software

Contact: U.S. Department of Energy

URL: http://www1.eere.energy.gov/manufacturing/tech_deployment/software_fsat.html

Combined Heat and Power Application tool (CHP)

Description: The Combined Heat and Power Application Tool (CHP) helps industrial users evaluate the feasibility of CHP for heating systems such as fuel-fired furnaces, boilers, ovens, heaters, and heat exchangers.

Target Group: Any industrial heat and electricity user

Format: Downloadable software

Contact: U.S. Department of Energy

URL: http://www1.eere.energy.gov/manufacturing/tech_deployment/software_chp.html

Pumping 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

URL: http://www1.eere.energy.gov/manufacturing/tech_deployment/software_psat.html

Plant Energy Profiler/Integrated Tool Suite

Description: The Plant Energy Profiler, or ePEP (formerly called Quick PEP), is an online software tool provided by the U.S. Department of Energy to help industrial plant managers in the United States identify how energy is being purchased and consumed at their plant and also identify potential energy and cost savings. ePEP is designed so that the user can complete a plant profile in about an hour. The ePEP online tutorial explains what plant information is needed to complete an ePEP case.

Target Group: Any industrial plant

Format: Online software tool

Contact: U.S. Department of Energy

URL: http://www1.eere.energy.gov/manufacturing/tech_assistance/printable_versions/software_epep.html

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/buildings/facility-owners-and-managers/existing-buildings/use-portfolio-manager

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

URL: http://www1.eere.energy.gov/industry/bestpractices/iacs.html

Energy Assessments

Description: The U.S. DOE conducts plant energy assessments to help manufacturing facilities across the nation identify immediate opportunities to save energy and money, primarily by focusing on energy-intensive systems, including process heating, steam, pumps, fans, and compressed air.

Target Group: Large plants

Format: Online request

Contact: U.S. Department of Energy

URL: http://www1.eere.energy.gov/manufacturing/tech_deployment/energy_assessment.html

Better Building, Better Plants (BBBP)

Description: The Better Building, Better Plants program is a national partnership initiative to drive a 25% reduction in industrial energy intensity in 10 years while decreasing carbon emissions and enhancing U.S. competitiveness. Leaders of industrial companies are invited to take a corporate-wide voluntary Pledge to reduce the energy intensity of their industrial operations by 25% or more in 10 years. Companies in partnership with the U.S. DOE, will work to improve energy management and identify the most cost-effective options for energy and carbon savings.

Target Group: Building and industry

Contact: U.S. Department of Energy

URL: http://www4.eere.energy.gov/challenge/home

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.nist.gov/mep/

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=bulk_purchasing.bus_purchasing

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/

Workforce Development and Training

Description: The 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 U.S. DOE also provides training on other industrial energy equipment, often in coordination with conferences.

Target Group: Technical support staff, energy and plant managers

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

Contact: U.S. Department of Energy

URL: http://www1.eere.energy.gov/industry/bestpractices/training.html

Compressed Air Challenge®

Description: The not-for-profit Compressed Air Challenge® develops and provides training on compressed air system energy efficiency via a network of sponsoring organizations in the United States and Canada. Three levels of training are available: (1) Fundamentals (1 day); (2) Advanced (2 days); and (3) Qualified Specialist (3-1/2 days plus an exam). Training is oriented to support implementation of an action plan at an industrial facility.

Target Group: Compressed air system managers, plant engineers

Format: Training workshops

Contact: Compressed Air Challenge: Info@compressedairchallenge.org

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

Financial Assistance

Below major federal programs are summarized 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). However, these programs can change over time, so it is recommended to review current policies when making any financial investment decisions.

Energy Efficiency and Renewable Energy (EERE) Financial Opportunities

Description: The Office of EERE works with business, industry, universities, and others to increase the use of renewable energy and energy efficiency technologies. One way EERE encourages the growth of these technologies is by offering financial assistance opportunities for their development and demonstration.

Target Group: Business, industry, universities, consumers, federal energy managers, inventors, and states.

Format: Solicitations

Contact: U.S. Department of Energy

URL: http://www1.eere.energy.gov/financing/business.html

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. These programs can change over time, so it is recommended to review current policies when making any financial investment decisions.

Database of State Incentives for Renewables & Efficiency (DSIRE)

Description: DSIRE is a comprehensive source of information on state, local, utility, and federal incentives and policies that promote renewable energy and energy efficiency. Established in 1995, DSIRE is an ongoing project of the NC Solar Center and the Interstate Renewable Energy Council funded by the U.S. Department of Energy.

Target Group: Any industry

URL: http://www.dsireusa.org/

Summary of Motor and Drive Efficiency Programs by State

Description: A report that provides an overview of state-level programs that support the use of NEMA Premium® motors, ASDs, motor management services, system optimization and other energy management strategies.

Target Group: Any industry

Contact: Consortium for Energy Efficiency (CEE), (617) 589-3949

URL: http://www.cee1.org/ind/programsummary/index.php

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/contracts/index.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 $95,000.

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

California – Savings By Design

Description: Design assistance is available to building owners and to their design teams for energy-efficient building design. Financial incentives are available to owners when the efficiency of the new building exceeds minimum thresholds, generally 10% better than California's Title 24 standards. The maximum owner incentive is $150,000 per free-standing building or individual meter. Design team incentives are offered when a building design saves at least 15%. The maximum design team incentive per project is $50,000.

Target Group: Nonresidential new construction or major renovation projects

Format: Open year round

URL: http://www.savingsbydesign.com/

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: The Energy Center provides loan funds equal to 50% of the total financed cost of a project (up to $1 million) at 0% interest. 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.iowaenergycenter.org/alternate-energy-revolving-loan-program-aerlp/

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.ny.gov/en/Funding-Opportunities.aspx

Oregon – Energy Trust Production Efficiency Program

Description: Incentives for energy efficiency projects are offered for Oregon businesses that are serviced by either Pacific Power or Portland General Electric. Current incentive levels are $0.25/kWh saved up to 60% of the project cost. Lighting incentives are treated differently. There are standard incentive levels for specific fixture replacements (exp. $30/fixture). If a fixture replacement does not qualify for a standard incentive, but it does save energy, a custom incentive can be calculated using $0.17/kWh saved up to 35% of the project cost. Premium efficiency motor rebates are also offered at $10/hp from 1 to 200 hp motors. Over 200 hp, the current incentive levels of $0.25/kWh saved up to 60% of the project cost are used to calculate an incentive.

Target Group: Commercial and industrial companies in Oregon

Contact: Energy Trust of Oregon

URL: http://energytrust.org/industrial-and-ag/

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://www.focusonenergy.com/