# Energy Efficiency Improvement Opportunities for the Cement Industry

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**January 2008**

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## ABSTRACT

This report provides information on the energy savings, costs, and carbon dioxide emissions reductions associated with implementation of a number of technologies and measures applicable to the cement industry. The technologies and measures include both state-of-the-art measures that are currently in use in cement enterprises worldwide as well as advanced measures that are either only in limited use or are near commercialization.

This report focuses mainly on retrofit measures using commercially available technologies, but many of these technologies are applicable for new plants as well. Where possible, for each technology or measure, costs and energy savings per tonne of cement produced are estimated and then carbon dioxide emissions reductions are calculated based on the fuels used at the process step to which the technology or measure is applied. The analysis of cement kiln energy-efficiency opportunities is divided into technologies and measures that are applicable to the different stages of production and various kiln types used in China: raw materials (and fuel) preparation; clinker making (applicable to all kilns, rotary kilns only, vertical shaft kilns only); and finish grinding; as well as plant wide measures and product and feedstock changes that will reduce energy consumption for clinker making. Table 1 lists all measures in this report by process to which they apply, including plant wide measures and product or feedstock changes. Tables 2 through 8 provide the following information for each technology: fuel and electricity savings per tonne of cement; annual operating and capital costs per tonne of cement or estimated payback period; and, carbon dioxide emissions reductions for each measure applied to the production of cement.

This information was originally collected for a report on the U.S. cement industry (Worrell and Galitsky, 2004) and a report on opportunities for China's cement kilns (Price and Galitsky, in press). The information provided in this report is based on publicly-available reports, journal articles, and case studies from applications of technologies around the world.

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# Introduction

This report provides information on the energy savings, costs, and carbon dioxide emissions reductions associated with implementation of a number of technologies and measures applicable to the cement industry. The technologies and measures include both state-of-the-art measures that are currently in use in cement enterprises worldwide as well as advanced measures that are either only in limited use or are near commercialization. Mainly the focus is on retrofit measures using commercially available technologies, but many of these technologies are applicable for new plants as well. Where possible, for each technology or measure, costs and energy savings per tonne of cement produced are estimated and then carbon dioxide emissions reductions are calculated based on the fuels used at the process step to which the technology or measure is applied. The analysis of cement kiln energy-efficiency opportunities is divided into technologies and measures that are applicable to the different stages of production and various kiln types used in China: raw materials (and fuel) preparation; clinker making (applicable to all kilns, rotary kilns only, vertical shaft kilns only); and finish grinding; as well as plant wide measures and product and feedstock changes that will reduce energy consumption for clinker making.

# Energy Efficiency Improvement Opportunities

*Table 1. Energy Efficiency Measures and Technologies for the Cement Industry.*

**Raw Materials Preparation**

Efficient transport systems (dry process)
Raw meal blending systems (dry process)
Process control vertical mill (dry process)
High-efficiency roller mills (dry process)
High-efficiency classifiers (dry process)
Slurry blending and homogenization (wet process)
Conversion to closed circuit wash mill (wet process)

**Fuel Preparation**

Roller mills for fuel preparation
Roller press for coal grinding

**Finish Grinding**

Energy management and process control
High-pressure roller press
High efficiency classifiers
Improved grinding media (ball mills)

**General Measures**

Preventative maintenance (insulation, compressed air system, maintenance)
High efficiency motors
Efficient fans with variable speed drives
Optimization of compressed air systems
Efficient lighting

**Product & Feedstock Changes**

Blended cements
Use of waste derived fuels
Limestone cement
Low alkali cement
Use of steel slag in kiln

**All Kilns**

Improved refractories
Kiln shell heat loss reduction
Energy management & process control
Adjustable speed drive for kiln fan

**Vertical Shaft Kilns**

Convert to new suspension preheater/precalciner kiln
Kiln combustion system improvements

**Rotary Kilns**

Preheater kiln upgrade to precalciner kiln
Long dry kiln upgrade to preheater/precalciner kiln
Older dry kiln upgrade to multi-stage preheater kiln
Convert to reciprocating grate cooler
Kiln combustion system improvements
Indirect Firing
Optimize heat recovery/upgrade clinker cooler
Seal replacement
Low temperature heat recovery for power (capital costs given in $/kW)
High temperature heat recovery for power
Low pressure drop cyclones
Efficient kiln drives

Table 1 shows the energy efficiency measures included in this report by process step as well as general measures. Efficiency measures are described below in more detail in the applicable section, by process step.

### *Raw Materials Preparation*

Table 2 shows fuel and electricity savings, estimated payback period and carbon dioxide ($CO_2$) savings for each measure related to raw materials preparation (including the preparation of fuels). A description for each measure is given below.

*Table 2. Energy Efficiency Measures for Raw Materials Preparation in Cement Plants. More information can be found in the description of the measures below.*

| **Energy Efficiency Measure (for raw materials production)** | **Fuel Savings (GJ/t)** | **Electricity Savings (kWh/t)** | **Estimated Payback Period (years) (1)** | **$CO_2$ Savings (kgC/t)** |
|---|---|---|---|---|
| Efficient Transport System | - | 3.4 | > 10 (1) | 0.78 |
| Raw Meal Blending | - | 1.7-4.3 | NA (1) | 0.4-1.0 |
| Process Control Vertical Mill | - | 1.4-1.7 | 1 | 0.3-0.4 |
| High-Efficiency Roller Mill | - | 10.2-11.9 | > 10 (1) | 2.3-2.7 |
| High-Efficiency Classifiers | - | 4.8-6.3 | > 10 (1) | 1.1-1.4 |
| Slurry Blending and Homogenizing | | 0.5-0.9 | < 3 | 0.1-0.2 |
| Wash Mills with Closed Circuit Classifier | - | 8.5-11.9 | > 10 (1) | 2.0-2.7 |
| Roller Mills for Fuel Preparation | - | 0.7-1.1 | NA (1) | 0.2-0.3 |

**Notes:**
All data is given per tonne of cement
(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.
NA = not available

**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 to be 2.0 kWh/t raw material with a switch to mechanical conveyor systems. Installation costs for the system are estimated to be $3/t raw material production based on the Holderbank study (1993). Conversion to mechanical conveyors is cost-effective when replacement of conveyor systems is needed to increase reliability and reduce downtime.

**Raw Meal Blending (Homogenizing) Systems (Dry Process).** To produce a good quality product and to maintain optimal and efficient combustion conditions in the kiln, it is crucial that the raw meal is completely homogenized. Quality control starts in the quarry and continues to the blending silo. On-line analyzers for raw mix control are an integral part of the quality control system (Fujimoto, 1993; Holderbank, 1993).

Most plants use compressed air to agitate the powdered meal in so-called air-fluidized homogenizing silos (using 1.1-1.5 kWh/t raw meal). Older dry process plants use mechanical systems, which simultaneously withdraw material from 6-8 different silos at variable rates (Fujimoto, 1993), using 2.2-2.6 kWh/t raw meal. Modern plants use gravity-type homogenizing silos (or continuous blending and storage silos) reducing power consumption. In these silos, material funnels down one of many discharge points, where it is mixed in an inverted cone. Gravity-type silos may not give the same blending efficiency as air-fluidized systems. Although most older plants use mechanical or air-fluidized bed systems, more and more new plants seem to have gravity-type silos, because of the significant reduction in power consumption (Holderbank, 1993). Silo retrofit options are cost-effective when the silo can be partitioned with air slides and divided into compartments which are sequentially agitated, as opposed to the construction of a whole new silo system (Gerbec, 1999). The energy savings are estimated to be 1.0-2.5 kWh/t raw meal (Fujimoto, 1993; Holderbank, 1993; Alsop & Post, 1995, Cembureau, 1997b; Gerbec, 1999). Costs for the silo retrofit are estimated to be $3.7/t raw material (assuming $550K per silo and an average capacity of 150,000 tonnes annual capacity).

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

**Use of Roller Mills (Dry Process).** Traditional ball mills used for grinding certain raw materials (mainly hard limestone) can be replaced by high-efficiency roller mills, by ball mills combined with high-pressure roller presses, or by horizontal roller mills. The use of these advanced mills saves energy without compromising product quality. Energy savings of 6-7 kWh/t raw materials (Cembureau, 1997b) are assumed through the installation of a vertical or horizontal roller mill. An additional advantage of the inline vertical roller mills is that they can combine raw material drying with the grinding process by using large quantities of low grade waste heat from the kilns or clinker coolers (Venkateswaran and Lowitt, 1988). Various roller mill process designs are marketed.

In 1998, Arizona Portland cement (Rillito, Arizona, U.S.) installed a roller mill for raw material grinding increasing throughput, flexibility, raw meal fineness and reducing electricity consumption (De Hayes, 1999). Investments are estimated to be $5.5/t raw material (Holderbank, 1993).

**High-efficiency Classifiers/Separators.** A recent development in efficient grinding technologies is the use of high-efficiency classifiers or separators. Classifiers separate the finely ground particles from the coarse particles. The large particles are then recycled back to the mill. High efficiency classifiers can be used in both the raw materials mill and in the finish grinding mill.

Standard classifiers may have a low separation efficiency, which leads to the recycling of fine particles, and results in to extra power use in the grinding mill. Various concepts of high-efficiency classifiers have been developed (Holderbank, 1993; Süssegger, 1993). In high-efficiency classifiers, the material stays longer in the separator, leading to sharper separation, thus reducing overgrinding. Electricity savings through implementing high-efficiency classifiers are estimated to be 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 2.8-3.7 kWh/t raw material (Salzborn and Chin-Fatt, 1993; Süssegger, 1993). Replacing a conventional classifier by a high-efficiency classifier has led to 15% increases in the grinding mill capacity (Holderbank, 1993) and improved product quality due to a more uniform particle size (Salzborn and Chin-Fatt, 1993), both in raw meal and cement. The better size distribution of the raw meal may lead to fuel savings in the kiln and improved clinker quality. Investment costs are estimated to be $2.2/annual t raw material production, according to Holderbank (1993).

**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/t raw material (Cembureau, 1997b). 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/t (Cembureau, 1997b). Replacing the tube mill by a wash mill would reduce electricity consumption to 5-7 kWh/t (Cembureau, 1997b) 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/t, or 40-60%.

### *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. An impact mill would consume around 45-60 kWh/t and a tube mill around 25 – 26 kWh/t (total system requirements) (Cembureau, 1997b). 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. Coal roller mills are available for throughputs of 5.5 to 220 t/hour. Lehigh Portland Cement installed a vertical roller mill for coal grinding in 1999 at the Union Bridge, Maryland, U.S. plant.

Blue Circle cement has ordered a vertical roller mill for the new kiln line V at the Roberta plant in Calera, Alabama, U.S. It has a capacity of 41.3 t/hr and was commissioned in early 2001. Coal grinding roller mills can be found in many countries around the world, e.g. Brazil, Canada, China, Denmark, Germany, Japan and Thailand. All major suppliers of cement technology offer roller mills for coal grinding.

Vertical roller mills have been developed for coal grinding, and are used by over 100 plants around the world (Cembureau, 1997b). Electricity consumption for a vertical roller mill is estimated to be 16-18 kWh/t coal (Cembureau, 1997b). 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, 1997b), estimating savings at 7-10 kWh/t coal.

**Roller Press for Coal Grinding.** Roller presses, like those used for cement and raw material grinding, are generally more efficient than conventional grinding mills. Roller presses can be used to grind raw materials and coal interchangeably, although coal-grinding equipment needs special protection against explosions.

### *Clinker Making - All Kilns*

All kilns can implement improved refractories, kiln shell heat loss reduction measures, energy management and process control systems, and adjustable speed drives for the kiln fan. Although all kilns can benefit from kiln combustion system improvements, we have split this measure into two distinct measures for rotary and shaft kilns, in those respective sections, below. Distinctions between energy management and process control for each kiln type are explained in the measure description in this section. Table 3 provides information on the initial capital costs, the operations and maintenance (O&M) costs, the simple payback period, the specific fuel savings, the specific electric savings, the specific $CO_2$ emissions reductions, and the lifetime associated with each of these measures.

*Table 3. Energy-Efficiency Opportunities Applicable to All Kiln Types.*

| | Capital Costs ($/t) | O & M Costs ($/t) | Payback Period (years) | Fuel Savings (GJ/t) | Electric Savings (kWh/t) | $CO_2$ Savings (kgC/t) | Lifetime (years) |
|---|---|---|---|---|---|---|---|
| Improved refractories | NA | | NA | 0.4-0.6[1] | - | 10.3-15.5 | NA |
| Kiln shell heat loss reduction | 0.25 | | 1 | 0.1-0.63[2] | - | 2.8-10.3 | 20 |
| Energy management & process control | 0.3-1.7 | | < 2 | 0.1-0.2 | 1.5-3.2 | 2.9-5.9 | 10 |
| Adjustable speed drive for kiln fan | 0.23 | 0 | 2-3 | - | 6.1 | 1.4 | 10 |

Note: Energy savings and costs are based on case study data from the U.S., except where noted. Costs in China will vary depending on technology and availability. Where possible, we have included more data for China in the following text. All data are given per tonne of clinker. For U.S. data, the estimated savings and payback periods are based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio).

[1] Data taken from Chinese case studies

[2] Data from Chinese case studies indicate savings of 0.46 to 0.63 GJ/t clinker, while U.S. data show savings of 0.1 to 0.4 GJ/t clinker.

*NA = not available*

**Improved 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 higher quality refractories will lead to longer operating periods and reduced lost production time between relining of the kiln, and, hence, offset their higher costs (Schmidt, 1998; van Oss, 2002). It will also lead to additional energy savings due to the relative reduction in start-up time. The energy savings are difficult to quantify, as they will strongly depend on the current lining choice and management.

In one vertical shaft kiln in South China, a new energy-efficient lining was applied. Fuel consumption was reduced from 930 to 950 kcal/kg clinker (3.9 to 4.0 GJ/t clinker) to 800 to 820 kcal/kg clinker (3.4 to 3.5 GJ/t clinker), a savings of approximately 14% (ITIBMIC, 2004). The output also increased by about 1 tonne per hour. Another cement plant in North China utilizing vertical shaft kilns employed energy efficient lining and found a reduction of fuel use from 900 to 920 kcal/kg clinker (3.8 GJ/t clinker) to about 800 kcal/kg clinker (3.4 GJ/t clinker) (ITIBMIC, 2004). The output of the kiln also increased per unit of raw materials input.

Refractories are made by foreign companies operating in China, particularly in the Liaoning Province, such as Refratechnik (German) and RHI (Austrian) (Cui, 2006). China also produces medium and smaller refractories but the energy efficiency is poorer than those made by the leading international companies (Cui, 2006).

**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 0.12 to 0.4 GJ/t of clinker (Lowes and Bezant, 1990; COWIconsult, 1993; Venkateswaran and Lowitt, 1988). Costs for insulation systems are estimated to be $0.25/annual tonne 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.

Changjiang Cement Factory in Zhejiang City, Jangsu Province applied energy saving kiln lining to its shaft kiln and found energy savings of 0.46 to 0.63 GJ/t clinker (ITIBMIC, 2004). In addition to these energy savings, they were able to increase production. Generally this technology is imported (Cui, 2006).

**Energy Management and Process Control Systems.** Heat from the kiln may be lost through non-optimal process conditions or process management. Automated computer control systems may help to optimize the combustion process and conditions. Improved process control will also help to improve the product quality and grindability, e.g. reactivity and hardness of the produced clinker, which may lead to more efficient clinker grinding. In cement plants across the world, different systems are used, marketed by different manufacturers. Most modern systems use so-called 'fuzzy logic' or expert control, or rule-based control strategies. Expert control systems do not use a modeled process to control process conditions, but try to simulate the best human operator, using information from various stages in the process.

One such system, called ABB LINKman, was originally developed in the United Kingdom by Blue Circle Industries and SIRA (ETSU, 1988). The first system was installed at Blue Circle's Hope Works in 1985, which resulted in a fuel consumption reduction of nearly 8% (ETSU, 1988). The LINKman system has successfully been used in rotary kilns (both wet and dry). 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). Several companies in China also provide optimized information technology for energy management and process control, such as the ABB or the Chinese software company Yun Tian (Wang, 2006b).

All foreign produced control systems described above report typical energy savings of 3 to 8%, while improving productivity of the kiln. 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 Oregon plant in 1999.

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

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

Energy savings from foreign produced process control systems may vary between 2.5% and 10% (ETSU, 1988; Haspel and Henderson, 1993; Ruby, 1997), and the typical savings are estimated to be 2.5 to 5%. The economics of advanced process control systems are very good and payback periods can be as short as 3 months (ETSU, 1988). The system at Blue Circle's Hope Works (U.K.) needed an investment of £203,000 (1987), equivalent to $0.3/annual tonne clinker (ETSU, 1988), including measuring instruments, computer hardware and training. Holderbank (1993) notes an installation cost for on-line analyzers of $0.8 to 1.7/annual tonne 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 and improved control of free lime content in the clinker, and to 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 $0.35/annual tonne of clinker, with an estimated payback period of 1 year (Martin et al., 2001).

Combustion control in vertical kilns is more difficult than in rotary kilns where the flow of raw materials is controlled by a mechanically-rotating horizontally-oriented shaft at a slight angle instead of just gravity (Liu et al., 1995). In these kilns, operating skills and hence, proper training is more important for energy efficiency and product quality. If automatic controls are going to be successfully implemented, they must link all processes from mine management to raw materials input into the kiln to kiln fuel input in order to realize stable production; none should be done manually (ITIBMIC, 2004). Control technologies also exist for controlling the air intake. (For more information on kiln combustion system improvements and controls for VSKs, see “kiln combustion system improvements” in Energy Efficiency Opportunities for Clinker Production – Vertical Shaft Kilns, below). Raw materials and fuel mix can be improved by a careful analysis of the chemical and physical characteristics of each, and by automating the weighing process and the pellet production (water content and raw feed mixtures), the blending process, the kiln operation (optimizing air flow, temperature distribution, and the speed of feeding and discharging). Cui (2006) reports that most technologies for this measure are made by international companies such as Siemens and ABB; few if any are made by domestic companies.

**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) for the 1,000 horsepower 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 5.5 kWh/t of cement (6.1 kWh/t clinker). The Zhonglida Group, operating ten cement enterprises (with both VSKs and new dry rotary kilns), installed variable speed drives in 40 large motors (over 55 kW) and over 40 of its smaller motors (< 55 KW) and found energy savings of over 30% (ITIBMIC, 2004). ASDs are currently being made in China, although many of the parts and instrumentation are still being imported from Germany and/or Japan (Cui, 2006).

***Clinker Making – Rotary Kilns***

For rotary kilns, an existing preheater kiln may be converted to a multi-stage preheater/precalciner kiln by adding a precalciner and an extra preheater, an existing long dry kiln can be upgraded to use a multi-stage preheater/precalciner kiln, and older dry kilns can be upgraded to multi-stage preheater/precalciner kilns. Other energy-efficiency technologies and measures include kiln combustion system improvements, reciprocating grate coolers, optimize heat recovery and upgrade the clinker cooler, seal replacement, low temperature waste heat recovery for power generation, high temperature waste heat recovery for power generation, low pressure drop cyclones for suspension preheaters, and efficient kiln drives. Table 4 provides information on the initial capital costs, the operations and maintenance (O&M) costs, the simple payback period, the specific fuel savings, the specific electric savings, the specific carbon dioxide savings and the lifetime associated with each of these measures.

**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 precalciner). 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 to 100% (from 1100 tpd to 2000 to 2200 tpd), while reducing specific fuel consumption from 3.6 to 3.1-3.2 GJ/t clinker, resulting in savings of 11 to 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). The European Commission (2000) estimates a multi-stage preheater/precalciner kiln uses approximately 3 GJ/t clinker.

Older precalciners can also be retrofitted for energy efficiency improvement and NOx emission reduction. Retrofitting the precalciner 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 1500 tonnes/day to 2500 tonnes/day (Hrizuk, 1999). The reconstruction reduced fuel consumption by 0.16 to 0.7 GJ/t clinker (Hrizuk, 1999), while reducing NOx emissions. Capitol Cement (San Antonio, Texas) replaced an older in-line precalciner with a new downdraft precalciner 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 3.4 GJ/t clinker (Frailey & Happ, 2001).

*Table 4. Energy-Efficiency Opportunities Applicable to Rotary Kilns.*

| | Capital Costs ($/t) | O & M Costs ($/t)[1] | Payback Period (years) | Fuel Savings (GJ/t) | Electric Savings (kWh/t)[2] | $CO_2$ savings (kgC/t) | Lifetime (years) |
|---|---|---|---|---|---|---|---|
| Preheater kiln upgrade to precalciner kiln | 9.4-28 | -1.1 | 5 | 0.16-0.7 | | 4.1-18.1 | 40 |
| Long dry kiln upgrade to preheater/precalciner kiln | 8.6-29 | | > 10 | 1.4 | - | 36 | 40 |
| Older dry kiln upgrade to multi-stage preheater kiln | 28-41 | | > 10 | 0.9 | - | 23 | 40 |
| Convert to reciprocating grate cooler | 0.4-5.5 | 0.11 | 1-2 | 0.27 | -3.0 | 6.3 | 20 |
| Kiln combustion system improvements | 1.0 | 0 | 2 – 3 | 0.1-0.5 | - | 2.6-12.9 | 20 |
| Indirect Firing | 7.4 | | NA | 0.015-0.022 | - | 0.39-0.57 | NA |
| Optimize heat recovery/upgrade clinker cooler | 0.1-0.3 | | 1-2 | 0.05-0.16 | -2 | 0.8-3.7 | 20 |
| Seal replacement | NA | | ≤ 0.5 | 0.011 | - | 0.3 | NA |
| Low temperature heat recovery for power (capital costs given in $/kW) | 800-1250 ($/kW)[3] | 0.007 | < 3 | - | 20-35 | 4.6-8.1 | NA |
| High temperature heat recovery for power | 2.2-4.4 | 0.22-0.33 | 3 | - | 22 | 5.1 | 35 |
| Low pressure drop cyclones | 3 | | > 10 | - | 0.7-4.4 | 0.16-1.0 | 20 |
| Efficient kiln drives | +0-6% [4] | | NA | - | 0.55-3.9 | 0.13-0.9 | 10 |

*Note: Energy savings and costs below are based on case study data. Costs in China will vary depending on technology and availability. Where possible, we have included more data for China in the following text. All data are given per tonne of clinker. For U.S. data, the estimated savings and payback periods are based on the average performance of the U.S. cement industry (e.g. clinker to cement ratio).*

[1] Negative numbers represent operation and maintenance *savings*.

[2] Negative numbers represent an increase in electricity due to the measure.

[3] Domestic technology cost is 6000 to 10,000 RMB per investment, which is about 10,000 RMB less than foreign technology (16,000 to 22,000 RMB per kW). We use estimates from Chinese case studies to determine the numbers in the tables above.

[4] Initial costs given as the additional % required relative to standard U.S. technology (0 to 6%).

NA = data not available

According to Sauli (1993), average savings of new precalciners can be 0.4 GJ/t clinker. Sauli (1993) does not outline the investments made for the conversion project. Vleuten (1994) estimates the cost of adding a precalciner and suspension preheaters to be $28 U.S./annual tonne clinker annual capacity (it is not clear what is included in this estimate). Jaccard and Willis (1996) estimate a much lower cost of $9.4/t clinker capacity. The increased production capacity is likely to save considerably in operating costs, estimated to be $1.1/t clinker (Jaccard & Willis, 1996).The Hejiashan Cement Company, Ltd. in Jiangshan City, Zhejiang Province installed two new dry process kilns in 2001 and 2003 at a cost of 105 million RMB for a 1000 tonne per day kiln and 156 million RMB for a 1500 tonne per day kiln, respectively (ITIBMIC, 2004). This equates to roughly 300 RMB/t clinker ($37 U.S./t). Power consumption is expected to be 85.87 kWh/t clinker and fuel consumption 2.5GJ/t clinker for the 1000 tonne per day kiln.

Cui (2006) reports that many precalciner kilns have been constructed from 2001 and about 10 to 20% are imported while 80 to 90% are domestic technology. Cui states that domestic technology, made by a few leading manufacturers in China, costs roughly 1/3 to 1/5 the cost of imported technology but doesn't last as long. Most companies are adopting domestic technologies (Cui, 2006). Domestic technology, however, is not available for kiln sizes over 5000 tonne per day (Wang, 2006b).

**Conversion of Long Dry Kilns to Preheater/Precalciner Kiln.** A long dry kiln can be upgraded to the current state of the art multi-stage preheater/precalciner kiln. Energy savings are estimated to be 1.4 GJ/t 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 $23 to 29/t clinker for a pre-heater, pre-calciner kiln. Jaccard and Willis (1996) give a much lower value of $8.6/t clinker capacity.

**Dry Process Upgrade 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. 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 to 40%) as the feed enters the kiln. Also, the kiln length may be shortened by 20 to 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. 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 4.1 GJ/t clinker to 3.6 GJ/t 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 to be 0.9 GJ/t 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 $39 to 41/annual tonne clinker capacity for conversion to a multi-stage preheater kiln while Vleuten (1994) estimates a cost of $28/annual tonne clinker capacity for the installation of suspension pre-heaters.

**Conversion to Reciprocating Grate Cooler.** Four main types of coolers are used in the cooling of clinker: (1) shaft; (2) rotary; (3) planetary; and, (4) reciprocating grate coolers. There are no longer any rotary or shaft coolers in operation in North America; in China, there are few if any rotary or shaft coolers (Cui, 2006). However, some reciprocating grate coolers may still be in operation.

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 to 200°C, which is expected from planetary coolers (Vleuten, 1994). Tertiary heat recovery (needed for precalciners) is impossible with planetary coolers (Cembureau, 1997b), 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).

Modern reciprocating coolers have a higher degree of heat recovery than older variants, increasing heat recovery efficiency to 65% or higher, while reducing fluctuations in recuperation efficiency (i.e. increasing productivity of the kiln). In China, the Liulihe Cement Factory implemented a TCIDRI third generation grate cooler and achieved a heat recovery rate of over 72% on a 2500 tonne/day precalciner kiln (ITIBMIC, 2004). This aerated beam grate cooler also saves water by replacing the water spray cooling with air cooling (ITIBMIC, 2004). When compared to a planetary cooler, additional heat recovery is possible with grate coolers at an extra power consumption of approximately 3.0 kWh/t clinker (COWIconsult et al., 1993; Vleuten, 1994). The savings are estimated to be up to 8% of the fuel consumption in the kiln (Vleuten, 1994). Cooler conversion is generally economically attractive only when installing a precalciner, which is necessary to produce the tertiary air (see above), or when expanding production capacity. The cost of a cooler conversion is estimated to be between $.044 and $5.5/annual tonne clinker capacity, depending on the degree of reconstruction needed. Annual operation costs increase by $0.11/t clinker (Jaccard and Willis, 1996).

**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 to 10% depending on the kiln type (Venkateswaran and Lowitt, 1988). Lowes and Bezant, (1990) discuss advancements from combustion technology that improve combustion through the use of better kiln control. They also note 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 and Bezant, 1990).

For rotary kilns, the Gyro-Therm technology 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 irradiative 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, 1997a; Videgar, Rapson and Dhanjal, 1997). Costs for the technology vary by installation. An average cost of $1/annual tonne clinker capacity is assumed based on reported costs in the demonstration projects.

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

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

Excess air infiltration is estimated to result in heat losses equal to 75 MJ/t of clinker. Assuming a reduction of excess air between 20% and 30%, indirect firing may lead to fuel savings of 15 to 22 MJ/t 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. In 1997, California Portland's plant in Colton, California implemented an indirect firing system for their plant, resulting in NOx emission reductions of 30 to 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 clinker, or $7.4/t clinker.

**Optimize 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. All coolers heat the secondary air for the kiln combustion process and sometimes also tertiary air for the precalciner (Alsop and Post, 1995). Reciprocating grate coolers are the modern variant and are suitable for large-scale kilns (up to 10,000 tpd). Grate coolers use electric fans and excess air. The highest temperature portion of the remaining air can be used as tertiary air for the precalciner. Rotary coolers (used for approximately 5% of the world clinker capacity for plants up to 2200 to 5000 tpd) and planetary coolers (used for 10% of the world capacity for plants up to 3300 to 4400 tpd) do not need combustion air fans and use little excess air, resulting in relatively lower heat losses (Buzzi and Sassone, 1993; Vleuten, 1994).

Grate coolers may recover between 1.3 and 1.6 GJ/t clinker sensible heat (Buzzi and Sassone, 1993). Improving heat recovery efficiency in the cooler results in fuel savings, but may also influence product quality and emission levels. Heat recovery can be improved through reduction of excess air volume (Alsop and Post, 1995), control of clinker bed depth and new grates such as ring grates (Buzzi and Sassone, 1993; Lesnikoff, 1999). Control of cooling air distribution over the grate may result in lower clinker temperatures and high air temperatures. Additional heat recovery results in reduced energy use in the kiln and precalciner, due to higher combustion air temperatures. Birch, (1990) notes a savings of 0.05 to 0.08 GJ/t clinker through the improved operation of the grate cooler, while Holderbank, (1993) notes savings of 0.16 GJ/t clinker for retrofitting a grate cooler. COWIconsult et al. (1993) note savings of 0.08 GJ/t clinker but an increase in electricity use of 2.0 kWh/t clinker. The costs of this measure are assumed to be half the costs of the replacement of the planetary with a grate cooler, or $0.22/annual tonne clinker capacity.

A recent innovation in clinker coolers is the installation of a static grate section at the hot end of the clinker cooler. This has resulted in improved heat recovery and reduced maintenance of the cooler. Modification of the cooler would result in improved heat recovery rates of 2 to 5% over a conventional grate cooler. Investments are estimated to be $0.11 to $0.33/annual tonne clinker capacity (Young, 2002).

**Seal Replacement.** Seals are used at the kiln inlet and outlet to reduce false air penetration, as well as heat losses. Seals may start leaking, increasing the heat requirement of the kiln. Most often pneumatic and lamella-type seals are used, although other designs are available (e.g. spring-type). Although seals can last up to 10,000 to 20,000 hours, regular inspection may be needed to reduce leaks. Energy losses resulting from leaking seals may vary, but are generally relatively small. Philips Kiln Services (2001) 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% (0.011 GJ/t clinker). The payback period for improved maintenance of kiln seals is estimated to be 6 months or less (Canadian Lime Institute, 2001). This technology is produced and available domestically in China (Cui, 2006).

**Low Temperature Heat Recovery for Power Generation**[1]**.** Despite government

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[1] The adoption of low temperature waste heat recovery for electricity production in cement plants changes the temperature profile of the flue gas which may impact the low-temperature, catalytic dioxin formation

policies to promote adoption of the technology (through the *China Medium and Long Term Energy Conservation Plan*, for example), using low temperature waste heat for power generation has not been widely adopted by Chinese cements plants (GEI, 2005) although 45 cement rotary kilns have already adopted this measure (Cui, 2006). Even many large-scale rotary kilns built after 2003 do not use this technology. One plant has utilized this technology, received through donation from Japan (GEI, 2005). The Anhui Ningguo cement plant installed a power generation system on a 4000 tonne per day kiln cement production line and found electricity generated reached 39 kWh per tonne of clinker since operation began in 1998 (Anhui Ninggou, 2002). Pan (2005) estimates a cost for imported (Japanese) technology of 18,000 to 22,000 RMB ($2,250 to $2,750) per kW with an installation capacity over 6 MW. Chinese domestic technology was developed in 1996 and is currently available from three Chinese companies: Tianjin Designing Institute of Cement Industry, Zhongxin Heavy Machine Company, and Huaxiao Resource Co. Ltd. All three companies have on-going demonstration programs in Chinese cement plants. Installation cost of domestic technology and equipment is currently about 10,000 RMB ($1,250) per kW. The installation cost would be a bit lower if kilns and generation system are constructed simultaneously. At China United Cement Company, two 6000 kW systems were installed for RMB 101.8 million ($12.7 million 2006 U.S.), RMB 36 million ($4.5 million 2006 U.S.) of private capital and RMB 64 million of bank loans ($8 million 2006 U.S.), equaling about RMB 8500 per kW (CNBM, 2005). The electricity being generated is 79.8 kWh/t clinker. Beijing Cement Ltd. also installed waste heat recovery equipment on its 2400 tpd and 3200 tpd kilns (BEIC, 2006). Total capacity is now 7.5 MW and the total investment was RMB 47.43 million ($6 million 2006 U.S.), equaling about 6,300 RMB per kW ($800 2006 U.S. per kW). Of this, 70% was provided by the Beijing Energy Investment Company.

In another demonstration project summarized by GEI (2005), the waste heat from two clinker kilns of Taishan Cement Ltd is to be used. The capacity of the two kilns is 5000 tonnes per day and 2500 tonnes per day. Operation was to begin on 1st Oct 2005; equipment has already been installed but is still under adjustment. Maximum capacity is designed at 13.2 MW and annual output of 95 GWh. Of this, 90.8 GWh would be supplied to cement production, accounting for more than 30% of the energy needs of cement production (Guo, 2004).

ITIBMIC (2004) estimates for a 2000 tonne per day (730,000 annual tonne) kiln capacity, about 20 kWh/t clinker of electricity could be generated for an investment of 20 to 30 million RMB.

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reactions. Heat recovery from waste-to-energy boilers increases the residence time for the flue gas at the dioxin formation temperature window (700 -200 C) increases dioxin formation. Flue gas cooling temperature profile is one the important factors determining dioxin formation potential of a combustion facility. Some hazardous waste incinerators use rapid flue gas quenching to reduce residence time of the flu gas passing through the formation window for controlling dioxin formation. On the other hand, it may be due to less boiler surface area in the optimum temperature window in quenched vs. non-quenched systems, rather than a gas residence time. The surface area tends to accumulate reactive carbon and trace metals. More area likely means higher D/F concentrations. Research is needed to find out whether there is significant effect of waste heat recovery on dioxin emissions from cement kilns (Lee, 2006; Gullett, 2006).

In May 2002, the Tianjin Cement Industry Design and Research Institute in cooperation with the Shanghai Wanan Enterprise Corporation began renovations on a 1350 tonne four-stage cyclone preheater kiln to generate low-temperature waste heat electricity (ITIBMIC, 2004). They installed domestic low temperature waste heat recovery technology, and the facility now generates over 1.8 MW of electricity, operating 7000 hours per year. Including the 10% electricity required to operate the system, the facility generates an additional 11.34 GWh annually. With an electricity price of 0.50 RMB/kWh, the Tianjin Cement plant found savings of 11 to 14 RMB per tonne of clinker. The operating cost is about 0.06 RMB/kWh and the payback period about 3 years. Low-temperature waste heat recovery has been implemented at other plants, as well, including the 4000 tonne/day precalciner kiln at the Ningguo Cement Factory of the Conch Group and the Liuzhou Cement Factory (ITIBMIC, 2004).

ITIBMIC (2004) reports generating capacity of domestic technology to be approximately 24 to 32 kWh, while foreign technology will generate about 28 to 36 kWh. Cui (2006) most recently reported domestic technology could produce 35kWh/t of clinker while Japanese technology now produces 45 kWh/t of clinker; German technology better but no data is available. Investment, however, is much less – about 6000 RMB for domestic technology and 16,000 RMB for foreign equipment. Running time and required labor are approximately the same.

**High Temperature 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 converted into power. In the U.S., only in long-dry kilns is the temperature of the exhaust gas sufficiently high to cost-effectively recover the heat through power generation.[2] Cogeneration systems can either be direct gas turbines that utilize the waste heat (top cycle), or the installation of a waste heat boiler system that runs a steam turbine system (bottom cycle). This measure focuses on the steam turbine system since these systems have been installed in many plants worldwide and have proven to be economic (Steinbliss, 1990; Jaccard and Willis, 1996; Neto, 1990). Heat recovery has limited application for plants with in-line raw mills, as the heat in the kiln exhaust is used for raw material drying. While electrical efficiencies are still relatively low (18%), based on several case studies power generation may vary between 11 and 25 kWh/t clinker (Scheuer & Sprung, 1990; Steinbliss, 1990; Neto, 1990). Electricity savings of 22 kWh/t clinker are assumed. Jaccard and Willis (1996) estimate installation costs for such a system at $2.2 to 4.4/annual tonne clinker capacity with operating costs of $0.22 to 0.33/t clinker. In 1999, four U.S. cement plants cogenerated 486 million kWh (USGS, 2001). In China, most high temp waste heat is recycled to the preheated and precalciner.

**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

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[2] 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. In China, however, low temperature heat is being recovered; see previous measure for details.

plant with lower pressure losses will reduce the power consumption of the kiln exhaust gas fan system. Depending on the efficiency of the fan, 0.66 to 0.77 kWh/t clinker can be saved for each 50 mm W.C. (water column) the pressure loss is reduced. For most older kilns this amounts to savings of 0.66 to 1.1 kWh/t clinker (Birch, 1990). Fujimoto (1994) discussed a Lehigh Cement plant retrofit in which low-pressure drop cyclones were installed in their Mason City, Iowa plant and saved 4.4 kWh/t clinker (Fujimoto, 1994). Installation of the cyclones can be expensive, however, since it may often entail the rebuilding or the modification of the preheater tower, and the costs are very site specific. Also, new cyclone systems may increase overall dust loading and increase dust carryover from the preheater tower. However, if an inline raw mill follows it, the dust carryover problem becomes less of an issue. A cost of $3/annual tonne clinker is assumed for a low-pressure drop cyclone system. The best technology available in China is imported from the Austrian PMT Company (Cui, 2006).

**Efficient Kiln Drives.** A substantial amount of power is used to rotate the kiln. 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 0.55 kWh/t clinker at slightly higher capital costs (+6%). More recently, the use of alternate current (AC) motors is advocated to replace the traditionally used direct current (DC) drive. The AC motor system may result in slightly higher efficiencies (0.5 – 1% reduction in electricity use of the kiln drive) and has lower investment costs (Holland, 2001). Using high-efficiency motors to replace older motors or instead of re-winding old motors may reduce power costs by 2 to 8%.

*Clinker Making – Vertical Shaft Kilns*

For vertical shaft kilns, the main energy-efficiency opportunity is to replace the VSK with new suspension preheater/precalciner kilns. In addition, combustion system improvements can be made for the kiln. Table 5 provides information on the initial capital costs, the operations and maintenance (O&M) costs, the simple payback period, the specific fuel savings, the specific electric savings, the specific carbon dioxide savings and the lifetime associated with each of these measures.

**Replace vertical shaft kiln with new suspension preheater/precalciner kilns.** The new suspension preheater (NSP) technique is being developed for 1000 t/day, 2000 t/day and 4000 t/day (GEI, 2005). NSP should be used for medium- or large-scale cement plants that are being either enlarged or rebuilt. For the small cement plants, earthen vertical kiln (and hollow rotary kiln with dry method) should be gradually abandoned. Further description of these kilns is made above.

According to Liu et al. (1995), some "key" Chinese plants[3] use 5.4 GJ/t clinker, while advanced precalciner kilns use about 3 GJ/t clinker; a savings of 2.4 GJ/t clinker. The Liulihe Cement Factory installed a precalciner kiln with a 5-stage preheater and a preburning furnace and found fuel consumption to be 3.011 GJ/t (ITIBMIC, 2004).

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[3] "Key" Chinese plants generally refer to large, centrally administered state-owned enterprises (Sinton, 1996).

*Table 5. Energy-Efficiency Opportunities Applicable to Vertical Shaft Kilns.*

| | Capital Costs ($/t) | O & M Costs ($/t) | Payback Period (years) | Fuel Savings (GJ/t) | Electric Savings (kWh/t) | $CO_2$ savings (kgC/t) | Lifetime (years) |
|---|---|---|---|---|---|---|---|
| Convert to new suspension preheater/precalciner kiln | 28-41 | NA | 5-7[1] | 2.4 | - | 62 | 40 |
| Kiln combustion system improvements | NA | NA | NA | NA | NA | NA | NA |

*Note: Energy savings and costs below are based on case study data. Costs in China will vary depending on technology and availability. Where possible, we have included more data for China in the following text. All data are given per tonne of clinker.*

[1] Payback period calculated using approximate costs of bituminous coal for industrial boilers (bitu2) in China for the year 2005 (approximately $55/t coal).

NA = data not available; efficiency data unavailable because case studies generally measure fuel savings for a package of measures; *individual measures* are rarely applied and hence, savings for them are often not measured or calculated (Liu et al, 1995). For example, Liu et al. (1995) reports a package of measures for VSKs usually result in a 10-30% savings in fuel intensity and a payback period of 2 years.

By the end of 2004, China put into service 140 new suspension preheater/precalciner (NSP) and suspension preheater (SP) kilns; of those, 50 were new in 2004 (Cui, 2004). For more information on this technology, also see measures in Energy Efficiency Opportunities for Clinker Production – Rotary Kilns Section, above.

**Kiln Combustion System Improvements.** Fuel combustion systems in kilns can be contributors to kiln inefficiencies, often resulting in higher CO formation. Inefficiencies are caused by incomplete combustion of fuel, combustion with excess or inadequate air, uneven air distribution, and oversupply of coal (Venkateswaran and Lowitt, 1988; Liu et al., 1995). Inadequate blower capacity and leakage can result in insufficient air supply. Improvement of air distribution requires better quality raw material pellets and precise kiln operation. Sophisticated VSKs are mechanized with automatic feeding and discharging equipment, while older VSKs are still operated manually (Liu et al., 1995). Oversupply of coal often results from coal powder that has been overground, supplying high fuel density. At low temperatures and insufficient oxygen, overground coal reacts with $CO_2$ and generates CO. More information on automation of the kiln, feed, and blending can be found in the measure "Energy Management and Process Control Systems", above.

In China, domestic technologies are being used for medium and small cement plants; for larger plants, many are using imported technologies (Cui, 2006).

### *Finish Grinding*

Table 6 shows fuel and electricity savings, estimated payback period and carbon dioxide ($CO_2$) savings for each measure related to final grinding. A description for each measure is given below.

**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), South Africa (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). Pavilion Technologies (US) has developed a new control system using neural networks. Pavilion Technologies reports a 4-6% throughput increase (and corresponding reduction in specific power consumption) for installing a model predictive control system in finish ball mill (Martin et al., 2001). Payback periods are typically between 6 and 8 months (Martin and McGarel, 2001a).

*Table 6. Energy Efficiency Measures for Final Grinding of Products in Cement Plants. More information can be found in the description of the measures below.*

| Energy Efficiency Measure (for Finish Grinding) | Fuel Savings (GJ/t) | Electricity Savings (kWh/t) | Estimated Payback Period (years) [(1)] | $CO_2$ Savings (kgC/t) |
|---|---|---|---|---|
| Energy Management & Process Control | - | 3.8-4.2 | < 1 to 2 | 0.9-1.0 |
| High Pressure Roller Press | - | 8-28 | > 10 (1) | 1.8-6.3 |
| High-Efficiency Classifiers | - | 1.9-6.0 | > 10 (1) | 0.4-1.4 |
| Improved Grinding Media in Ball Mills | - | 3-5 | 8 (1) | 0.7-1.2 |

**Notes:**
All data is given per tonne of cement
[(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.

**Advanced Grinding Concepts.** The energy efficiency of ball mills for use in finish grinding is relatively low, consuming up to 30-42 kWh/t clinker depending on the fineness of the cement (Marchal, 1997; Cembureau, 1997b). Several new mill concepts exist that can significantly reduce power consumption in the finish mill to 20-30 kWh/t clinker, including roller presses, roller mills, and roller presses used for pre-grinding in combination with ball mills (Alsop and Post, 1995; Cembureau, 1997b; Seebach *et al.*, 1996). Roller mills employ a mix of compression and shearing, using 2-4 grinding rollers carried on hinged arms riding on a horizontal grinding table (Cembureau, 1997b; Alsop and Post, 1995). In a high-pressure roller press, two rollers pressurize the material up to 3,500 bar (Buzzi, 1997), improving the grinding efficiency dramatically (Seebach et al., 1996).

Air swept vertical roller mills with integral classifiers are used for finish grinding, whereas a recent off-shoot technology which is not air swept is now being used as a pre-grinding system in combination with a ball mill. A variation of the roller mill is the air swept ring roller mill, which has been shown to achieve an electricity consumption of 25 kWh/t with a Blaine of 3000 (Folsberg, 1997). A new mill concept is the Horomill, first demonstrated in Italy in 1993 (Buzzi, 1997). In the Horomill, a horizontal roller within a cylinder is driven. The centrifugal forces resulting from the movement of the cylinder cause a uniformly distributed layer to be carried on the inside of the cylinder. The layer passes the roller (with a pressure of 700-1000 bar) (Marchal, 1997). The finished product is collected in a dust filter. The Horomill is a compact mill that can produce a finished product in one step and hence has relatively low capital costs. Grinding Portland cement with a Blaine of 3200 $cm^2/g$ consumes approximately 23 kWh/t (Buzzi,1997) and even for pozzolanic cement with a Blaine of 4000, power use may be as low as 30 kWh/t (Buzzi,1997).

Today, high-pressure roller presses are most often used to expand the capacity of existing grinding mills, and are found especially in countries with high electricity costs or with poor power supply (Seebach et al, 1996). After the first demonstration of the Horomill in Italy, this concept is now also applied in plants in Mexico (Buzzi, 1997), Germany, Czech Republic and Turkey (Duplouy and Trautwein, 1997). New designs of the roller mills allow for longer operation times (> 20,000 hours). The electricity savings of a new finish grinding mill when replacing a ball mill is estimated to be 28 kWh/t cement. The addition of a pre-grinding system to a ball mill will result in savings of 7-24 kWh/t cement for (Cembureau, 1997b; Holland et al., 1997; Scheuer and Sprung, 1990) Capital cost estimates for installing a new roller press vary widely in the literature, ranging from low estimates like \$2.5/annual tonne cement capacity (Holderbank, 1993) or \$3.6/annual tonne cement capacity (Kreisberg, 1993) to high estimates of \$8/annual tonne cement capacity (COWIconsult *et al.*, 1993). The capital costs of roller press systems are lower than those for other systems (Kreisberg, 1993) or at least comparable (Patzelt, 1993). Some new mill concepts may lead to a reduction in operation costs of as much as 30-40% (Sutoh *et al.*, 1992).

**High Efficiency Classifiers.** A recent development in efficient grinding technologies is the use of high-efficiency classifiers or separators. Classifiers separate the finely ground particles from the coarse particles. The large particles are then recycled back to the mill. Standard classifiers may have a low separation efficiency, which leads to the recycling of fine particles, resulting in extra power use in the grinding mill. In high-efficiency classifiers, the material is more cleanly separated, thus reducing over-grinding. High efficiency classifiers or separators have had the greatest impact on improved product quality and reducing electricity consumption.

A study of the use of high efficiency classifiers in Great Britain found a reduction in electricity use of 7 kWh/t 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 (6 kWh/t cement) while other studies estimate 1.9-2.5 kWh/t cement (Salborn and Chin-Fatt, 1993; Süssegger, 1993). Newer designs of high-efficiency separators aim to improve the separation efficiency further and reduce the required volume of air (hence reducing power use), while optimizing the design. All major suppliers market new classifier designs, e.g. Polysius (SEPOL), F. L.

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 6 kWh/t (Van den Broeck, 1998), and investment costs were \$2/annual tonne finished material based on Holderbank (1993).

**Improved Grinding Media.** Improved wear resistant materials can be installed for grinding media, especially in ball mills. Grinding media are usually selected according to the wear characteristics of the material. Increases in the ball charge distribution and surface hardness of grinding media and wear resistant mill linings have shown a potential for reducing wear as well as energy consumption (Venkateswaran and Lowitt, 1988). Improved balls and liners made of high chromium steel is one such material but other materials are also possible. Other improvements include the use of improved liner designs, such as grooved classifying liners. These have the potential to reduce grinding energy use by 5-10% in some mills, which is equivalent to estimated savings of 3-5 kWh/t cement (Venkateswaran and Lowitt, 1988).

### *Plant Wide Measures*

Table 7 shows fuel and electricity savings, estimated payback period and carbon dioxide ($CO_2$) savings for each plant wide measure. A description for each measure is given below.

*Table 7. Energy Efficiency Measures for Plant Wide Measures in Cement Plants. More information can be found in the description of the measures below.*

| Energy Efficiency Measure (Plant Wide Measures) | Fuel Savings (GJ/t) | Electricity Savings (kWh/t) | Estimated Payback Period (years) | $CO_2$ Savings (kgC/t) |
|---|---|---|---|---|
| Preventative Maintenance | 0.05 | 0-6 | < 1 | 1.3-2.6 |
| High Efficiency Motors | - | 0-6 | < 1 | 0-1.3 |
| Adjustable Speed Drives | - | 6-8 | 2- 3 | 1-2 |
| Optimization of Compressed Air Systems | - | 0-6 | < 3 | 0-1 |
| Efficient Lighting | - | 0-0.6 | <3 | 0-0.1 |

**Notes:**
All data is given per tonne of cement

**Preventative Maintenance.** Preventative maintenance includes training personnel to be attentive to energy consumption and efficiency. Successful programs have been launched in a variety of industries (Caffal, 1995; Nelson, 1994). While many processes in cement production are primarily automated, there still are opportunities, requiring minimal training of employees, to increase energy savings. Also, preventative maintenance (e.g. for the kiln refractory) can also increase a plant's utilization ratio, since it has less downtime over the long term. Birch (1990) mentions that the reduction of false air input into the kiln at the kiln hood has the potential to save 0.05 GJ/t. Lang (1994) notes a reduction of up to 5 kWh for various preventative maintenance and process control measures (typically around 3 kWh/t). Based on similar programs in other industries, annual and start up costs for implementing this training are estimated to be minimal and would be paid back in less than one year. For preventative maintenance of compressed air systems, see below.

**High-Efficiency Motors and Drives.** Motors and drives are used throughout the cement plant to move fans (preheater, cooler, alkali bypass), to rotate the kiln, to transport materials and, most importantly, for grinding. In a typical cement plant, 500-700 electric motors may be used, varying from a few kW to MW-size (Vleuten, 1994). Power use in the kiln (excluding grinding) is roughly estimated to be 40-50 kWh/tonne clinker (Heijningen *et al*., 1992). Variable speed drives, improved control strategies and high-efficiency motors can help to reduce power use in cement kilns. If the replacement does not influence the process operation, motors may be replaced at any time. However, motors are often rewired rather than being replaced by new motors. Power savings may vary considerably on a plant-by-plant basis, ranging from 3 to 8% (Fujimoto, 1994). Vleuten (1994) estimates the potential power savings at 8% of the power use. Based on an analysis of motors in the U.S. Department of Energy's MotorMaster+ software, and a breakdown of motors in a 5,000 tpd cement plant given in Bösche (1993), it is assumed that high-efficiency motors replace existing motors in all plant fan systems with an average cost of $0.22/annual tonne cement capacity.

**Adjustable or Variable Speed Drives.** Drives are the largest power consumers in cement making. The energy efficiency of a drive system can be improved by reducing the energy losses or by increasing the efficiency of the motor (see above). Decreasing throttling can reduce energy losses in the system and coupling losses through the installation of adjustable speed drives (ASD). Most motors are fixed speed AC models. However, motor systems are often operated at partial or variable load (Nadel *et al*., 1992). Also, in cement plants large variations in load occur (Bösche, 1993). There are various technologies to control the motor (Worrell *et al*., 1997). The systems are offered by many suppliers and are available worldwide. Worrell *et al.* (1997) provide an overview of savings achieved with ASD in a wide array of applications. The savings depend on the flow pattern and loads. The savings may vary between 7 and 60%. ASD equipment is used more and more in cement plants (Bösche, 1993; Fujimoto, 1993), but the application may vary widely, depending on electricity costs. Within a plant, ASDs can mainly be applied for fans in the kiln, cooler, preheater, separator and mills, and for various drives. For example, Blue Circle's Bowmanville plant (Canada) installed a variable air inlet fan, reducing electricity and fuel use in the kiln (because of reduced inlet air volume), saving C$75,000/year in energy costs (approximately $47,000 in U.S. dollars) (CIPEC, 2001). One case study for a modern cement plant estimated potential application for 44% of the installed motor power capacity in the plant (Bösche, 1993). ASDs for clinker cooler fans have a low payback, even when energy savings are the only reason for installing ASDs (Holderbank, 1993). Energy savings strongly depend on the application and flow pattern of the system on which the ASD is installed. Although savings are significant (Holderbank, 1993), not many quantitative studies are available for the cement industry. One hypothetical case study estimates the savings at 70%, compared to a system with a throttle valve (or 37% compared with a regulated system) for the raw mill fan (Bösche, 1993). In practice savings of 70% are unrealistic (Young, 2002). Fujimoto, (1994) notes that Lafarge Canada's Woodstock plant replaced their kiln ID fans with ASDs and reduced electricity use by 6 kWh/t. It is estimated that the potential savings are 15% for 44% of the installed power, or roughly equivalent to 8 kWh/t cement. The specific costs depend strongly on the size of the system. For systems over 300 kW the costs are estimated to be 70 ECU/kW (75 US$/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 to be roughly $0.9 to 1.0/annual tonne cement capacity. Other estimates vary between $0.4 and $3/annual tonne cement (Holland et al., 1997; Holderbank, 1993).

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

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

- *Keep the compressor and intercooling surfaces clean and foul-free.* Blocked filters increase pressure drop. By inspecting and periodically cleaning filters, the pressure drop may be kept low. Seek filters with just a 1 psig pressure drop over 10 years. The payback for filter cleaning is usually under 2 years (Ingersoll-Rand, 2001). Fixing improperly operating filters will also prevent contaminants from entering into tools and causing them to wear out prematurely. Generally, when pressure drop exceeds 14 to 20 $kN/m^2$, replace the particulate and lubricant removal elements, and inspect all systems at least annually. Also, consider adding filters in parallel that decrease air velocity, and, therefore, decrease air pressure drop. A 2% reduction of annual energy consumption in compressed air systems is projected for more frequent filter changing (Radgen and Blaustein, 2001).
- *Keep motors properly lubricated and cleaned.* Poor motor cooling can increase motor temperature and winding resistance, shortening motor life, in addition to increasing energy consumption. Compressor lubricant should be changed every 2 to 18 months and checked to make sure it is at the proper level. In addition to energy savings, this can help avoid corrosion and degradation of the system.
- *Inspect drain traps* periodically to ensure they are not stuck in either the open or closed position and are clean. Some users leave automatic condensate traps partially open at all times to allow for constant draining. This practice wastes substantial energy and should never be undertaken. Instead, install simple pressure driven valves. Malfunctioning traps should be cleaned and repaired instead of left open. Some auto drains, such as float switch or electronic drains do not waste air. Inspecting and maintaining drains typically has a payback of less than 2 years (Ingersoll-Rand, 2001).

- *Maintain the coolers* on the compressor to ensure that the dryer gets the lowest possible inlet temperature (Ingersoll-Rand, 2001).
- *Check belts for wear* and adjust them. A good rule of thumb is to adjust them every 400 hours of operation.
- *Replace air lubricant separators* according to specifications or sooner. Rotary screw compressors generally start with their air lubricant separators having a 14 to 20 kN/$m^2$ pressure drop at full load. When this increases to 70 kN/$m^2$, change the separator (LBNL at al., 1998).
- *Check water cooling systems* for water quality (pH and total dissolved solids), flow, and temperature. Clean and replace filters and heat exchangers per manufacturer's specifications.

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

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

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

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

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

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

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

Modulating or throttling controls allow the output of a compressor to be varied to meet flow requirements by closing down the inlet valve and restricting inlet air to the compressor. Throttling controls are applied to centrifugal and rotary screw compressors. Changing the compressor control from on/zero/off to a variable speed control can save up to 8% per year (CADDET, 1997b).

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

**Heat Recovery for Water Preheating.** As much as 80 to 93% of the electrical energy used by an industrial air compressor is converted into heat. In many cases, a heat recovery unit can recover 50 to 90% of this available thermal energy for space heating, industrial process heating, water heating, makeup air heating, boiler makeup water preheating, industrial drying, industrial cleaning processes, heat pumps, laundries or preheating aspirated air for oil burners (Parekh, 2000). It's been estimated that approximately 50 MJ/hour of energy is available for each 0.05 $m^3$/second of capacity (at full load) (LBNL et al., 1998). Paybacks are typically less than one year. Heat recovery for space heating is not as common with water-cooled compressors because an extra stage of heat exchange is required and the temperature of the available heat is lower. However, with large water cooled compressors, recovery efficiencies of 50 to 60% are typical (LBNL et al., 1998). Implementing this measure saves up to 20% of the energy used in compressed air systems annually for space heating (Radgen and Blaustein, 2001).

### *Plant Wide Lighting*

Energy use for lighting in the cement industry is very small. Still, energy efficiency opportunities may be found that can reduce energy use cost-effectively. Lighting is used either to provide overall ambient lighting throughout the manufacturing, storage and office spaces or to provide low-bay and task lighting to specific areas. High-intensity discharge

(HID) sources are used for the former, including metal halide, high-pressure sodium and mercury vapor lamps. Fluorescent, compact fluorescent (CFL) and incandescent lights are typically used for task lighting in offices.

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

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

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

**Replace Metal Halide HID with High-Intensity Fluorescent Lights.** Traditional HID lighting can be replaced with high-intensity fluorescent lighting. These new systems incorporate high-efficiency fluorescent lamps, electronic ballasts and high-efficacy fixtures that maximize output to the work plane. Advantages to the new system are many; they have lower energy consumption, lower lumen depreciation over the lifetime of the lamp, better dimming options, faster start-up and restrike capability, better color rendition, higher pupil lumens ratings and less glare (Martin, et al., 2000). High-intensity fluorescent systems yield 50% electricity savings over standard metal halide HID. Dimming controls that are impractical in the metal halide HIDs can also save significant energy. Retrofitted systems cost about $185 per fixture, including installation costs (Martin, et al., 2000). In addition to energy savings and better lighting qualities, high-intensity fluorescents can help improve productivity and have reduced maintenance costs.

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

### *Product and Feedstock Change*

Product and feedstock changes include the production of blended cements, use of waste-derived fuels, production of limestone cement and low alkali cement, and the use of steel slag in the kiln. Table 8 provides information on the initial capital costs, the operations and maintenance (O&M) costs, the simple payback period, the specific fuel savings, the specific electric savings, the specific carbon dioxide savings and the lifetime associated with each of these measures.

**Blended Cements.** The production of blended cements involves the intergrinding of clinker with one or more additives (fly ash, pozzolans, granulated blast furnace slag, silica fume, volcanic ash) in various proportions. The use of blended cements is a particularly attractive efficiency option since the intergrinding of clinker with other additives not only allows for a reduction in the energy used (and carbon emissions) in clinker production, but also corresponds to a reduction in carbon dioxide emissions in calcination as well. Blended cement has been used for many decades around the world.

*Table 8. Product and Feedstock Changes to Improve the Energy Efficiency of Clinker Production.*

| | **Capital Costs ($/t)** | **O & M Costs ($/t)** | **Payback Period (years)** | **Fuel Savings (GJ/t)** | **Electric Savings (kWh/t) [1]** | **$CO_2$ savings (kgC/t)** | **Lifetime (years)** |
|---|---|---|---|---|---|---|---|
| Blended cements | 0.7 | -0.06 | < 1 | 0.9-3.4 [2] | -11 | 21-85 | 20 |
| Use of waste-derived fuels | 0.1-3.7 | < 0 [3] | 1 | > 0.6 | - | 12 [4] | 20 |
| Limestone cement [5] | minimal | -5% | < 1 | 0.3 | 2.8 | 8.4 | NA |
| Low alkali cement (rotary only) | 0 | 0 | Immediate | 0.19-0.5 | [6] | 4.6-12.1 | NA |
| Use of steel slag in kiln | * | | < 2 | 0.19 | - | 4.9 | NA |

*Note: Energy savings and costs below are based on case study data, except where noted. Costs in China will vary depending on technology and availability. Where possible, we have included more data for China in the following text. All data are given per tonne of clinker.*

[1] Negative numbers represent an increase in electricity due to the measure.

[2] Data from Chinese case studies indicate savings of 2.6 to 3.4 GJ/t clinker, while U.S. data shows savings of 0.9 GJ/t clinker (or 1.4 GJ/t cement at a clinker to cement ratio of 0.65).

[3] Reduces operating costs but amount is not known

[4] In calculating specific $CO_2$ savings for this measure, we used an emission factor for solvents of 0.02 tC/GJ.

[5] Savings for this measure are calculated based on data given on a per tonne of cement basis and a clinker to cement ratio of 0.85. O&M savings are given based on percent savings in the kiln operating costs.

[6] Some electricity is saved but exact amounts are unknown.

* Total investment costs are $400,000 to $1,000,000 per installation.

NA = data not available

Blended cements are very common in Europe; blast furnace and pozzolanic cements account for about 12% of total cement production with Portland composite cement accounting for an additional 44% (Cembureau, 1997b). Blended cements were introduced in the U.S. to reduce production costs for cement (especially energy costs), to 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). It allows wider applications of additives. Many other countries around the world use blended cement. In China, a range of materials are used in blended cements (see below), but cement plants mainly produce Portland cement (about 95% of total output) (Cui, 2004). 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. However, Portland ordinary cement and Portland slag cement are used widely in cement produced in China (ITIBMIC, 2005). In addition, due to technical advancement and market development allowing the production of different kinds and grades of cement, some industrial byproducts like blast furnace slag, fly ash, coal gangue, limestone, zeolite, pozzolana as well as natural minerals are widely used in cement production. The average percentage of admixtures in Chinese cement products stands at 24% to 26% (ITIBMIC, 2005). Table 9 gives the prices and different methods of transportation for the various additives used in China. Prices for different additives vary greatly. Prices change with location, output, market need, produce type and ways of handling. ITBIMIC (2005) estimates fuel savings of at least 10%, and a similar increase in production.

*Table 9. Prices and Transportation Modes for Different Additives Used in China*

| **Additive** | **Blast Furnace Slag** | **Fly ash** | **Cinder** | **Coal gangue** | **Lime-stone** | **Gypsum** | **Pebble** | **Kiln dust** |
|---|---|---|---|---|---|---|---|---|
| Price (Yuan/t) | 13 - 80 | 12 - 35 | 14 - 26 | 10 - 38 | 11 - 40 | 52 | 19 | 0 |
| Method of transportation | Train and truck | Truck and pipe | Train and truck | Truck | Truck and belt | Truck | Truck | Pipe |

Adapted from ITIBMIC, 2005, Table 26. Prices of additives vary according to location, market need, product type and method of transportation.

For blended cement with, on average, a clinker/cement ratio of 65%, the reduction in clinker production corresponds to a specific fuel savings of 1.42 GJ/t cement. There is an increase in fuel use of 0.09 GJ/t cement for drying of the blast furnace slags but a corresponding energy savings of 0.2 GJ/t cement for reducing the need to use energy to bypass kiln exit gases to remove alkali-rich dust. Energy savings are estimated to be 9 to 23 MJ/t cement 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 inter-ground materials also lower alkali-silica reactivity (ASR), thereby allowing a reduction in energy consumption needed to remove the high alkali content kiln dusts. In practice, bypass savings may be minimal to avoid plugging of the preheaters, requiring a minimum amount of bypass volume. This measure therefore results in total fuel savings of 1.4 GJ/t blended cement (0.9 GJ/t clinker for 0.65 clinker to cement ratio). However, energy consumption 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[4], the increased electricity costs for (finer) grinding, the reduced fuel costs for clinker production and electricity costs for raw

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

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 16.5 kWh/t cement (11 kWh/t clinker) (Buzzi, 1997) is estimated while an investment cost of $0.72/t cement capacity ($0.5/t clinker), which reflects the cost of new delivery and storage capacity (bin and weigh-feeder) is assumed.

The Lianzhuo cement Factory in Guangdong Province, China, replaced some of its high grade limestone with 33 to 34% calcium oxide (CaO), along with copper tailing high content iron sulfide from a nearby county (ITIBMIC, 2004). They found fuel savings of 2.6 to 3.4 GJ/t clinker, a coal savings of over 50%. The clinker production has increased from 2 tonne/day to 14 tonne/day, its strength has improved and its quality is stable (ITIBMIC, 2004).

China produces 25 Mt of blast furnace slag per year and has a long history of using this type of waste (Cui, 2006). Where utilized, about 20 to 25% of clinker is replaced; the country's highest slag ratio is 50% (Cui, 2006). In addition, blast furnace slag is added into concrete as well as clinker. Fly ash is also increasingly being used in China. China has 100 Mt of blast furnace slag and 300 tonnes of fly ash (Cui, 2006).

**Use of Waste-Derived Fuels.** Waste fuels can be substituted for traditional commercial fuels in the kiln. For example, the U.S. cement industry is increasingly using waste fuels. In 1999 tires accounted for almost 5% of total fuel inputs in the industry in the U.S., while all wastes total about 17% of all fuel inputs. The trend towards increased waste use will likely increase after successful tests with different wastes in Europe and North America are performed. New waste streams include carpet and plastic wastes, filter cake, paint residue and (dewatered) sewage sludge (Hendriks et al., 1999). Cement kilns also use hazardous wastes. Since the early 1990's cement kilns burn annually almost 1 Mt of hazardous waste (CKRC, 2002). The revenues from waste intake have helped to reduce the production costs of all waste-burning cement kilns, and especially of wet process kilns. Waste-derived fuels may replace the use of commercial fuels, and may result in net energy savings and reduced $CO_2$ emissions, depending on the alternative use of the wastes (e.g. incineration with or without energy recovery). Currently, in China only three cement plants are burning waste fuels. Beijing Cement Plant has the capacity to dispose of 10 kt per year of 25 types of waste; the plant is burning solid waste from the chemical industry, some paints, solvents and waste sludge from water treatment (Cui, 2004; Wang, 2006a). Shanghai Jinshan Cement Plant disposes of sludge dredged from the Huangpu River which runs through Shanghai (Cui, 2004). Hong Kong Cement Plant purchases waste from other provinces to utilize in its kilns (Wang, 2006a). Other plants are utilizing wastes but the amounts are very small (Wang, 2006a).

A cement kiln is an efficient way to recover energy from waste. The carbon dioxide emission reduction depends on the carbon content of the waste-derived fuel, as well as the alternative use of the waste and efficiency of use (e.g. incineration with or without heat recovery). In Table 8, we used the carbon content of solvents to determine the $CO_2$ savings. The high temperatures and long residence times in the kiln destroy virtually all organic compounds, while efficient dust filters may reduce some other potential emissions to safe levels (Hendriks et al., 1999; Cembureau, 1997b).

In North America, many of the alternative fuels are focused on the use of tires or tire-derived fuel. Since 1990 more than 30 cement plants have gained approval to use tire-derived fuels, burning around 35 million tires per year (CKRC, 2002). The St. Lawrence Cement Factory in Joliette, Quebec completed a project in 1994 where they installed an automated tire feed system to feed whole tires into the mid-section of the kiln, which replaced about 20% of the energy (CADDET, 1996). This translates to energy savings of 0.6 GJ/t clinker. Costs for the installation of the Joliette system ran about \$3.70/annual tonne clinker capacity. Costs for less complex systems where the tires are fed as input fuel are \$0.11 to \$1.1/annual tonne clinker. Other plants have experience injecting solid and fluid wastes, as well as ground plastic wastes. A net reduction in operating costs (CADDET, 1996; Gomes, 1990, Venkateswaran and Lowitt, 1988) is assumed. Investment costs are estimated to be \$1.1/annual tonne clinker for a storage facility for the waste-derived fuels and retrofit of the burner (if needed).

**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 as well as $CO_2$ emissions from calcination and energy use. The addition of up to 5% limestone has shown to have no negative impacts on the performance of Portland cement, while optimized limestone cement would improve the workability slightly (Detwiler and Tennis, 1996). Adding 5% limestone would reduce fuel consumption by 5% (or on average 0.35 GJ/t clinker), power consumption for grinding by 3.3 kWh/t cement, and $CO_2$ emissions by almost 5%. Additional costs would be minimal, limited to material storage and distribution, while reducing kiln operation costs by 5%.

**Low-Alkali Cement.** In North America, part of the production of the cement industry are cements with a low alkali content (probably around 20 to 50% of the market), a much higher share than found in many other countries (Holderbank, 1993). In some areas in the U.S. as well as China, aggregate quality may be such that low-alkali cements are required by the cement company's customers or by the climate in a particular region (e.g., alkali cements are more suitable the south of China in areas of higher rainfall than in drought areas in the North). Reducing the alkali content is achieved by venting (called the by-pass) hot gases and particulates from the plant, loaded with alkali metals. The by-pass also avoids plugging in the preheaters. This becomes cement kiln dust (CKD). Disposal of CKD is regulated under the Resource Conservation and Recovery Act (RCRA). Many customers demand a lower alkali content, as it allows greater freedom in the choice of aggregates. The use of fly-ash or blast-furnace slags as aggregates (or in the production of blended cement, see below) may reduce the need for low-alkali cement. Low alkali cement production leads to higher energy consumption. Savings of 8 to 21 MJ/t (2 to 5 Kcal/kg) per percent bypass are assumed (Alsop and Post, 1995). The lower figure is for precalciner kilns, while the higher figure is for preheater kilns. Typically, the bypass takes 10 to 70% of the kiln exhaust gases (Alsop and Post, 1995). Additionally, electricity is saved due to the increased cement production, as the CKD would otherwise end up as clinker and not cement, requiring further processing. For illustrative purposes, assume a 20% point reduction in bypass volume, resulting in energy savings of 0.19 to 0.5 GJ/t 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. Low alkali cement is produced using domestic technology in China (Cui, 2006).

**Use of Steel Slag in Kiln.** Texas Industries (Midlothian, Texas) in 1994 developed a system to use electric arc furnace (EAF) slags of the steel industry as input in the kiln, reducing the use of limestone. The slag that contains tricalcium silicate ($C_3S$) 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 0.055 and 0.21 tonnes of slag per tonne of steel (on average 0.12 tonnes/tonne) (U.S. DOE OIT, 1996). The CemStar® process allows replacing 10 to 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 5 cm lumps. Depending on the location of injection it may also save heating energy. Calcination energy is estimated to be 1.9 GJ/t 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). For illustrative purposes alone, using a 10% injection of slags would reduce energy consumption by 0.19 GJ/t 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 measurements at two kilns (Battye et al., 2000). Equipment costs are mainly for material handling and vary between $200,000 and $500,000 per installation. Total investments are approximately double the equipment costs. CemStar® charges a royalty fee (Battye et al., 2000). Costs savings consist of increased income from additional clinker produced without increased operation and energy costs, as well as reduced iron ore purchases (as the slag provides part of the iron needs in the clinker). The iron content needs to be balanced with other iron sources such as tires and iron ore. In the U.S., the U.S. Environmental Protection Agency awarded the CemStar® process special recognition in 1999 as part of the ClimateWise program.

China does not produce this technology domestically, and to date the measure has not been implemented in cement kilns in China (Cui, 2006).

## Acknowledgements

This work was supported by the Climate Protection Partnerships Division of the U.S. Environmental Protection Agency as part of its ENERGY STAR program through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. Revision of this report for use in China was undertaken with funding provided by the Energy Foundation's China Sustainable Energy Program and Dow Chemical Company. We would like to thank the U.S. EPA, the Energy Foundation and the Dow Chemical

Corporation for their support in making the first version and this Chinese version of this report.

Any remaining errors in this report are the responsibility of the authors. The views expressed in this report do not necessarily reflect those of the U.S. Environmental Protection Agency, the U.S. Department of Energy or the U.S. Government.

## References

Albert, O., 1993. MCE – An Expert System for Mill Plant Control, Krupp Polysius, Germany.

Alsop, P.A. and J.W. Post. 1995. The Cement Plant Operations Handbook, (First edition), Tradeship Publications Ltd., Dorking, UK

Anhui Ningguo Cement Plant, 2002. The Report on Power Generation by Waste Heat of the Kiln in Ningguo Cements Plant. http://green.cei.gov.cn/doc/LY31/200204192475.htm (in Chinese).

Battye, R., S. Walsh, J. Lee-Greco. 2000. NOx Control Technologies for the Cement Industry, Prepared for U.S. Environmental Protection Agency, Triangle Park, NC.

Beijing Energy Investment Company (BEIC), 2006. Electrical Power Station with Pure Low Temperature & Waste Heat in Beijing Cement Ltd.; Geothermal Heating Supply in BioYuan Uptown. Presentation on CDM proposed projects by BEIC.

Birch, E. 1990. Energy Savings in Cement Kiln Systems Energy Efficiency in the Cement Industry (Ed. J. Sirchis), London, England: Elsevier Applied Science: 118-128.

Bösche, A., 1993. "Variable Speed Drives in Cement Plants," *World Cement* 6 **24** pp.2-6 (1993).

Buzzi, S. 1997. Die Horomill® - Eine Neue Mühle für die Feinzerkleinerung, ZKG International 3 50: 127-138.

Buzzi, S. and G. Sassone. 1993. Optimization of Clinker Cooler Operation, Proc. VDZ Kongress 1993: Verfahrenstechnik der Zementherstellung Bauverlag, Wiesbaden, Germany: 296-304.

Caffal, C. 1995. Energy Management in Industry, *CADDET Analyses Series 17*, Sittard, the Netherlands: CADDET.

Canadian Lime Institute. 2001. Energy Efficiency Opportunity Guide in the Lime Industry, Office of Energy Efficiency, Natural Resources Canada, Ottawa, ON.

Cembureau, 1997a. Alternative Fuels in Cement Manufacture: Technical and Environmental Review. Brussels: Cembureau. http://www.cembureau.be/Documents/Publications/Alternative_Fuels_in_Cement_Manufacture_CEMBUREAU_Brochure_EN.pdf

Cembureau, 1997b. Best Available Techniques for the Cement Industry, Brussels: Cembureau.

Cement Kiln Recycling Coalition (CKRC). 2002. Volume of Hazardous Wastes Used as Fuel in Cement Kilns Washington, D.C. Available at: http://www.ckrc.org/infocen.html.

Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET), International Energy Agency. 1996. Tyres used as fuel in cement factory, Sittard, the Netherlands: CADDET.

Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET), International Energy Agency. 1997. Revolutionary low-NOx high-efficiency gas burner, Sittard, the Netherlands: CADDET.

Centre for the Analysis and Dissemination of Demonstrated Energy Technologies (CADDET), International Energy Agency, 1997b. Saving Energy with Efficient Compressed Air Systems, Maxi Brochure 06, Sittard, The Netherlands.

China National Building Material Group Corporation (CNBM), 2005. Zhonglian Julong Huaihai Cement Co., Ltd.: Low Temperature Residual Heat Power Generation Project. Presentation by CNBM, October, 2005.

CIPEC, 2001. Blue Circle Cement Fires Up Energy savings at Ontario Plants, *Heads Up CIPEC* 5 **21** pp.1-2 (2001). Published by Office of Energy Efficiency, Natural Resources Canada, Ottawa, ON, Canada.

COWIconsult, March Consulting Group and MAIN. 1993. Energy Technology in the Cement Industrial Sector, Report prepared for CEC - DG-XVII, Brussels, April 1992.

Cui, Y., 2004 and 2006. Personal communication with Prof. Cui Yuansheng, VP of the Institute of Technical Information for Building Materials Industry of China (ITIBMIC).

De Hayes, L.J., 1999. Flexibility, Availability and Maintenance Concept for the Quadropol, Polysius Teilt Mit No. **208**, pp.33-38, Krupp Polysius, Germany.

Detwiler, R.J. and P.D. Tennis. 1996. The Use of Limestone in Portland Cement: a State-of-the-Art Review, Skokie, IL: Portland Cement Association.

Dolores, R. and M.F. Moran. 2001. Maintenance and Production Improvements with ASDs Proc.2001 IEEE-IAS/PCA Cement Industry Technical Conference: 85-97.

Duplouy, A. and J. Trautwein. 1997. Umbau und Optimierung der Drehofenanlagen im Werk Karsdorf der Lafarge Zement Gmbh. ZKG International 4 50: 190-197.

Energy Technology Support Unit (ETSU). 1988. High Level Control of a Cement Kiln, Energy Efficiency Demonstration Scheme, Expanded Project Profile 185, Harwell, United Kingdom.

European Commission (EC). 2000. Directorate-General Joint Research Centre, Institute for Prospective Technological Studies. Integrated Pollution Prevention and Control (IPPC): Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries. Seville, Spain. March.

Folsberg, J., 1997. Future Grinding, *Asian Cement,* January 1997, pp.21-23.

Frailey, M.L. and K.R. Happ, 2001. Capitol Cement's Project 2000, Proceedings IEEE 2001 Cement Industry Technical Conference, May 2001.

Fujimoto, S., 1993. Modern Technology Impact on Power Usage in Cement Plants, Proc. 35th IEEE Cement Industry Technical Conference, Toronto, Ontario, Canada, May 1993.

Fujimoto, S., 1994. Modern Technology Impact on Power Usage in Cement Plants, IEEE Transactions on Industry Applications, Vol. 30, No. 3, June.

Gerbec, R., 1999. Fuller Company. Personal Communication.

Global Environment Institute (GEI). 2005. Financing of Energy Efficiency Improvement for Cement Industry in China. January.

Goebel, Alexander, 2001. Personal communication with Alexander Goebel, Krupp Polysius, Beckum, Germany, December 20th, 2001

Gomes, A. S. 1990. Energy Saving and Environmental Impact in the Cement Industry, Energy Efficiency in the Cement Industry (Ed. J. Sirchis), London, England: Elsevier Applied Science: 23-26.

Guo, Jie. 2004. The contract of flash distillation waste heat power generation demonstration project of Taishan Cement signed (in Chinese).
Available at http://cncement.com

Haspel, D., and W. Henderson. 1993. A New Generation of Process Optimisation Systems, International Cement Review, June: 71-73.

Heijningen, R.J.J., J.F.M. Castro, and E. Worrell (eds.), 1992. Energiekentallen in Relatie tot Preventie en Hergebruik van Afvalstromen, NOVEM/RIVM, Utrecht/Bilthoven, The Netherlands.

Hendriks, C.A., E. Worrell, L. Price, N. Martin and L. Ozawa Meida. 1999. The Reduction of Greenhouse Gas Emissions from the Cement Industry, IEA Greenhouse Gas R&D Programme, Cheltenham, United Kingdom (Report PH3/7), May.

Holland, M. 2001. AC DC Kilns, Proc. 2001 IEEE-IAS/PCA Cement Industry Technical Conference: 75- 84.

Holland, M., H. M. Seebach, M., and Ranze, W., 1997. Variable Speed Drives for Roller Presses. *Proc.1997 IEEE/PCA Cement Industry Technical Conference XXXIX Conference Record*, Institute of Electrical and Electronics Engineers: New Jersey.

Holderbank Consulting, 1993. Present and Future Energy Use of Energy in the Cement and Concrete Industries in Canada, CANMET, Ottawa, Ontario, Canada.

Hrizuk, M.J. 1999. Expansion is Key at Durkee, International Cement Review, May.

Ingersoll Rand, 2001. Air Solutions Group—Compressed Air Systems Energy Reduction Basics, http://www.air.ingersoll-rand.com/NEW/pedwards.htm. June 2001.

Institute of Technical Information for Building Materials Industry (ITIBMIC). 2004. Final Report on Cement Survey. Prepared for the United Nations Industrial Development Organization (UNIDO) for the Contract Entitled Cement Sub-sector Survey for the Project Energy Conservation and GHG Emissions Reduction in Chinese TVEs-Phase II. Contract no. 03/032/ML, P.O. No. 16000393, September 9.

Institute of Technical Information for Building Materials Industry (ITIBMIC). 2005. A Survey on the Chinese Market of Cement Admixtures for Holcim Company.

Jaccard, M.K. & Associates and Willis Energy Services Ltd. 1996. Industrial Energy End-Use Analysis and Conservation Potential in Six Major Industries in Canada. Report prepared for Natural Resources Canada, Ottawa, Canada.

Kreisberg, A., 1993. Selection and Application of Roller Press for Raw Meal Preparation at Alpena, *Proc. KHD Symposium '92, Volume 1, Modern Roller Press Technology*, KHD Humboldt Wedag, Cologne, Germany.

Lang, Theodor A., 1994. Energy Savings Potential in the Cement Industry and Special Activities of the ‘Holderbank’ Group, in *Industrial Energy Efficiency: Policies and Programmes Conference Proceedings* (May 26-27, 1994). Paris: International Energy Agency and U.S. Department of Energy.

Lawrence Berkeley National Laboratory (LBNL) and Resource Dynamics Corporation, 1998. Improving Compressed Air System Performance, a Sourcebook for Industry, prepared for the U.S. Department of Energy, Motor Challenge Program, Berkeley, CA: LBNL.

Lee, C-W., 2006. Personal communication with Chun-Wai Lee, U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory.

Lesnikoff, G. 1999. Hanson Cement, Cupertino, CA, personal communication.

Lowes, T.M. and Bezant, K.W. 1990. Energy Management in the UK Cement Industry Energy Efficiency in the Cement Industry (Ed. J. Sirchis), London, England: Elsevier Applied Science.

Liu, F., M. Ross and S. Wang. 1995. Energy Efficiency of China's Cement Industry. Energy 20 (7): 669-681.

Marchal, G. 1997. Industrial Experience with Clinker Grinding in the Horomill *Proc.1997 IEEE/PCA Cement Industry Technical Conference XXXIX Conference Record*, Institute of Electrical and Electronics Engineers: New Jersey.

Martin, N., E. Worrell, and L. Price. 1999. Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Cement Industry. Lawrence Berkeley National Laboratory, Berkeley, CA. September. (LBNL-44182).

Martin, G., T. Lange, and N. Frewin. 2000. Next Generation Controllers for Kiln/Cooler and Mill Applications based on Model predictive Control and Neural Networks, Proceedings IEEE-IAS/PCA 2000 Cement Industry Technical Conference, Salt Lake City, UT, May 7th – 12th.

Martin, G. and S. McGarel. 2001a. Automation Using Model Predictive Control in the Cement Industry. Pavillion Technologies, Inc., Austin, TX (based on a paper published in International Cement Review, February: 66-67). Available at: http://www.pavtech.com/

Martin, G. and S. McGarel, 2001b. Automated Solution, International Cement Review, February 2001, pp.66-67.

Martin, G., S. McGarel, T. Evans, and G. Eklund. 2001. Reduce Specific Energy Requirements while Optimizing NOx Emissions Decisions in Cement with Model Predictive Control, Personal Communication from Pavilion Technologies, Inc., Austin, TX, December 3.

Mathée, H. 1999. NOx Reduction with the Prepol MSC Process at the Lengerich Plant of Dyckerhoff Zement GmbH, Polysius Teilt Mit, 208: 53-55, Krupp Polysius, Germany.

Menzel, K. 1997. Experience with the Prepol-MSC Calciner and a Review of the Possibilities it Offers, Polysius Teilt Mit, 198: 29-33, Krupp Polysius, Germany.

Nadel, S., M. Shepard, S. Greenberg, G. Katz and A. de Almeida, 1992. Energy Efficient Motor Systems: A Handbook on Technology, Program and Policy Opportunities, ACEEE, Washington, D.C., USA.

Nelson, K., 1994. Finding and Implementing Projects that Reduce Waste, in R. Socolow, C. Andrews, F. Berkhout and V. Thomas, *Industrial Ecology and Global Change*, Cambridge, UK: Cambridge University Press.

Neto, M. 1990. Waste Gas Heat Recovery in Cement Plants Energy Efficiency in the Cement Industry (Ed. J. Sirchis), London, England: Elsevier Applied Science.

Pan, Jiong. 2005. The technique and application of power generation by waste heat in moderate and low temperature in cement plant (in Chinese). www.chinacement.org

Parekh, P., 2000. Investment Grade Compressed Air System Audit, Analysis, and Upgrade, In: Proceedings 22nd National Industrial Energy Technology Conference Proceedings. Houston, Texas. April 5-6: pp 270-279.

Parkes, F.F., 1990. Energy Saving by Utilisation of High Efficiency Classifier for Grinding and Cooling of Cement on Two Mills at Castle Cement (Ribblesdale) Limited, Clitheroe, Lancashire, UK, *Energy Efficiency in the Cement Industry* (Ed. J. Sirchis), London, England: Elsevier Applied Science.

Patzelt, N., 1993. Finish Grinding of Slag, *World Cement* 10 **24** pp.51-58.

Philips Kiln Services. 2001. Philips Enviro-Seal, Case Study – M/S Maihar cement, Available at: http://www.kiln.com, accessed November 2001.

Price, A. and M.H. Ross, 1989. Reducing Industrial Electricity Costs – an Automotive Case Study, The Electricity Journal. July: 40-51.

Price, L. K. and C. Galitsky. 2006 (in press). Opportunities for Improving Energy and Environmental Performance of China’s Cement Kilns. Berkeley, CA: Lawrence Berkeley National Laboratory.

Radgen, P. and E. Blaustein (eds.), 2001. Compressed Air Systems in the European Union, Energy, Emissions, Savings Potential and Policy Actions, Fraunhofer Institute for Systems Technology and Innovation, Karlsruhe, Germany.

Regitz, John. 1996. Evaluation of Mill Drive Options IEEE Transactions on Industry Applications 3 32: 653.

Ruby, C.W. 1997. A New Approach to Expert Kiln Control. Proc.1997 IEEE/PCA Cement Industry Technical Conference XXXIX Conference Record, Institute of Electrical and Electronics Engineers: New Jersey.

Salzborn, D. and A. Chin-Fatt, 1993. Operational Results of a Vertical Roller Mill Modified with a High Efficiency Classifier *Proc. 35th IEEE Cement Industry Technical Conference*, Toronto, Ontario, Canada, May 1993.

Sauli, R.S. 1993. Rotary Kiln Modernization and Clinker Production Increase at Testi Cement Plant of S.A.C.C.I. Spa., Italy Proc. KHD Symposium '92, 2 Modern Burning Technology, KHD Humboldt Wedag, Cologne, Germany.

Scheuer, A. and Sprung, S., 1990. Energy Outlook in West Germany's Cement Industry. Energy Efficiency in the Cement Industry (Ed. J. Sirchis), London, England: Elsevier Applied Science.

Schmidt, H-J. 1998. Chrome Free Basic Bricks – A Determining Factor in Cement Production Proc.1998 IEEE-IAS/PCA Cement Industry Technical Conference: 155-167.

Seebach, H.M. von, E. Neumann and L. Lohnherr, 1996. State-of-the-Art of Energy-Efficient Grinding Systems *ZKG International* 2 **49** pp.61-67.

Smart, J. and B. Jenkins. 2000. Combustion in the Rotary Kiln, The Combustion Institute, Leeds, UK. Available at:
http://www.chemeng.ucl.ac.uk/research/combustion/nl2000_1/nl00_1_9.html

Steinbliss, E. 1990. Traditional and Advanced Concepts of Waste Heat Recovery in Cement Plants Energy Efficiency in the Cement Industry (Ed. J. Sirchis), London, England: Elsevier Applied Science.

Süssegger, A., 1993. Separator-Report '92 Proc. KHD Symposium '92, Volume 1 Modern Roller Press Technology, KHD Humboldt Wedag, Cologne, Germany.

Sutoh, K., M. Murata, S. Hashimoto, I. Hashimoto, S. Sawamura and H. Ueda, 1992. Gegenwärtiger Stand der Vormahlung von Klinker und Zement-rohmaterialien nach dem CKP-System, *ZKG* 1 **45** pp.21-25.

United States Department of Energy, Office of Industrial Technologies (U.S.DOE OIT). 1996. Energy and Environmental Profile of the U.S. Iron and Steel Industry, Washington, DC: U.S.DOE OIT.

United States Environmental Protection Agency (U.S. EPA), 2001. "Green Lights Program (Part of the ENERGY STAR Program)," http://es.epa.gov/partners/green/green.html.

United States Geological Survey, 2001. Minerals Yearbook, Washington, D.C., USGS. Available at http://minerals.er.usgs.gov/minerals/.

Van den Broeck, M., 1998. A SD100 Sturtevant High-Efficiency Classifier for Origny-Rochefort, *International Cement Journal* 2 pp.39-45.

Van den Broeck, M., 1999. GO Control Goes ‘Multi-Circuit’ *International Cement Journal* 1, pp.35-37.

Van Oss, H. 1999. Personal Communication. U.S. Geological Survey, February 9.

Van Oss, H. 2002. Personal Communication. U.S. Geological Survey, March – May, 2002.

Venkateswaran, S.R. and H.E. Lowitt. 1988. The U.S. Cement Industry, An Energy Perspective, U.S. Department of Energy, Washington D.C., USA.

Videgar, R., Rapson, D. and Dhanjal, S., 1997. Gyro-therm Technology Boosts Cement Kiln Output, Efficiency and Cuts NOx Emissions. Proceedings1997 IEEE/PCA Cement Industry Technical Conference XXXIX Conference Record, Institute of Electrical and Electronics Engineers: New Jersey.

Vleuten, F.P. van der. 1994. Cement in Development: Energy and Environment Netherlands Energy Research Foundation, Petten, The Netherlands.

Wang, Xuemin, 2006a. Personal communication with Prof. Wang Xuemin of the Institute of Technical Information for Building Materials Industry of China (ITIBMIC). February.

Wang, Yanjia of Tsinghua University, Beijing, China. 2006b. Personal written communication.

Worrell, E., J.W. Bode, J.G. de Beer, 1997. Energy Efficient Technologies in Industry - Analysing Research and Technology Development Strategies - The 'Atlas' Project, Department of Science, Technology & Society, Utrecht University, Utrecht, The Netherlands.

Worrell, E. and Galitsky, C., 2004. Energy Efficiency Improvement Opportunities for Cement Making: An ENERGY STAR® Guide for Energy and Plant Managers. Berkeley, CA: Lawrence Berkeley National Laboratory (LBNL-54036).

Worrell, E., L. Price, N. Martin, C. Hendriks and L. Ozawa Meida. 2001. Carbon Dioxide Emissions from the Global Cement Industry, Annual Review of Energy and the Environment 26: 303-329.

Young, G. 2002. Personal communication from Gerald I. Young, Penta Engineering Corp., St. Louis Missouri, March.