

Opportunities for Improving Energy Efficiency, Reducing Pollution and Increasing Economic Output in Chinese Cement Kilns

Christina Galitsky and Lynn Price, Lawrence Berkeley National Laboratory

ABSTRACT

China produces roughly half of the world's cement, a large share of which is made in energy inefficient, highly polluting kilns. The cement industry is a major source of multiple air pollutants, among them dioxins, mercury, particulate matter and greenhouse gas emissions. In 2005, just over one billion tonnes of cement was produced in China and cement demand will continue to be high in the near future as development goals are pursued.

In the kiln, production of clinker, the main ingredient of cement, consumes about 80% of the energy used at a cement plant. Clinkering is also the source of almost all carbon dioxide (CO₂) and toxic emissions produced from cement manufacture. This paper examines measures that can be used to retrofit or to replace older, inefficient Chinese cement kilns to improve their energy efficiency, reduce pollution and maximize the industry's economic performance and output. We provide costs, savings and payback periods upon implementation for case studies around the world, and where possible, specifically in China. Fourteen of the technologies and measures examined have simple payback periods of three years or less. Of the rest, some, such as kiln replacement, are capital intensive and could have payback periods of greater than ten years.

Introduction

China produces half of the world's cement using myriad types of cement kilns of diverse vintages and levels of technological advancement. A large share of the cement produced in China is made in relatively inefficient and polluting vertical shaft kilns (VSKs), although recent trends indicate that some of these kilns are being closed as larger rotary kilns are being constructed, especially in the more developed regions in eastern China. Cement kilns are China's biggest industrial source of carbon monoxide and particulate matter emissions as well as multiple air toxics such as dioxins and dioxin-like compounds, and a major source of mercury and possibly other heavy metals. Cement kilns in China are often operated with poor combustion efficiency and are major sources of greenhouse gas emissions.

China's Cement Industry

There are two main types of cement kilns used for the production of clinker: vertical shaft kilns and rotary kilns. A rotary kiln consists of a longer and wider drum oriented horizontally and at a slight incline on bearings, with raw material entering at the higher end and traveling as the kiln rotates towards the lower end, where fuel is blown into the kiln. A shaft kiln essentially consists of a large drum set vertically with a packed mixture of raw material and fuel traveling down through it under gravity.

Shaft kilns, while common in China, are not used in the West. The technology has a number of advantages that suit it to local conditions, and intensive domestic research and development have improved the kilns considerably since the 1970s. Parallel evolution of shaft

kiln technology with the more complex dry process rotary kilns keep the mix of pyroprocessing technologies in China's cement industry more diverse than in almost any other country. The unit sizes of shaft kilns are much smaller than those of rotary kilns, making the former attractive given the system of distributed production that has been encouraged by lack of sufficient infrastructure and by political, economic, and other factors. Moreover, construction time for a shaft kiln is one year or less, so it can come on line much faster than a large rotary kiln, which takes two to three years to build.

There are three basic types of shaft kilns: ordinary, mechanized, and improved shaft kilns. In ordinary (or non-mechanized) shaft kilns, fuel (anthracite, nearly always a high-ash type) and raw materials are layered in the kiln, often manually. These kilns typically produce inferior quality cement, have high energy consumption, and severe environmental pollution. Mechanized kilns feed mixed raw materials and fuel to the top of the kiln with a manually operated feed chute. They also have a reciprocating or rotating grate at the outlet for clinker removal. Improved shaft kilns are those that have been upgraded and that produce higher quality cement with lower environmental impacts (Sinton, 1996; ITIBMIC, 2004).

Rotary kilns are either wet or dry process kilns. Wet process rotary kilns are more energy-intensive. Energy-efficient dry process rotary kilns can be equipped with grate or suspension preheaters to heat the raw materials using kiln exhaust gases prior to their entry into the kiln. In addition, the most efficient dry process rotary kilns use precalciners to calcine the raw materials after they have passed through the preheater but before they enter the rotary kiln (WBCSD, 2004).

Coal is the primary fuel burned in cement kilns, but petroleum coke, natural gas, and oil are also consumed. Waste fuels, such as hazardous wastes from painting operations, metal cleaning fluids, electronic industry solvents, as well as tires, are often used as fuels in cement kilns as a replacement for more traditional fossil fuels (Gabbard and Gossman, 1990).

Table 1 provides information on the number of kilns and production by kiln type for 2001 through 2004 and 2005, respectively. Shaft kilns dominate the Chinese cement industry, comprising 90% of all cement kilns in 2004. Mechanical shaft kilns increased by 660 kilns between 2001 and 2004. This growth was partially off-set by the closure of 600 ordinary shaft kilns. There were 415 new large & medium sized new suspension preheater and precaliner/suspension preheater (NSP/SP) rotary kilns put into production between 2001 and 2004, while closures were seen among the small NSP/SP kilns, cyclone pre-heater, shaft pre-heater, Lepol, and small dry process hollow kilns. Production increased during the entire period.

Recent Chinese Cement Market Trends

Cement demand will continue to be high in China in the near future as development goals are pursued. For example, the 2004 “National Highway Network Plan” calls for building 85,000 kilometers of highways by 2020, of which 29,000 kilometers have currently been constructed (GEI, 2005). China’s 11th Five-Year Plan also outlines ambitious “mega-projects” such as the 2008 Beijing Olympics, the 2010 Shanghai World Expo, the south-to-North Water Diversion, and the West-East natural gas transmission project (Hong Liang, 2006). Table 2 provides the projected cement production included in China’s National Plan for 2006 through 2010 and an estimate of the 2011 through 2014 production (Cui, 2006a) indicating that cement production is expected to peak at 1,250 Mt in the 2010-2011 period and then begin to slowly decline.

Table 1. Annual Cement Production (Million tonne) and Number of Kilns (#) by Kiln Type

	2001		2002		2003		2004		2005
Rotary Kilns	Mt	#	Mt	#	Mt	#	Mt	#	Mt
<i>Large & medium NSP/SP kilns</i>	71	151	121	228	199	326	319	566	473
<i>Small NSP/SP kilns</i>	7	101	8	101	6	101	4	66	
<i>Cyclone pre-heater kilns</i>	2	72	2	72	2	64	1	34	
<i>Shaft pre-heater kilns</i>	10	290	9	280	5	236	3	148	
<i>Semi-dry process kilns</i>	5	12	6	14	7	16	7	16	
<i>Cogenerative kilns</i>	13	113	14	115	14	121	17	150	
<i>Lepol kilns</i>	3	20	3	20	3	19	3	19	
<i>Small dry-process hollow kilns</i>	8	330	8	320	8	320	4	170	
<i>Wet-process kilns</i>	34	206	40	250	40	250	40	250	
Rotary Kilns Sub-Total	153	1295	211	1400	282	1453	397	1419	564
Shaft Kilns									
<i>Improved shaft kilns</i>	91	850	115	885	145	1150	155	1240	
<i>Mechanical shaft kilns</i>	312	8400	339	8350	372	9280	363	9060	
<i>Ordinary shaft kilns</i>	64	3000	55	2800	64	3150	48	2400	
Shaft Kilns Sub-Total	467	12250	509	12035	581	13580	566	12700	500
Total	620	13545	720	13435	863	15033	963	14119	1064

Sources: Cui, 2006a; Cui, 2005; ITIBMIC, 2004

Table 2. Projected Cement Production in China (Million tonnes), 2006-2014

	2006	2007	2008	2009	2010	2011	2012	2013	2014
Output (Mt)	1,110	1,160	1,200	1,225	1,250	1,250	1,225	1,200	1,150

2006-2010: National Plan; 2011-2014: ITIBMIC estimate. Source: Cui, 2006a.

Energy Efficiency and Environmental Opportunities for Clinker Production

Opportunities exist within Chinese cement plants to improve energy efficiency while maintaining or enhancing productivity. While many improvements exist at all stages of production, this paper focuses on improvements for the kiln itself, as well as product and feedstock changes which will also result in reduction of fuel consumed in the kiln. We have provided descriptions of each technology and a table of the capital costs, operations and maintenance (O&M) costs, payback periods, energy savings, CO₂ emission reduction potentials and lifetimes for each measure.¹ The costs and savings documented in this report will vary for any specific site and process configuration. This information could be used to identify measures worth evaluating, but should not be used for definitive investment decisions. The information is based on case study examples as reported in the open literature (no confidential information is used) for installations in various countries around the world; where possible, China-specific information has been used.

Opportunities for All Kiln Types

All kilns can implement improved refractories, 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. Table 3 provides data on costs, payback period, specific fuel and electricity savings, specific carbon dioxide savings and the lifetime associated with each of these measures. Due to space constraints, we are unable to provide more information on these measures¹.

¹ For more data, case studies and further references refer to Price et al. (2007).

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	0.25		1	0.4-0.63 ¹	-	10.3-16.3	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. All data are given per tonne of clinker and are based on average performance of the industry (e.g. clinker: cement).

¹ Data taken from Chinese case studies

GJ = Gigajoule; kWh = kilowatt hour; kgC = kilogram carbon; t = tonne

Opportunities for Rotary Kilns

For rotary kilns, various kiln types can be converted or upgraded to more efficient kilns, either by adding a precalciner and extra preheaters, or by replacement of the kiln. Other energy-efficiency technologies and measures include kiln combustion system improvements, optimizing heat recovery, upgrading or replacing the clinker coolers, seal replacement, low or high temperature waste heat recovery for power generation, low pressure drop cyclones for suspension preheaters, and efficient kiln drives. Table 4 provides specific data for each of these measures. Due to space constraints, we have focused on only a few of these measures with the largest potential for energy and CO₂ savings¹.

Installation or upgrading of a preheater to a preheater/precalciner kiln. An existing preheater kiln may be converted to a multi-stage preheater/precalciner kiln by adding a precalciner and, when possible an extra preheater. The addition of a precalciner will generally increase the capacity of the plant, while lowering the specific fuel consumption and reducing thermal NO_x emissions (due to lower combustion temperatures in the 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.

Conversion of long dry kilns to preheater/precalciner kiln. A long dry kiln can also be upgraded to the current state of the art multi-stage preheater/precalciner kiln (see previous measure for more information on Preheater/Precalciner Kilns).

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. By installing new preheaters, the productivity of the kiln will increase, due to a higher degree of precalcination (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.

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. All data are given per tonne of clinker and are based on average performance of the industry (e.g. clinker: cement).

¹ Negative values represent operation and maintenance savings.

² Negative values represent an increase in electricity due to the measure.

³ Domestic technology cost is 6000 to 10,000 Renminbi (RMB) per investment, which is about 10,000 RMB less than foreign technology (16,000 to 22,000 RMB/kW). Numbers above are derived from Chinese case studies.

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

NA = data not available

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. In China, there are few if any rotary or shaft coolers (Cui, 2006b). However, some planetary grate coolers may still be in operation. The reciprocating grate cooler is the modern variant and is used in almost all modern kilns. The advantages of the reciprocating 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)), recovering more heat than the other types of coolers. For large capacity plants, reciprocating grate coolers are the preferred equipment. For plants producing less than 500 tonnes per day, however, this grate cooler may be too expensive (COWIconsult et al., 1993).

Kiln combustion system improvements. Fuel combustion systems in kilns can be contributors to kiln inefficiencies with such problems as poorly adjusted firing, incomplete fuel burn-out with high CO formation, and combustion with excess air (Venkateswaran and Lowitt, 1988). Improved combustion systems aim to optimise the shape of the flame, the mixing of combustion air and fuel and reducing the use of excess air. Various approaches have been developed. For rotary kilns, the Gyro-Therm technology improves gas flame quality while reducing NO_x emissions. Originally developed at the University of Adelaide (Australia), the Gyro-Therm technology can be applied to gas burners or gas/coal dual fuel. The Gyro-Therm burner uses a patented "precessing jet" technology. The nozzle design produces a gas jet leaving the burner in

a gyroscopic-like precessing motion. This stirring action produces rapid large scale mixing in which pockets of air are engulfed within the fuel envelope without using high velocity gas or air jets. The combustion takes place in pockets within the fuel envelope under fuel rich conditions. This creates a highly luminous flame, ensuring good irradiative heat transfer.

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 (exiting the kiln and entering the preheaters) for the kiln combustion process and sometimes the tertiary air (exiting the cooler and entering the pre-calciner through a special duct) (Alsop and Post, 1995). Reciprocating grate coolers are the modern variant and are suitable for large-scale kilns (up to 10,000 tonnes per day or 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).

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. 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.

Low temperature heat recovery for power generation². Government policies are promoting this technology (through the *China Medium and Long Term Energy Conservation Plan*, for example) and many projects are planned though few have been implemented to date (Wang, 2007). Many large-scale rotary kilns built after 2003 do not use this technology. The first plant to utilize this technology received through donation from Japan (GEI, 2005). CONCH (Hai Luo) has eleven sets of waste heat recovery projects under construction to be finished by the end of 2007. In 2006, ten projects designed by Tianjing Cement Institute were commissioned, another two were commissioned in February and March of 2007, sixteen are under construction and eight are in the design stage (as of June, 2007) (Waste Heat Seminar, 2007). If waste heat recovery is designed for a new cement plant, the cost of the improvement could be low (Wang, 2007).

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. Cogeneration systems can either be direct gas turbines that utilize the waste heat (top cycle), or the installation of a waste heat boiler system that runs a steam turbine system (bottom cycle). This report focuses on the steam turbine system since these systems have

² Adopting low temperature waste heat recovery for electricity production changes the temperature profile of the flue gas which may impact the catalytic dioxin formation reactions. 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).

been installed in many plants worldwide and have proven to be economical. (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.

Opportunities for Vertical Shaft Kilns

For vertical shaft kilns, the main energy-efficiency opportunity is to replace the VSK with NSP/SP kilns. In addition, combustion system improvements can be made for the kiln. Table 5 provides for each of these measures with details given below.

Replace vertical shaft kiln with new suspension preheater/precalcliner kilns. The NSP technique has been developed for 1000 t/day, 2000 t/day and 4000 t/day (GEI, 2005). NSP can 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. By the end of 2004, China put into service 140 NSP and 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 CO₂ and generates CO.

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/precalcliner kiln	28-41		5-7 ¹	2	-	52	40
Kiln combustion system improvements	NA	NA	NA	NA	NA	NA	NA

Note: Energy savings and costs are based on case study data. Costs in China will vary depending on technology and availability. 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 \$50/tonne coal).

NA = 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).

Opportunities in Product and Feedstock Changes

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 6 provides data for 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.

In China, a range of materials are used in blended cements, 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 sulphates, 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.

Portland ordinary cement and Portland slag cement are used widely 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 6. Product and Feedstock Changes in 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: Costs in China will vary depending on technology and availability. All data are given per tonne of clinker.

¹ Negative values 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 CO₂ 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

China produces 25 Mt of blast furnace slag per year and has a long history of using this type of waste (Cui, 2006b). Where utilized, about 20 to 25% of clinker is replaced; the country's highest slag ratio is 50% (Cui, 2006b). 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 available (Cui, 2006b).

Limestone portland cement. Limestone can be interground with clinker to produce cement, reducing the needs for clinker-making and calcination. This reduces energy use in the kiln and

clinker grinding, and resulting emissions, as well as CO₂ emissions from calcination. The addition of up to 5% limestone has shown to have no negative impacts on the performance of portland cement, while slightly improving its workability (Detwiler and Tennis, 1996).

Use of waste-derived fuels. Waste fuels can be substituted for traditional commercial fuels in the kiln. New waste streams include carpet and plastic wastes, filter cake, paint residue and (dewatered) sewage sludge (Hendriks et al., 1999). Cement kilns also burn hazardous wastes; since the early 1990's cement kilns burned 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, especially in wet process kilns. Waste-derived fuels may result in net energy savings and reduced CO₂ emissions, depending on the alternative use of the wastes (e.g. incineration with energy recovery). In China, only three cement plants are currently burning significant 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, paints, solvents and wastewater sludge (Cui, 2004; Wang, 2006). 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 for its kilns (Wang, 2006). Other plants utilizing wastes but in very small amounts (Wang, 2006). 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, 1997).

Low-alkali cement. In North America, a relatively large part of the production of the cement industry are cements with a low alkali content (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 blended cement, see above) may reduce the need for low-alkali cement.

Use of steel slag in kiln. In 1994, Texas Industries developed the CemStar[®] process to use electric arc furnace (EAF) slags of the steel industry as input in the kiln, reducing the use of limestone (approximately 1.6 times the weight in limestone). EAFs produce between 55 and 210 kg of slag per tonne of steel (on average 116 kg/tonne) (U.S. DOE OIT, 1996). The slag that contains tricalcium silicate (C₃S) can more easily be converted to free lime than limestone. CemStar[®] can replace 10 to 15% of the clinker by EAF-slugs, reducing combustion energy (and its associated CO₂ emissions), as well as the CO₂ emissions from calcination because the lime in the slag is already calcined. CemStar[®] can also avoid grinding energy because slags can be added in 5 cm lumps. Depending on the location of injection, it may also save heating energy. The reduced combustion energy and lower flame temperatures also lead to reduced NO_x emissions (Battye et al., 2000). China does not produce this technology domestically, and to date the measure has not been implemented in cement kilns in China (Cui, 2006b).

Conclusions

The preceding technical analysis identified 22 technologies or measures that can be used to retrofit or to replace old, inefficient cement kilns to improve their energy efficiency. Most of the technologies and measures reduce fuel consumption, while some reduce electricity consumption and others reduce both. Using publicly available data on the initial capital costs as well as identified operating and maintenance costs combined with the energy savings,³ simple payback periods were calculated. Fourteen of these technologies and measures have simple payback periods of three years or less, others have payback periods of up to ten or more years.

Based on the identified energy savings, reductions in emissions of carbon dioxide were also calculated. These reductions ranged from a low of 0.13 kgC/t clinker with the installation of efficient kiln drives to a high of 85 kgC/t clinker for maximum use of blended cement. Assuming a 90% clinker-to-cement ratio, a plant that produces 1 Mt cement per year could realize carbon emissions reductions of 144 tC to 94,444 tC, respectively, for these improvements. Savings in addition to energy could be realized from carbon emission credits for these measures, assuming the Clean Development Mechanism additionality test of the Kyoto Protocol could be met.

Acknowledgments

This work was supported by the U.S. Environmental Protection Agency's Office of International Affairs, Office of Technology Cooperation and Assistance through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231. We would also like to thank Ernst Worrell of Ecofys, Wang Yanjia of Tsinghua University, and Cui Yuansheng of the Institute of Technical Information for the Building Materials Industry of China for their help.

References

- Alsop, P.A. and J.W. Post. (1995). *The Cement Plant Operations Handbook*, (First edition), Tradeship Publications Ltd., Dorking, UK
- 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.
- Buzzi, S. and G. Sassone. (1993). "Optimization of Clinker Cooler Operation," *Proc. VDZ Kongress 1993: "Verfahrenstechnik der Zementherstellung"* Bauverlag, Wiesbaden, Germany: 296-304.
- Cembureau, 1997. *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>.

³ Energy costs, savings and payback periods are based on 1994 U.S. average prices of coal at \$1.75/GJ, industrial sector final electricity at \$12.33/GJ and primary electricity at \$37.98/GJ (U.S. EIA, 1998). For comparison, the 2005 Chinese average coal price of \$2.06/GJ, the Chinese national average final electricity price of \$27.55/GJ and primary electricity of \$84.85/GJ were all higher than the 1994 U.S. energy prices (Fridley, 2006; BECON, 2005).

- 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., 2006a. *Status Quo of the Chinese Cement Industry in 2005 and Future Prospect*. Presentation, Mideast & North Africa Cement Conference, Dubai, United Arab Emirates, March 20-21, 2006.
- Cui, Y., 2004, 2005, 2006b. Personal communication with Prof. Cui Yuansheng, VP of the Institute of Technical Information for Building Materials Industry of China (ITIBMIC).
- 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.
- Gabbard, W.D. and Gossman, D., 1990. "Hazardous Waste Fuels and the Cement Kilns," *ASTM Standardization News*. <http://gcisolutions.com/HWF&CKS.htm>
- Global Environment Institute (GEI). (2005). "Financing of Energy Efficiency Improvement for Cement Industry in China." January.
- 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.
- Holderbank Consulting. (1993). "Present and Future Energy Use of Energy in the Cement and Concrete Industries in Canada," CANMET, Ottawa, Ontario, Canada.
- Hong Liang, 2006. *Merge and Acquisition Analysis of China Cement Industry 2005*. ChinaCement.net (2006-1-23). <http://www.cementchina.net/news/shownews.asp?id=1520#>
- Institute of Technical Information for Building Materials Industry (ITIBMIC). (2005). "A Survey on the Chinese Market of Cement Admixtures for Holcim Company".
- 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.
- 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.
- Lesnikoff, G. (1999). Hanson Cement, Cupertino, CA, personal communication.
- Liu, F., M. Ross and S. Wang. (1995). "Energy Efficiency of China's Cement Industry". *Energy* **20** (7): 669-681.

- Neto, M. (1990). "Waste Gas Heat Recovery in Cement Plants" *Energy Efficiency in the Cement Industry* (Ed. J. Sirchis), London, England: Elsevier Applied Science.
- Point Carbon, 2006. <http://www.pointcarbon.com/>
- Price, L and C. Galitsky. (2007). Opportunities for Improving Energy and Environmental Performance of China's Cement Kilns. Lawrence Berkeley National Laboratory, Berkeley, CA.
- Sinton, J.E., 1996. *Energy Efficiency in Chinese Industry: Positive and Negative Influences of Economic System Reforms*. PhD Thesis, University of California- Berkeley.
- 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.
- 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 Energy Information Administration (U.S. EIA), 1998. *Manufacturing Energy Consumption Survey*. Washington, DC: EIA.
- Van Oss, H. (1999). Personal Communication. U.S. Geological Survey, February 9.
- Van Oss, H. (2002). Personal Communication. U.S. Geological Survey, March to May.
- 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.
- Vleuten, F.P. van der. (1994). "Cement in Development: Energy and Environment" Netherlands Energy Research Foundation, Petten, The Netherlands.
- Wang, Xuemin, Institute of Technical Information for Building Materials Industry of China (ITIBMIC). 2006. Personal communication. February.
- Wang, Yanjia of Tsinghua University, Beijing, China. (2006 and 2007). Personal written communication.
- Waste Heat Seminar. (2007). The 3rd Cement Power Generation.
- World Business Council for Sustainable Development (WBCSD), 2004. *Formation and Release of POP's in the Cement Industry*. Foundation for Industrial and Scientific Research of Norway. <http://www.wbcd.ch/web/projects/cement/pop-report.pdf>