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Opportunities for Improving Energy and Environmental Performance of China's Cement Kilns

Lynn Price, Christina Galitsky

**Environmental Energy
Technologies Division**

August 2006

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Executive Summary

This report examines 22 technologies or measures that can be used to retrofit or to replace older, inefficient cement kilns to improve their energy efficiency. Such technologies can help China achieve two goals, often erroneously believed to be in conflict: (1) reduce energy use and pollution; and (2) maximize the industry's economic performance and output. The barrier to their implementation is not the lack of economically feasible technology, but rather the lack of a mechanism to finance investment and outreach to the cement and financial sectors.

Fourteen of the technologies and measures examined have simple payback periods of three years or less. At the current price of carbon, sale of associated carbon credits would yield an additional $1,300 – $850,000 on top of the energy cost savings (ranging from 0 to 3.4 GJ/t of fuel and -11 to 35 kWh of electricity), assuming the Clean Development Mechanism requirements could be met.

China produces roughly half of the world's cement, most of which is made in energy inefficient, highly polluting kilns. The cement industry is a major source of multiple air pollutants, among them dioxins and dioxin-like chemicals, mercury, particulate matter and greenhouse gas emissions.

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 and toxic emissions produced from cement manufacture, including several persistent bioaccumulative toxics that can be transported inter-continentally. This report provides information related to retrofitting cement kilns in China with technologies and measures to improve energy efficiency and to reduce greenhouse gas emissions as well as effective particulate control technologies.

In 2005, just over one billion tons of cement were produced in China. Cement demand will continue to be high in the near future as development goals are pursued. Cement production is expected to peak at 1,250 Mt in the 2010-2011 period and then begin to slowly decline.

Cement production facilities are found in every province and autonomous region of China. At the end of 2004, there were 5027 cement producers in China that owned over 14,000 cement kilns and employed 1.4 million workers. Prices continued to rise in 2004. In the first quarter of 2004 profits increased by 63.95% compared with the same period of the last year.

In recent years, the Chinese cement industry has experienced domestic reorganization through mergers and acquisitions as well as an increase in foreign investment. Large

cement companies have all expanded through mergers and acquisitions. Foreign investors such as Holcim, Lafarge, and Heidelberg Cement are acquiring shares in domestic facilities and Lafarge has built cement factories in Beijing, Chengdu, and Chongqing.

While many energy-efficiency improvement opportunities exist at all stages of cement production, this report focuses on technologies and measures for improving the energy efficiency of the kiln itself, as well as product and feedstock changes which will also result in reduction of fuel consumed in the kiln. In addition, the report describes case studies where measures have been implemented in China and, where data are available, what the costs and savings would be upon implementation. The report notes whether the technologies are available in China as domestic or foreign imports. For some domestically-produced technologies and measures, although the cost can be much lower, the performance of a domestic technology might be inferior in energy efficiency to imported technologies. There are a number of domestic cement equipment manufacturers in China. Some foreign companies have set up branches in China to provide equipment, while for other technologies, some components are imported but then assembled in China, potentially with other parts manufactured domestically.

The analysis of cement kiln energy-efficiency opportunities is divided into technologies and measures that are applicable to all kilns, those that are only applicable to rotary kilns, those that are only applicable to vertical shaft kilns, and product and feedstock changes that will reduce energy consumption for clinker making. Most measures reduce fuel consumption in the kiln, which is the focus of this report. Some measures reduce kiln fuel consumption while also reducing electricity consumption. A few measures applicable to cement kilns only reduce electricity consumption. While these measures are not the focus of this report, they have been included in order to provide a comprehensive overview of the energy-efficiency opportunities for cement kilns. Details on each energy-efficiency technology and measure, including a description, case studies, and data are provided.

Opportunities for Improving Energy and Environmental Performance of China’s Cement Kilns

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List of Abbreviations

AAGR	average annual growth rate
ABB	Asea Brown Boven, Ltd.
AC	alternate current
AR	autonomous region
ASDs	adjustable speed drives
ASR	alkali-silica reactivity
BEIC	Beijing Energy Investment Company
C	Celsius
C_3S	tricalcium silicate
CADDET	Centre for the Analysis and Dissemination of Demonstrated Energy Technologies
CaO	calcium oxide
CKRC	Cement Kiln Recycling Coalition
CKD	cement kiln dust
CNBM	China National Building Material Group Corporation
CO	carbon monoxide
CO_2	carbon dioxide
DC	direct current
DOE	Department of Energy
EAF	electric arc furnace
EPA	Environmental Protection Agency
ETSU	Energy Technology Support Unit
GEI	Global Environment Institute
GJ	gigajoule
GWh	gigawatt hour
IFC	International Finance Corporation
ITIBMIC	Institute of Technical Information for Building Materials Industry
kcal	kilocalorie
kg	kilogram
kgC	kilogram carbon
kgce	kilogram coal equivalent
kW	kilowatt
kWh	kilowatt hour
kt	thousand metric tons
ktpy	thousand metric tons per year
LBNL	Lawrence Berkeley National Laboratory
MJ	megajoule
Mt	million metric tons
MtC	million metric tons carbon dioxide (in units of carbon)
MW	megawatt
NA	not available
NDRC	National Development and Reform Commission
NOx	nitrogen oxides
NSP	new suspension preheater

O&M	operations & maintenance
OIT	Office of Industrial Technologies
PC	Precalciner
PJ	petajoules
RCRA	Resource Conservation and Recovery Act
RMB	Renminbi
SOCAM	Shui On Construction and Materials
SP	suspension preheater
t	metric tons
tC	metric tons carbon
tce	tons coal equivalent
tpd	tons per day
U.K.	United Kingdom
U.S.	United States
USGS	United States Geological Society
VSKs	vertical shaft kilns
WBCSD	World Business Council for Sustainable Development
W.C.	water column

Opportunities for Improving Energy and Environmental Performance of China’s Cement Kilns

1. INTRODUCTION

China produces half of the world’s cement using myriad types of cement kilns of diverse vintages and levels of technological advancement. Most of the cement produced in China is made in relatively inefficient and polluting vertical shaft kilns, 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. China’s cement industry is the largest source of multiple air toxics such as dioxins and dioxin-like compounds, and a major source of mercury and possibly other heavy metals. Cement kilns are China’s biggest industrial source of carbon monoxide and particulate matter emissions. Cement kilns in China are often operated with poor combustion efficiency and are major sources of greenhouse gas emissions.

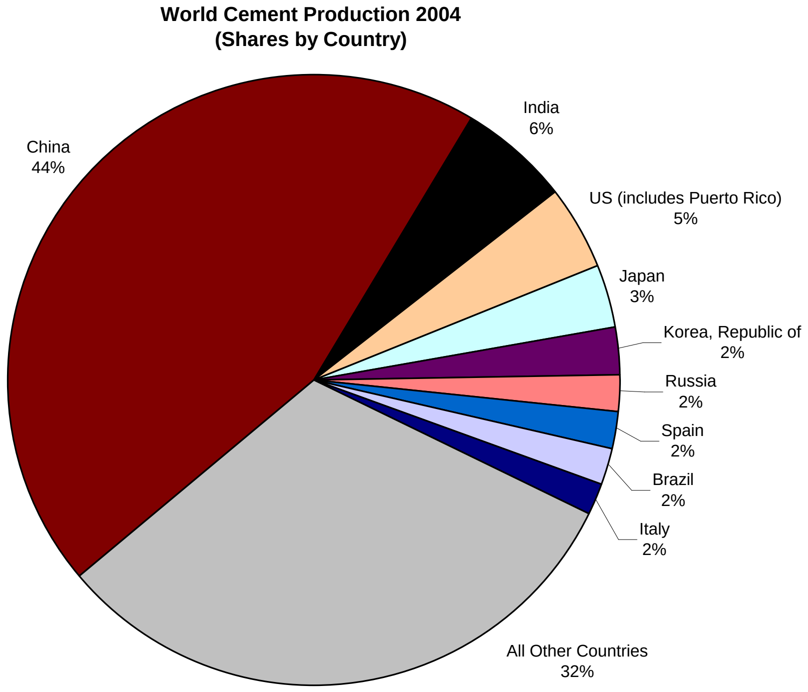
Cement kilns destroy dioxins in the hazardous waste fuels during the clinker combustion process, but dioxins can be formed after combustion if the offgases are not quickly cooled. To reduce fine particulate emissions these exhaust gases must pass through air pollution control devices such as electrostatic precipitators or fabric filtration baghouses in order to remove the cement kiln dust. 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 dioxins/furans produced from cement manufacture.

Lawrence Berkeley National Laboratory (LBNL) was asked by the U.S. Environmental Protection Agency’s (EPA’s) Office of Technology Cooperation and Assistance to provide information related to retrofitting vertical shaft and rotary cement kilns in China with technologies and measures to improve energy efficiency and reduce greenhouse gas emissions as well as effective particulate control technologies.

This report begins with an overview of China’s cement industry, providing information on China’s current production levels relative to other cement producers worldwide as well as a description of the two main kiln types used in China. This is followed by a more detailed market analysis section that provides information on historical cement production trends in China, cement production by specific kiln types, the geographic distribution of Chinese cement production, ownership characteristics, China’s largest cement enterprises, government policies related to cement production, and recent cement market trends. The next section provides an estimate of China’s cement sector energy consumption and greenhouse gas emissions by kiln type and then describes energy efficiency measures that can be used to improve kiln efficiency in both vertical and rotary kilns in China. These measures are all commercially available, tested and proven technologies available from multiple countries and are often even produced domestically in China. The final section of the report provides information on the energy and carbon savings provided by the identified technologies and measures.

2. CHINA’S CEMENT INDUSTRY

China is the world's largest producer of cement, manufacturing 970 million metric tons (Mt) in 2004 (Cui and Wang, 2004)[1]. Figure 1 shows that the next highest producers are India and the U.S., producing 110 Mt and 97 Mt, respectively (USGS, 2005). Cement production in China is expected to have reached 1,064 Mt in 2005 (Cui, 2006a). China’s cement production has grown about 10 percent per year over the past two decades and is expected to reach a saturation point of 1,250 Mt around 2010.



Source: US Geological Survey, 2005 and Cui, 2005

Figure 1. World Cement Production in 2004.

Cement is made by combining clinker, a mixture of limestone and other raw materials that have been pyroprocessed in the cement kiln, with gypsum and other cementitious additives. Clinker production typically occurs in kilns heated to about 1450°C. Clinker production is the most energy-intensive process in cement manufacturing.

There are basically two types of cement kilns used for the production of clinker: vertical shaft kilns and rotary kilns. Figure 2 provides an example of a Chinese kiln of each type. 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

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[1] The U.S. Geological Survey’s preliminary 2004 production value for China cement is 934 Mt (USGS, 2005), lower than the value provided by China’s Institute of Technical Information for the Building Materials Industry of China (Cui, 2006a; Cui and Wang, 2004).

consists of a large drum set vertically with a packed mixture of raw material and fuel traveling down through it under gravity.

Shaft kilns are refractory lined tubes, typically 2 to 3 meters in diameter and 7 to 10 meters in height. Most commonly the kilns are made of steel, lined with refractory materials specially manufactured for shaft kilns, and housed in buildings 20 to 30 meters in height. The most common capacities are 150 tons per day (tpd) and 300 tpd, roughly equivalent to 50 thousand tons per year (ktpy) and 100 ktpy under normal operating conditions. Shaft kilns require that the kiln be entirely filled with a mixture of raw materials and fuel, with air entering the bottom of the kilns and exhaust gases exiting at the top. The raw material goes through the various pyroprocessing stages as it travels from the top of the kiln to the outlet at the bottom. Preheating and calcination typically occur in the top 15% of the height of the kiln. Clinkering occurs in another relatively small layer. The remainder of the kiln is devoted to a cooling zone. Since air is blown up through the bottom of the kiln nearly all the heat from the cooling clinker is used to preheat combustion air. Shaft kilns require constant attention from operators on a platform at the top of the kiln, who monitor burning conditions, control the rate of kiln feed, open and close vent doors, and manipulate the burning material at the kiln surface with long steel poles.

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 kept 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 an 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.[2] Figure 3 provides a schematic of a typical mechanized vertical shaft kiln. Improved shaft kilns are those that have been upgraded and that produce higher quality cement with lower environmental impacts (Sinton, 1996; ITIBMIC, 2004).

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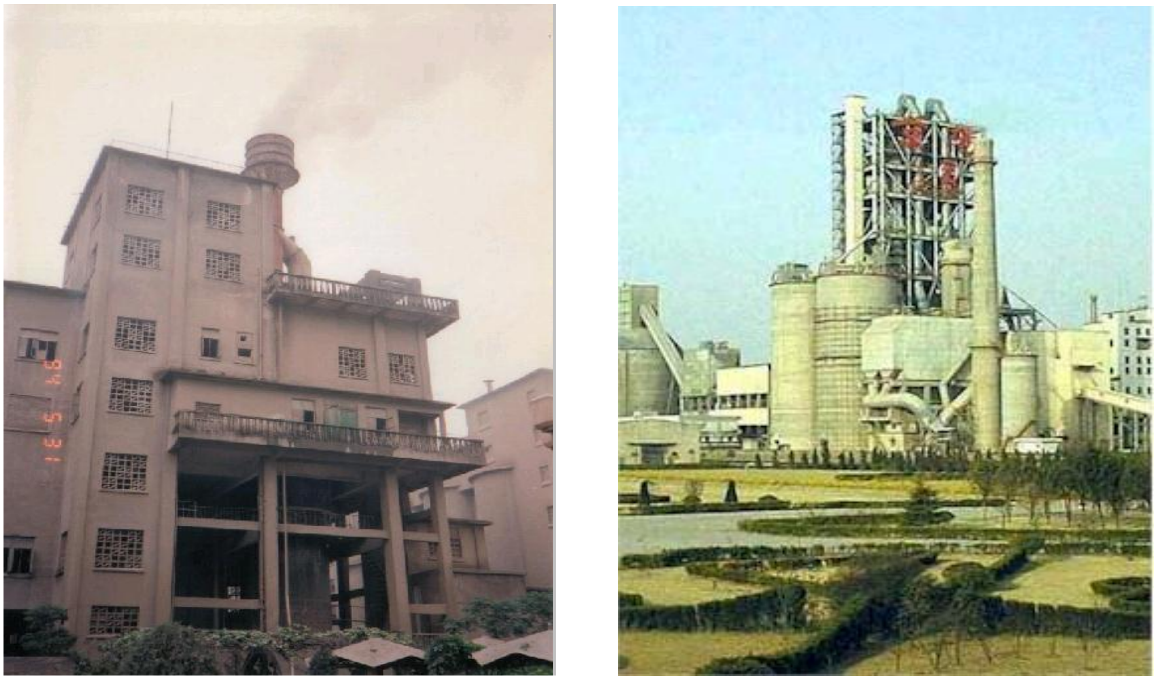
[2] These grates are generally conical or hemispherical devices with coarsely textured surfaces (often studded with steel projections) that turn and cause clinker to drop through a gap between the grate and the bottom of the kiln.

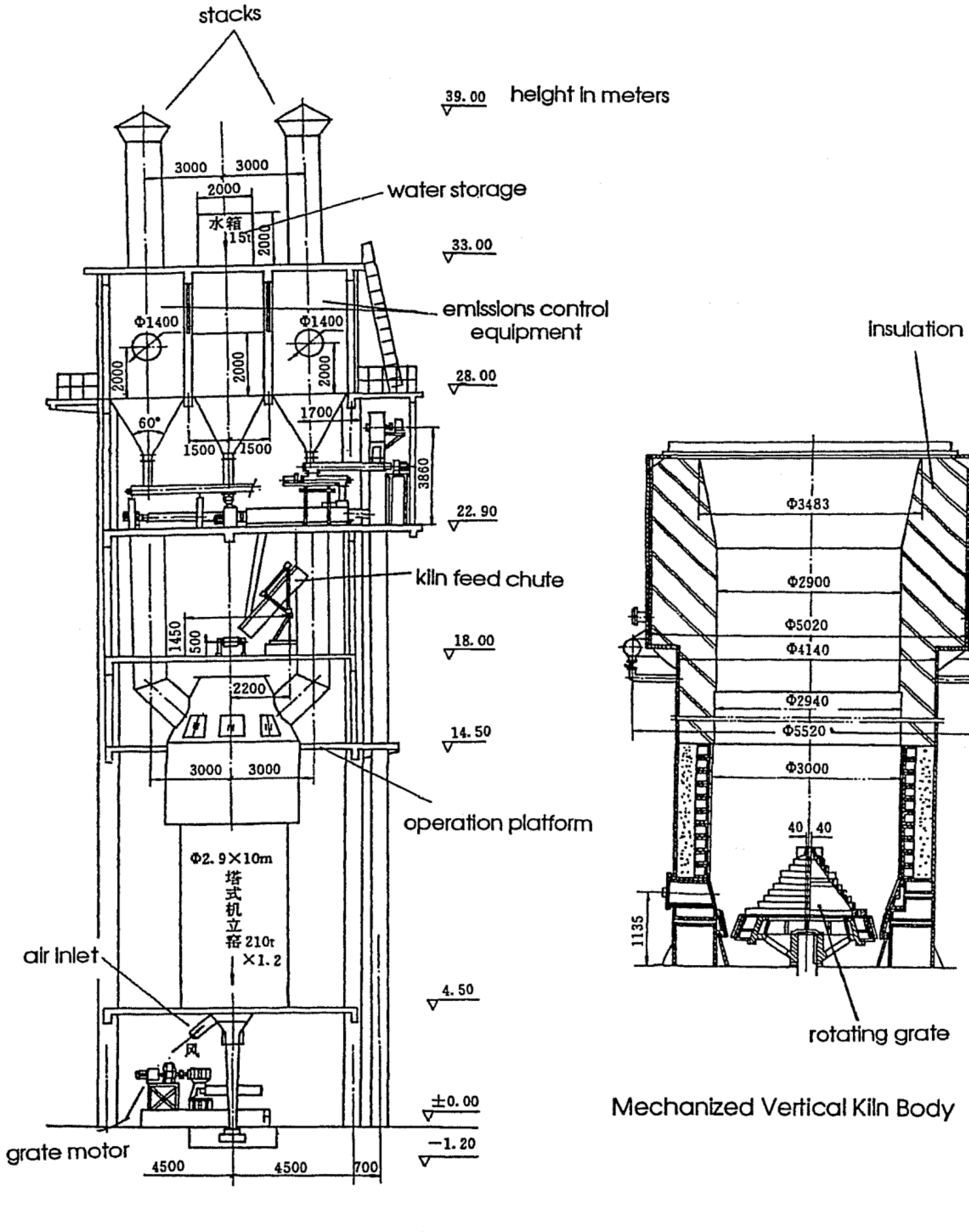


Vertical Shaft Kiln Rotary Kiln

Figure 2. Typical Chinese Vertical Shaft Kiln and Rotary Kiln

Rotary kilns can be either wet process or dry process kilns (see Figure 4). Wet process rotary kilns are more energy-intensive and have been rapidly phased out over the past few decades in almost all industrialized countries except the U.S. and the former Soviet Union. 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 industrial or commercial painting operations (spent solvents, paint solids), metal cleaning fluids (solvent based mixtures, metal working and machining lubricants, coolants, cutting 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).



Mechanized Vertical Kiln with Superstructure and Associated Equipment

Mechanized Vertical Kiln Body

Figure 3. Schematic of a Typical Mechanized Vertical Shaft Kiln.
Source: Sinton,1996.

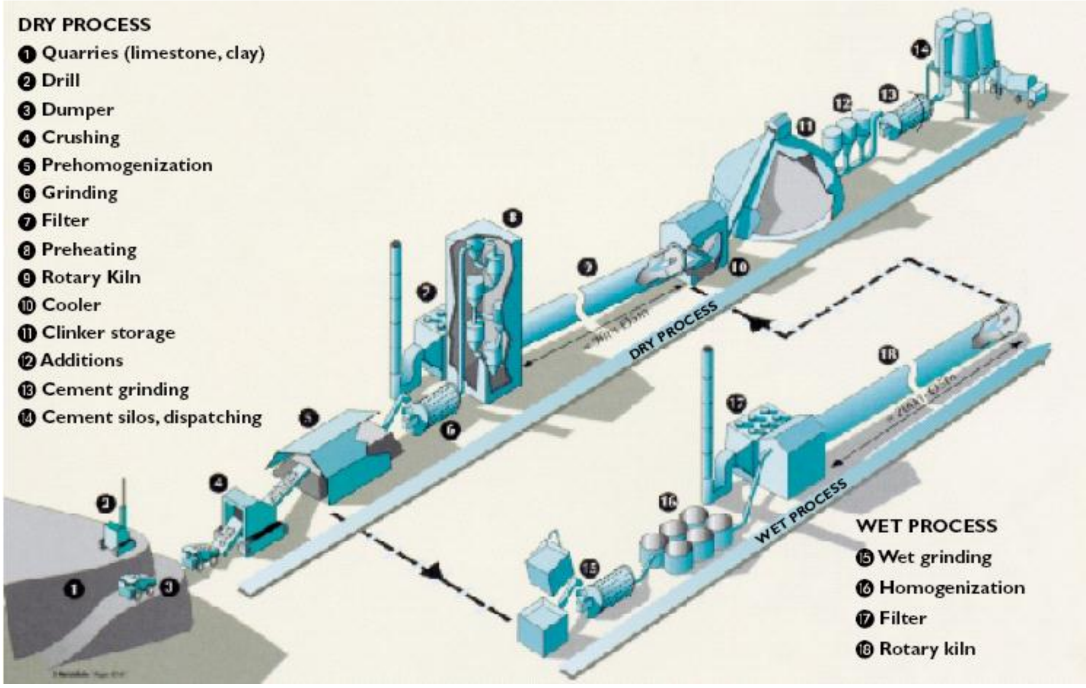


Figure 4. Schematic of the Dry and Wet Cement Manufacturing Processes
Source: Cembureau, 1997a.

3. MARKET ANALYSIS

The Chinese cement industry is extremely diverse and includes facilities of all sizes and vintages, using many different types of technologies, spread all throughout China with many different ownership configurations. This section begins with a discussion of overall Chinese cement industry production trends, and then provides information on the geographic distribution of cement production, cement production ownership characteristics, the largest cement enterprises, government policies related to cement production, and recent cement market trends.

3.1 Chinese Cement Industry Production Trends

There are basically two types of cement kilns used for the production of clinker: vertical shaft kilns and rotary kilns, but many variations of each type exist in China. Figure 5 provides an overview of the historical growth seen in the two main types of kilns, showing that production from shaft kilns continued to grow until it peaked in 2003, at which time the explosive growth in new rotary kilns began.

Rotary kilns, which include wet process kilns, small dry-process kilns, Lepol kilns, semi-dry process kilns, cyclone pre-heater kilns, and small, medium, and large suspension preheater (SP) and new suspension preheater which includes precalciners (NSP) dry process kilns, produced 564 Mt or 53% of China’s cement in 2005, while improved shaft kilns, mechanical shaft kilns, and ordinary shaft kilns produced 500 Mt in 2005 (Cui, 2006a). Table 1 provides annual cement production values by kiln type for 1997 through 2005, illustrating the significant growth in large and medium sized NSP/SP kilns and improved shaft kilns.

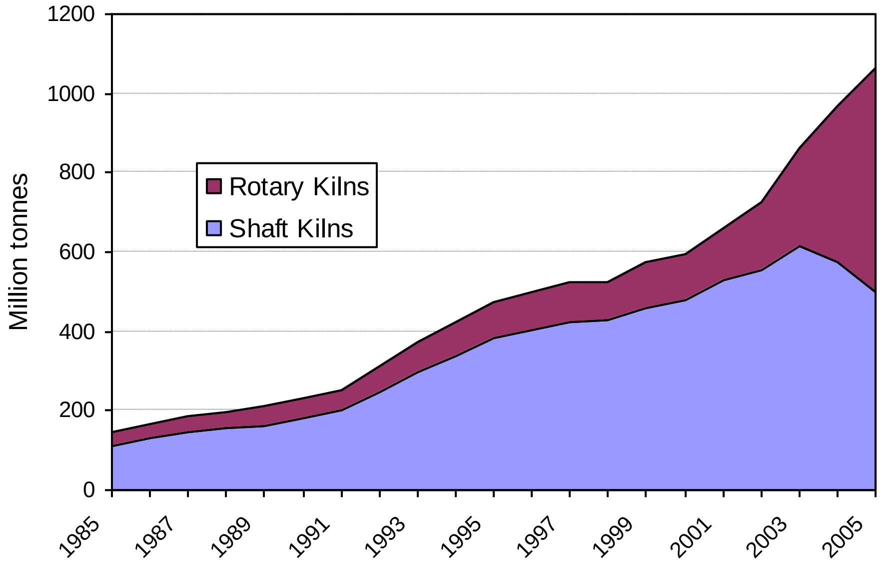


Figure 5. Annual Chinese Cement Production by Rotary and Shaft Kilns, 1985-2005.
Sources: Cui, 2006a ; Cui, 2005; ITIBMIC, 2004; Soule, et al., 2002.

Table 1. Annual Cement Production by Kiln Type (Mt).

	1997	1998	1999	2000	2001	2002	2003	2004	2005
Rotary Kilns									
Large & medium NSP/SP kilns	33	35	45	56	71	121	199	319	473
Small NSP/SP kilns	1	1	6	7	7	8	6	4	
Cyclone pre-heater kilns	2	2	2	2	2	2	2	1	
Shaft pre-heater kilns	8	8	10	10	10	9	5	3	
Semi-dry process kilns	3	3	3	4	5	6	7	7	
Cogenerative kilns	10	11	11	11	13	14	14	17	
Lepol kilns	3	3	3	3	3	3	3	3	
Small dry-process hollow kilns	9	9	8	8	8	8	8	4	
Wet-process kilns	32	33	34	34	34	40	40	40	
Rotary Kilns Sub-Total	***100***	***104***	***122***	***133***	***153***	***211***	***282***	***397***	***564***
Shaft Kilns									
Improved shaft kilns	42	44	64	75	91	115	145	155	
Mechanical shaft kilns	300	307	310	301	312	339	372	363	
Ordinary shaft kilns	68	81	77	67	64	55	64	48	
Shaft Kilns Sub-Total	***410***	***432***	***451***	***443***	***467***	***509***	***581***	***566***	***500***
Total	**510**	**535**	**573**	**576**	**620**	**720**	**863**	**963**	**1064**

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

Table 2 provides information on the number of kilns by kiln type for 2001 through 2004. 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 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.

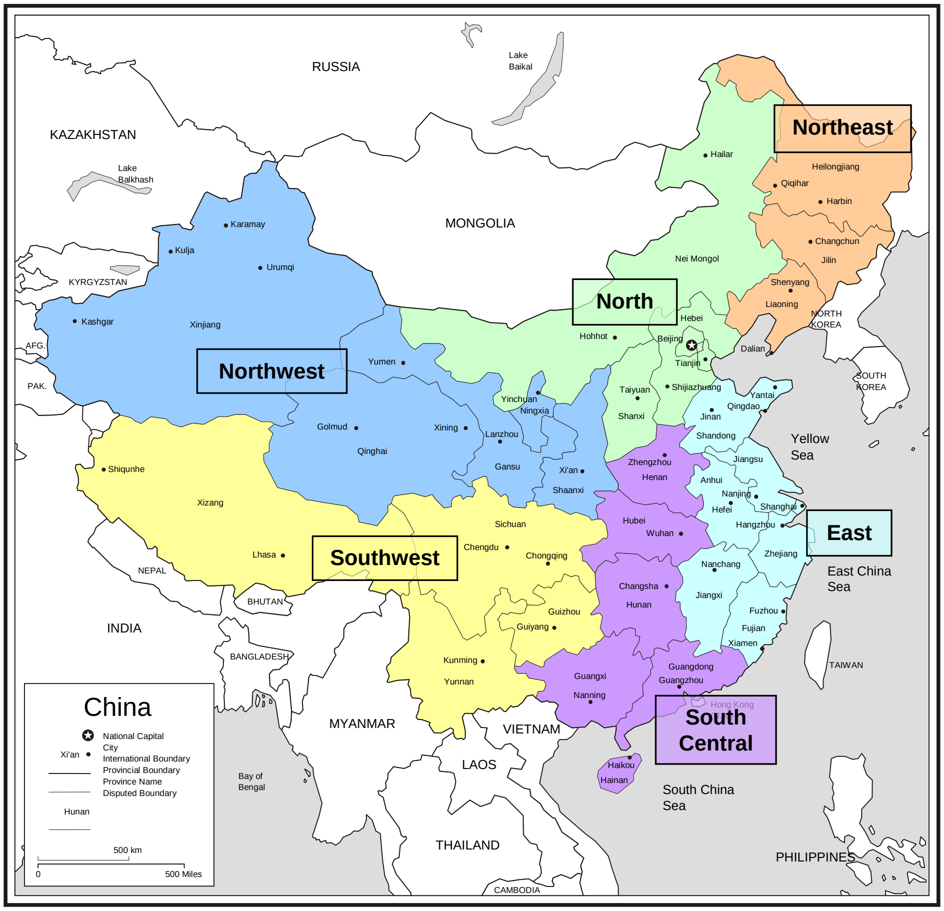
Table 2. Number of Cement Kilns by Kiln Type.

	2001	2002	2003	2004
Rotary Kilns				
Large & medium NSP/SP kilns	151	228	326	566
Small NSP/SP kilns	101	101	101	66
Cyclone pre-heater kilns	72	72	64	34
Shaft pre-heater kilns	290	280	236	148
Semi-dry process kilns	12	14	16	16
Cogenerative kilns	113	115	121	150
Lepol kilns	20	20	19	19
Small dry process hollow kilns	330	320	320	170
Wet process kilns	206	250	250	250
Rotary Kilns Sub-Total	***1295***	***1400***	***1453***	***1419***
Shaft Kilns				
Improved shaft kilns	850	885	1150	1240
Mechanical shaft kilns	8400	8350	9280	9060
Ordinary shaft kilns	3000	2800	3150	2400
Shaft Kilns Sub-Total	***12250***	***12035***	***13580***	***12700***
Total	**13545**	**13435**	**15033**	**14119**

Source: ITIBMIC, 2004.

3.2 Geographic Distribution of Chinese Cement Production

Cement production facilities are found in every province and autonomous region of China. In 2004, production levels ranged from a low of 1 million metric tonnes (Mt) in the Xizang Autonomous Region (Tibet) to 124 Mt in Shandong province. Figure 6 illustrates the distribution of cement manufacturing in terms of the major regions in China. The greatest production is found in the East Region, where Shanghai as well as a number of more developed provinces are located. The South Central and North Regions, where the major cities of Guangdong and Beijing are located, follow. The Northeast Region, which is only made up of three provinces, produced the least amount of cement, followed by the Northwest and Southwest Regions. Table 3 provides detailed information on cement production for each of these major regions by province, municipality, and autonomous region for 2000 through 2004.



	Total Cement Production (Mt)				
	2000	**2001**	**2002**	**2003**	**2004**
North Region	***76.12***	***82.97***	***94.22***	***111.58***	***125.96***
Northeast Region	***36.17***	***39.74***	***39.93***	***46.73***	***49.76***
East Region	***205.97***	***235.01***	***264.37***	***336.96***	***376.71***
South Central Region	***169.66***	***187.16***	***203.67***	***218.96***	***234.03***
Southwest Region	***65.14***	***77.55***	***79.34***	***98.66***	***94.53***
Northwest Region	***30.12***	***38.60***	***40.29***	***49.18***	***52.69***

Figure 6. Distribution of Cement Production by Major Region in China.

Source: National Bureau of Statistics, 2001; 2002; 2003; 2004; 2005.

Table 3. Geographic Distribution of Chinese Cement Production, 2000-2004.

		Total Cement Production (Mt)					**AAGR**
		2000	**2001**	**2002**	**2003**	**2004**	**2000-04**
North Region		***76.12***	***82.97***	***94.22***	***111.58***	***125.96***	***13%***
北 京	Beijing Municipality	8.27	8.09	8.84	9.99	11.28	8%
天 津	Tianjin Municipality	2.67	3.39	3.78	4.51	5.37	19%
河 北	Hebei Province	46.95	48.78	57.69	68.11	78.26	14%
山 西	Shanxi Province	11.94	15.73	16.80	19.49	19.23	13%
内蒙古	Neimengu AR (Inner Mongolia)	6.30	6.98	7.11	9.48	11.82	17%
Northeast Region		***36.17***	***39.74***	***39.93***	***46.73***	***49.76***	***8%***
辽 宁	Liaoning Province	19.55	21.01	21.46	24.40	24.72	6%
吉 林	Jilin Province	7.59	9.07	8.89	11.19	13.76	16%
黑龙江	Heilongjiang Province	9.04	9.66	9.58	11.14	11.28	6%
East Region		***205.97***	***235.01***	***264.37***	***336.96***	***376.71***	***16%***
上 海	Shanghai Municipality	3.12	4.34	3.52	7.45	6.65	21%
江 苏	Jiangsu Province	46.00	52.47	60.35	78.25	79.93	15%
浙 江	Zhejiang Province	42.57	47.91	57.43	71.94	81.92	18%
安 徽	Anhui Province	19.06	23.72	24.04	30.73	32.35	14%
福 建	Fujian Province	15.14	17.62	16.99	24.00	22.45	10%
江 西	Jiangxi Province	14.63	16.08	19.66	25.24	29.76	19%
山 东	Shandong Province	65.47	72.87	82.39	99.35	123.64	17%
South Central Region		***169.66***	***187.16***	***203.67***	***218.96***	***234.03***	***8%***
河 南	Henan Province	37.23	46.86	44.81	47.23	53.94	10%
湖 北	Hubei Province	24.61	27.97	29.49	34.46	37.68	11%
湖 南	Hunan Province	23.96	27.62	27.47	31.35	33.58	9%
广 东	Guangdong Province	58.72	60.18	74.42	75.30	77.85	7%
广 西	Guangxi Zhuang AR	21.98	21.40	24.01	26.65	26.80	5%
海 南	Hainan Province	3.15	3.13	3.47	3.98	4.19	7%
Southwest Region		***65.14***	***77.55***	***79.34***	***98.66***	***94.53***	***10%***
重 庆	Chongqing Municipality	14.03	16.99	17.5	20.38	19.57	9%
四 川	Sichuan Province	27.66	31.62	32.94	40.60	38.20	8%
贵 州	Guizhou Province	7.84	12.04	11.21	15.91	14.29	16%
云 南	Yunnan Province	15.12	16.41	17.09	20.53	21.51	9%
西 藏	Xizang AR (Tibet)	0.49	0.50	0.59	1.25	0.96	18%
Northwest Region		***30.12***	***38.60***	***40.29***	***49.18***	***52.69***	***15%***
陕 西	Shaanxi Province	9.89	14.93	13.28	18.28	18.01	16%
甘 肃	Gansu Province	7.24	8.92	10.81	11.61	13.53	17%
青 海	Qinghai Province	1.24	1.76	2.64	3.07	3.43	29%
宁 夏	Ningxia Hui AR	2.80	3.19	3.74	4.94	5.83	20%
新 疆	Xinjiang Uygur AR	8.95	9.81	9.82	11.28	11.90	7%
	Total of Provinces	***583.19***	***661.04***	***721.81***	***862.08***	***933.69***	***12%***
	National Total	***597.00***	***661.04***	***725.00***	***862.08***	***970.00***	***13%***

Source: National Bureau of Statistics, 2001; 2002; 2003; 2004; 2005. Notes: AAGR = average annual growth rate; AR = autonomous region; total of provinces = provinces, ARs, and municipalities; national total = published national-level statistics. Differences between "total of provinces" and "national total" are due to unreported production in Hong Kong and Macao, unreported military usage, and statistical errors.

3.3 Chinese Cement Production Ownership Characteristics

At the end of 2004, there were 5027 cement producers in China that owned over 14,000 cement kilns and employed 1.4 million workers (Cui and Wang, 2005). In 2003, 29% of Chinese cement enterprises were owned by private companies, followed by 23% owned by collectives and 15% that were state owned. Various other ownership types are found in China also (see Table 4) (ITIBMIC, 2004).

Table 4. Chinese Cement Production Ownership by Type, 2003.

Ownership Type	Number of Enterprises	Share of Total
State-owned enterprises	732	15%
Collective	1095	23%
Limited Cooperative	257	5%
Limited Company	266	6%
Private Company	1368	29%
Foreign-Funded*	180	4%
Others	882	18%
Total	**4780**	

Source: ITIBMIC, 2004.

* includes Hong Kong-funded, Macao-funded, and Taiwan-funded

3.4 China's Largest Cement Enterprises

China's cement enterprises, or companies, often own a number of cement production facilities. Table 5 provides a list of 15 of the largest cement enterprises and their 2005 cement production. The largest company by far is Anhui Conch Group. In 2004, when Anhui Conch produced nearly 38 Mt, it owned 26 dry process kiln lines and a limited number of wet kilns at 12 locations in Jiangsu, Zhejiang, Shanghai, Anhui, Jianxi, Fujian, Guangdong, and Guangxi provinces. Anhui expanded in 2005, adding a new plant in Hunan province and acquiring or constructing additional new facilities (Armstrong, 2006).

Table 5. China's Largest Cement Enterprises, 2005.

Enterprise Name	Cement Production 2005
Anhui Conch Group	55.96
Lafarge Shui On (Ruian)	16.99
Taini	16.30
Zhonglian	13.88
Shanshui	13.80
Huaxin	12.37
Sanshi	10.76
Tianshan	10.21
Jidong	9.89
Hongshi	8.83
Yani	8.32
Tongli	7.75
Yatai	6.79
Guangyu	5.43
Tianrui	5.23

Source: Cui, 2006a.

3.5 Chinese Government Policies Related to Cement Production

The National Development and Reform Commission's (NDRC's) 2004 *China Medium and Long Term Energy Conservation Plan* provides clear guidance related to desired technological improvements for the cement industry as well as policies that should be used to achieve the goals (NDRC, 2004a). The Plan explains that "by 2010, China's products as a whole are expected to reach or approach the advanced international level of the early 1990s…, of which large and medium sized enterprises are expected to reach the advanced international level at the beginning of the 21st century; and by 2020 China is expected to reach or approach the international advanced level." For cement, this means that the target for energy consumption for 2010 is 148 kilograms coal equivalent (kgce)/t (4.3 GJ/t) cement and for 2020 is 129 kgce/t (3.8 GJ/t). In comparison, China's 2004 overall cement intensity was 4.8 GJ/t while international best practice for dry process cement kilns is 3.0 GJ/t (final energy, not accounting for electricity generation, transmission, and distribution losses). The Plan specifically promotes the adoption of low temperature waste heat recovery technology for production of electricity in cement plants with production of 2,000 tonnes per day or greater, stating "we should every year establish 30 power generating units using medium and low temperature residual heat, and thus 3 million tce will be saved per year."

In 2006, NDRC further outlined goals for structural adjustment of the cement industry between 2005 and 2010. These goals include increase in the share of new dry process cement kiln production from 40% to 70%, closure of 250 Mt of inefficient production capacity, increase in scale and reduction of the total number of cement enterprises to 3500, annual production capacity of the top 10 cement enterprises should be at or above 35 Mt, energy consumption reduced from 130 kgce/t (3.8 GJ/t) clinker to 110 kgce/t (3.2 GJ/t) clinker, integrated energy consumption should decrease by 25% and emissions of air pollutants should decrease by 50% (CementChina.net, 2006a).

The government of China also has an official policy restricting construction and retrofits of shaft kilns in order to promote the use of larger, more efficient, and cleaner rotary kilns. The government has provided the following guidance (NDRC, 2004b; NDRC, 2004c; NDRC, 2005):

- No construction other than new dry process production line will be allowed.
- No shaft kiln reconstruction will be allowed.
- Any new construction and expansion of mechanical shaft kilns, dry-process without preheating rotary kilns, lepol kilns, and wet-process kilns should be strictly banned.
- Production licenses must not be granted to enterprises that violate the industry policies and establish new shaft kilns.
- Enterprises that operate without licenses must be shut down.
- Financial institutions should not offer loans to backward cement construction restricted and banned by the industry policies.
- For shaft kilns and other rotary kilns which are forbidden by state industry policies, the projects under construction shall be immediately stopped.

3.6 Recent Chinese Cement Market Trends

Recently, significant changes have been experienced in the Chinese cement market. Vertical shaft kilns, especially in eastern China, are beginning to be closed and production from these older, less efficient kilns dropped for the first time in 2004. Construction of the more efficient NSP/SP cement kilns has increased rapidly over the past few years. In 1999, 9.5% of total cement production in China was by NSP/SP kiln cement plants, but by 2005, production by these plants had grown to 473 Mt, or 44% of total cement production (Cui, 2006a). Older NSP/SP kilns, however, were less efficient than the newer, larger kilns currently being installed, so efficiency opportunities exist even for these type of kilns (Zeng, 2006).

Although China's cement industry was unprofitable in 1998 and 1999, this turned around in 2000 and the situation continued to improve in the following years. In 2001 and 2002, cement sales income increased 9% and 14.6%, respectively. Sales revenue of cement products in 2002 was 144 billion yuan, an increase of 17.23 billion yuan over 2001 and profits rose 55%. The greatest profits were made by the larger-sized enterprises (ITIBMIC, 2004). In 2003, average national cement prices reached an historic high of 300 yuan/t, with regional prices as high as 600 yuan/t. Prices continued to rise in 2004. Profits of the larger-sized cement manufacturing enterprises 10.884 billion yuan, an historic high. In the first quarter of 2004 a 3.05 billion yuan profit was realized, up by 63.95% comparing with the same period of the last year (ITIBMIC, 2004).

The National Development and Reform Commission reported that the industry continued to grow in 2005, with sales of 260.8 billion RMB (US$32.3 billion) and profits of 8.05 billion RMB (US$1 billion) (CementChina.net, 2006b). Industry experts expect that cement prices will rise slightly in 2006 and production costs will fall slightly, leading to a predicted increase in cement industry profit of 30% (CementChina.net 2006c). Even so, nearly 36% of Chinese cement producers lost money in 2005, compared to 28% in 2004 (China Economic Review, 2006).

In recent years, the Chinese cement industry has experienced domestic reorganization through mergers and acquisitions as well as an increase in foreign investment. Large cement companies such as the Conch Group, the Hua Xin Group, the Shan Shui Group, the Zhong Lian Group, Chongqing Teng Hui, and Hua Run Cement have all expanded through mergers and acquisitions in recent years (Zeng, 2004). Foreign investors such as Holcim, Lafarge, and Heidelberg Cement are acquiring shares in domestic facilities (Hong Liang, 2006) and Lafarge has built cement factories in Beijing, Chengdu, and Chongqing (Zeng, 2004). In August 2005, Lafarge and Shui On Construction and Materials Limited (SOCAM), the leading cement producer in Southwest China, announced a joint venture partnership to merge their cement operations in China. Lafarge also joined with RuiAn of Hong Kong to purchase Shuang Ma cement in Sichuan province (Cui, 2006a). In September 2005, Tangshan Jidong Cement signed agreements with Heidelberg Cement Holding Hong Kong, a wholly owned subsidiary of Heidelberg Cement, to form a 50-50 joint venture to produce and market cement in Shaanxi province of Northwest China (CementChina.net, 2006b). Zeng Xuemin, Secretary-General of the

China Cement Association, commenting on the foreign investment trends in China's cement industry explained that "Their speed of expansion has been spectacular. It is envisaged that the future environment for the major players will be very competitive" (Zeng, 2004).

In 2005, the World Bank's International Finance Corporation (IFC) disbursed a loan of 650 million RMB ($81 million) to China's largest cement company, Ahnui Conch Cement. The local currency loan was funded from the proceeds of IFC's 1.13 billion RMB Panda Bond, which was launched in the Chinese domestic market in late 2005. In addition, Ahnui Conch Cement also obtained a 800 million RMB ($100 million) loan from several foreign banks (Hong Liang, 2006). The IFC Environmental Review Summary reports that "the capital expenditure to be financed by the loan will include construction of new energy efficient clinker production lines and the installation of heat recovery power plants at all of its major cement kilns. These new heat recovery units will reduce the company's total electricity offtake from the national grid – which is largely generated by coal fired power plants – by 124 MW, thereby resulting in a significant offset of CO_2" (IFC, 2005).

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 6 provides the projected cement production included in China's National Plan for 2006 through 2010 and an estimate of the 2011 through 2014 production provided by the Institute of Technical Information for the Building Materials Industry (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 6. Projected Cement Production in China, 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.

At the same time, NDRC will continue to push for elimination of small and outdated cement production facilities, including requiring smaller projects of less than 2000 tonnes per day of production to apply to the State Council, instead of provincial authorities, for construction permission. Previous efforts related to this type of restructuring seem to have begun to have an effect in 2005, when about 35% of China's cement producers – mostly those with small production capacity and outdated technology – reported losses, up from 28% in 2004. Even so, the average scale of Chinese cement production facilities is about 175,000 tonnes, significantly lower than that of developed countries which is closer to 1 Mt per year, indicating continued potential for closure of smaller facilities and upgrading existing facilities (CementChina.net, 2006b).

4. TECHNICAL ANALYSIS

4.1 China's Cement Sector Energy Consumption and Greenhouse Gas Emissions

Cement production is a highly energy-intensive process. The kiln, which predominantly burns coal, is the major energy-consuming component of the cement-making process. Most electricity is consumed in the grinding of the raw materials and finished cement, but additional electricity is also used for conveyor belts and packing of cement. The production of cement results in the emission of carbon dioxide from both the consumption of fuels (primarily in the kiln) and from the calcination of limestone.

Table 7 provides an estimate of China's cement sector energy consumption and carbon dioxide emissions by kiln type for 2004. The largest total energy consumption and carbon dioxide emissions are found in the mechanical shaft kilns, followed by the advanced NSP/SP kilns.

Table 7. China Cement Production Total Energy Consumption and Carbon Dioxide Emissions, 2004.

Kiln Type	Total Final Energy (PJ)	Total Primary Energy (PJ)	Carbon Dioxide Emissions (MtC)
Advanced NSP/SP kilns	920	1,129	58.01
Older and smaller NSP/SP kilns	342	408	19.21
Cyclone Pre-heater kiln	4	5	0.24
Shaft pre-heater kiln	15	17	0.80
Lepol kiln	18	20	0.86
Waste heat power generation kiln	82	95	4.38
Wet process kiln	241	270	11.66
Dry process hollow kiln	29	30	1.24
Semi-dry process kilns	35	40	1.81
All Rotary Kilns	***1685***	***2013***	***98.21***
Improved shaft kilns	752	876	41.76
Mechanical shaft kilns	1,958	2,250	102.88
Ordinary shaft kilns	313	352	15.00
All Shaft Kilns	***3022***	***3477***	***159.64***
Total	***4708***	***5491***	***257.85***

Sources for kiln energy intensities: ITIBMIC, 2004; Cui and Wang, 2005. Assumed clinker-to-cement ratio of 90% for rotary kilns and 95% for shaft kilns. Final energy calculated by multiplying kiln fuel energy and electricity intensities for each kiln type by 2004 production by kiln type. Primary energy calculated by multiplying electricity consumption for each kiln type by 3.03 to account for generation, transmission, and distribution losses. Carbon dioxide emissions calculated by multiplying fuel energy consumption by 0.0258 tC/GJ, multiplying final electricity consumption by 0.23 kgC/kWh, and multiplying total clinker production by 0.136 tC/t clinker to account for process emissions.

4.2 Energy Efficiency 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 section focuses on technologies and measures for improving the energy efficiency of the kiln itself, as well as product and feedstock changes which will also result in reduction of fuel consumed in the kiln. This section provides detailed estimates on cement kiln energy-efficiency technologies and measures, their costs, and potential for implementation. This information is adapted from a recent report (Worrell and Galitsky, 2004) that focused on implementation of these measures in the United States.

In addition, in the text below, we describe case studies where measures have been implemented in China, and where data are available, what the costs and savings would be upon implementation. We note whether the technologies are available in China as domestic or foreign imports, and correspondingly, what costs and savings would be. For some domestically-produced technologies and measures, although the cost can be much lower, the performance of a domestic technology might be inferior in energy efficiency to imported technologies. There are a number of domestic cement equipment manufacturers in China (ITIBMIC, 2004). Some foreign companies have set up branches in China to provide equipment, while for other technologies, some components are imported but then assembled in China, potentially with other parts manufactured domestically (Wang, 2006). For example, the burner for the advanced precalciner kiln (see description, below) is imported from France but assembled in China. Wang (2006) also notes that several companies provide optimized information technology for energy management and process control, such as ABB or the Chinese software company Yun Tian.

The analysis of cement kiln energy-efficiency opportunities is divided into technologies and measures that are applicable to all kilns, those that are only applicable to rotary kilns, those that are only applicable to vertical shaft kilns (VSKs), and finally, product and feedstock changes that will reduce energy consumption for clinker making. Most measures reduce fuel consumption in the kiln, which is the focus of this report. Some measures reduce kiln fuel consumption while also reducing electricity consumption. A few technologies and measures applicable to cement kilns only reduce electricity consumption. While these measures are not the focus of this report, they have been included in order to provide a comprehensive overview of the energy-efficiency opportunities for cement kilns. Details on each energy-efficiency technology and measure, including a description, case studies, and data are described below.

4.2.1 All Kiln Types

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 7 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 (CO_2) emissions reductions, and the lifetime associated with each of these measures.

Table 8. 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 an average of 940 kcal/kg clinker (3.9 GJ/t clinker) to an average of 810 kcal/kg clinker (3.4 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, 2006b). China also produces medium and smaller refractories but the energy efficiency is poorer than those made by the leading international companies (Cui, 2006b).

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, 2006b).

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, 2006).

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 at 8 months, even with typically very low coal prices in South Africa (Martin & McGarel, 2001).

Additional process control systems include the use of on-line analyzers that permit operators to instantaneously determine the chemical composition of raw materials being processed, 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 at 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, 2001).

Process control of the clinker cooler can help to improve heat recovery, material throughput, improved control of free lime content in the clinker and reduced 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 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 (2006b) 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)[3]. ASDs are currently being made in China, although many of the parts and instrumentation are still being imported from Germany and/or Japan (Cui, 2006b).

4.2.2 Rotary Kilns

For rotary kilns, an existing preheater kiln may be converted to a multi-stage preheater/precalciner kiln by adding a precalciner and extra preheaters, 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 9 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

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[3] These ASDs likely included other motors besides the kiln fan motors.

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).

Table 9. 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

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 (Fraily & Happ, 2001).

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 at $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 (2006b) 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 does not last as long. Most companies are adopting domestic technologies (Cui, 2006b). Domestic technology, however, is not available for kiln sizes over 5000 tonne per day (Wang, 2006).

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 at 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, precalciner 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 preheater, precalciner 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 at 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, 2006b). 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 optimise the shape of the flame, the mixing of combustion air and fuel and reducing the use of excess air. Various approaches have been developed. One technique developed in the U.K. for flame control resulted in fuel savings of 2 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, 1997). A second demonstration project at the Ash Grove plant in the U.S. (Durkee, Oregon) found fuel savings between 2.7% and 5.7% with increases in output between 5 and 9% (CADDET, 1997; Vidergar, 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 at $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 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) (Philips Kiln Services, 2001). The payback period for improved maintenance of kiln seals is estimated at 6 months or less (Canadian Lime Institute, 2001). This technology is produced and available domestically in China (Cui, 2006b).

Low Temperature Heat Recovery for Power Generation[4]

Despite government 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, 2006b). Even many large-scale rotary kilns built after 2003 do not use this technology.

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[4] 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 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).

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, 2005).

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.

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 (2006b) most recently reported domestic technology could produce 35kWh/t of clinker while Japanese technology now produces 45 kWh/t of clinker. 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.[5] Cogeneration systems can either be direct gas turbines that utilize the waste heat (top cycle), or the installation of a waste heat boiler system that runs a steam turbine system (bottom cycle). This report focuses on the steam turbine system since these systems have been installed in many plants worldwide and have proven to be economic (Steinbliss, 1990; Jaccard and Willis, 1996; Neto, 1990). Heat recovery has limited application for plants with in-line raw mills, as the heat in the kiln exhaust is used for raw material drying. While electrical efficiencies are still relatively low (18%), based on several case studies power generation may vary between 11 and 25 kWh/t clinker (Scheur & 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 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, 2006b).

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[5] 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.

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%.

4.2.3 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 9 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[6] 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).

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.

Table 10. 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	NA	NA	NA	NA	NA	NA	NA

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

improvements							

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 $50/ton 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.

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, 2006b).

4.2.4 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 11 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 11. Product and Feedstock Changes to Improve the Energy Efficiency of Clinker Production.

	Capital	O & M	Payback	Fuel	Electric	CO_2

	Costs ($/t)	Costs ($/t)	Period (years)	Savings (GJ/t)	Savings (kWh/t)[1]	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, and 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 cement was introduced to reduce production costs for cement (especially energy costs), expand capacity without extensive capital costs, to reduce emissions from the kiln. In Europe a common standard has been developed for 25 types of cement (using different compositions for different applications). The European standard allows wider applications of additives. Many other countries around the world use blended cement. 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 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.

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 12 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 12. 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 at 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[7], the increased electricity costs for (finer) grinding, the reduced fuel costs for clinker production and electricity costs for raw material grinding and kiln drives, as well as the reduced handling and mining costs. These costs will vary by location, and would need to be assessed on the basis of individual plants. An increase in electricity consumption of 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) and copper tailing high content iron sulphide 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

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[7] 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.

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, 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 (Cui, 2006b).

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%.

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. In Europe, some kilns use up to 50% biomass like sewage sludge and animal wastes and some are paid to use waste fuel, giving them negative fuel costs. 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, 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 to utilize in its kilns (Wang, 2006). Other plants are utilizing wastes but the amounts are very small (Wang, 2006).

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 11, 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 at $1.1/annual tonne clinker for a storage facility for the waste-derived fuels and retrofit of the burner (if needed).

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, 2006b).

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 110 and 420 pounds of slag per ton of steel (on average 232 lbs/ton) (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 at 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, 2006b).

4.3 Pollution Control Opportunities for Clinker Production

[more information requested]

Pollution control strategies for controlling dust, particulate matter, dioxins and furans include adding baghouses or electrostatic precipitators (ESP). Table 13 provides information on the initial capital costs, the operations and maintenance (O&M) costs, and the lifetime associated with each of these measures.

Table 13. Pollution Control Measures for Clinker Production.

	Capital Costs ($/t)	O & M Costs ($/t)	Lifetime (years)
Baghouses			
Electrostatic Precipitators			

Baghouses

Baghouses require replacement of the bag about every 2 to 3 years. Baghouses cannot be operated at temperatures above 350°C. ESPs can be replaced by a baghouse but it is very expensive to do as a retrofit.

Electrostatic precipitators

Electrostatic precipitators are used to remove particulate matter. ESPs have been used in Russia, Ukraine and Kazakhstan in power plants to remove PM at costs of about $11.00/t of PM, which includes all costs incurred and in-kind contributions from plants (Tumanowskiy et al., 2005). These costs are much less than the world standard of $125-150/t of PM captured (Tumanowskiy et al., 2005).

5. ECONOMIC ANALYSIS

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 any identified operating and maintenance costs combined with the energy savings,[8] simple payback periods were calculated. Fourteen of these technologies and measures have simple payback periods of three years or less.

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 savings of 144 tC to 94,444 tC, respectively, for these improvements. At the current price of carbon ($9/tC) (Point Carbon, 2006), carbon emissions credits of about $1,300 to $850,000 would be realized on top of the energy savings for these measures, assuming the Clean Development Mechanism additionality test could be met.

Of course, the costs and savings documented in this report will vary for any specific situation. The information provided here is based on case study examples as reported in the open literature (no confidential information has been used) for installations in various countries around the world. Where possible, China-specific information has been provided. However, the reader is cautioned that the information provided should be used as indicative, not definitive, and further detailed, plant-specific analyses should be performed before making investment decisions.

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

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