United States Environmental Protection Agency

Office of Air and Radiation **October 2010**

AVAILABLE AND EMERGING TECHNOLOGIES FOR REDUCING GREENHOUSE GAS EMISSIONS FROM THE PORTLAND CEMENT INDUSTRY

Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Portland Cement Industry

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October 2010

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Abbreviations and Acronyms

€	euro
°C	degrees Celsius
°F	degrees Fahrenheit
AC	alternating current
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
ASU	Air Separation Unit
BACT	best available control technology
Btu	British thermal unit
C_3S	tricalcium silicate
CaO	calcium oxide
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
De-NO_x	a NO_x removal process
DOE	U.S. Department of Energy
EnMS	Energy Management Systems
EPA	U.S. Environmental Protection Agency
EPI	Energy Performance Indicator
ft	feet
ft^3	cubic foot
GHG	greenhouse gas
GJ	gigaJoule
Hr	hour
ISO	International Standards Organization
Kcal	kilocalories
Kg	kilogram
Kt	kilotonnes
kWh	kilowatt hour
LD	Long dry
M	meter(s)
MMBtu	million British thermal units

Abbreviations and Acronyms (continued)

MEA	Monoethanolamine
MJ	megaJoule
MW	megawatts
Nm^3	normal cubic meter
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
ORC	organic Rankin cycle
PH	preheater
PH/PC	preheater/precalciner
PM	particulate matter
PSD	prevention of significant deterioration
scf	standard cubic feet
SO_2	sulfur dioxide
TBD	To be determined
tpy	tons per year
UK	United Kingdom
yr	year

I. Introduction

This document is one of several white papers that summarize readily available information on control techniques and measures to mitigate greenhouse gas (GHG) emissions from specific industrial sectors. These white papers are solely intended to provide basic information on GHG control technologies and reduction measures in order to assist States and local air pollution control agencies, tribal authorities, and regulated entities in implementing technologies or measures to reduce GHGs under the Clean Air Act, particularly in permitting under the prevention of significant deterioration (PSD) program and the assessment of best available control technology (BACT). These white papers do not set policy, standards or otherwise establish any binding requirements; such requirements are contained in the applicable EPA regulations and approved state implementation plans.

II. Purpose of this Document

This document provides information on control techniques and measures that are available to mitigate greenhouse gas (GHG) emissions from the cement manufacturing sector at this time. Because the primary GHG emitted by the cement industry is carbon dioxide (CO_2), the control technologies and measures presented in this document focus on this pollutant. While a large number of available technologies are discussed here, this paper does not necessarily represent all potentially available technologies or measures that that may be considered for any given source for the purposes of reducing its GHG emissions. For example, controls that are applied to other industrial source categories with exhaust streams similar to the cement manufacturing sector may be available through “technology transfer” or new technologies may be developed for use in this sector.

The information presented in this document does not represent U.S. EPA endorsement of any particular control strategy. As such, it should not be construed as EPA approval of a particular control technology or measure, or of the emissions reductions that could be achieved by a particular unit or source under review.

III. Description of the Cement Manufacturing Process

Cement is a finely ground powder which, when mixed with water, forms a hardening paste of calcium silicate hydrates and calcium aluminate hydrates. Cement is used in mortar (to bind together bricks or stones) and concrete (bulk rock-like building material made from cement, aggregate, sand, and water). By modifying the raw material mix and the temperatures utilized in manufacturing, compositional variations can be achieved to produce cements with different properties. In the U.S., the different varieties of cement are denoted per the American Society for Testing and Materials (ASTM) Specification C-150.

Cement is produced from raw materials such as limestone, chalk, shale, clay, and sand. These raw materials are quarried, crushed, finely ground, and blended to the correct chemical composition. Small quantities of iron ore, alumina, and other minerals may be added to adjust the raw material composition. The fine raw material is fed into a large rotary kiln (cylindrical furnace) which rotates while the contents are heated to extremely high temperatures. The high temperature causes the raw material to react and form a hard nodular material called "clinker". Clinker is cooled and ground with approximately 5 percent gypsum and other minor additives to produce Portland cement.

The heart of clinker production is the rotary kiln where the pyroprocessing stage occurs. The rotary kiln is approximately 20 to 25 feet (ft) in diameter and from 150 ft to well over 300 ft long; the kiln is set at a slight incline and rotates one to three times per minute. The kiln is most often fired at the lower end (sometimes, mid-kiln firing is used and new units incorporate preheating as well as precalcining), and the raw materials are loaded at the upper end and move toward the flame as the kiln rotates. The materials reach temperatures of 2500°F to well above 3000°F in the kiln. Rotary kilns are divided into two groups, dry-process and wet-process, depending on how the raw materials are prepared.

In wet-process kilns, raw materials are fed into the kiln as a slurry with a moisture content of 30 to 40 percent. To evaporate the water contained in the feedstock, a wet-process kiln requires additional length (in comparison to a dry kiln). Additionally, to evaporate the water contained in the slurry, a wet kiln consumes nearly 33 percent more kiln energy when compared to a dry kiln. Wet-process kilns tend to be older operations as compared to dry-processes where raw materials are fed into the process as a dry powder. There are three major variations of dry-process kilns in operation in the U.S.: long dry (LD) kilns, preheater (PH) kilns, and preheater/precalciner (PH/PC) kilns. In PH kilns and PH/PC kilns, the early stages of pyroprocessing occur before the materials enter the rotary kiln. PH and PH/PC kilns tend to have higher production capacities and greater fuel efficiency compared to other types of cement kilns. Table 1 shows typical average required heat input by cement kiln type.

Table 1. Typical Average Heat Input by Cement Kiln Type

Kiln Type	Heat Input, MMBtu/ton of cement
Wet	5.5
Long Dry	4.1
Preheater	3.5
Preheater/Precalciner	3.1

Source: EPA, 2007a (Table 3-3)

Three important processes occur with the raw material mixture during pyroprocessing. First, all moisture is driven from the materials. Second, the calcium carbonate in limestone dissociates into CO2 and calcium oxide (free lime); this process is called calcination. Third, the lime and other minerals in the raw materials react to form calcium silicates and calcium aluminates, which are the main components of clinker. This third step is known as clinkering or sintering. The formation of clinker concludes the pyroprocessing stage.

Once the clinker is formed in the rotary kiln, it is cooled rapidly to minimize the formation of a glass phase and ensure the maximum yield of alite (tricalcium silicate) formation, an important component for the hardening properties of cement. The main cooling technologies are either the grate cooler or the tube or planetary cooler. In the grate cooler, the clinker is transported over a reciprocating grate through which air flows perpendicular to the flow of clinker. In the planetary cooler (a series of tubes surrounding the discharge end of the rotary kiln), the clinker is cooled in a counter-current air stream. Reciprocating type grate coolers can also be used to cool the clinker. The cooling air is used as secondary combustion air for the kiln to improve efficiency since the cooling air has been preheated during the process of cooling the clinker.

After cooling, the clinker can be stored in the clinker dome, silos, bins, or outside in storage piles. The material handling equipment used to transport clinker from the clinker coolers to storage and then to the finish mill is similar to that used to transport raw materials (e.g. belt conveyors, deep bucket conveyors, and bucket elevators). To produce powdered cement, the nodules of clinker are ground to the consistency of powder. Grinding of clinker, together with additions of approximately 5 percent gypsum to control the setting properties of the cement can be done in ball mills, ball mills in combination with roller presses, roller mills, or roller presses. While vertical roller mills are feasible, they have not found wide acceptance in the U.S. Coarse material is separated in a classifier that is re-circulated and returned to the mill for additional grinding to ensure a uniform surface area of the final product. (Coito et al., 2005, and others.)

Figure 1 presents a diagram of the cement manufacturing process using a rotary kiln and cyclone preheater configuration. The schematic for a rotary kiln and precalciner configuration is very similar to that shown in Figure 1, with a calciner vessel located between the rotary kiln and cyclone preheater. Combustion for heat generation may occur in the riser to the preheater, in the calciner and/or in the kiln. These combustion processes are one of two primary sources of GHG emissions, the second being the calcinations reaction that occurs in the kiln. These GHG sources are the focus of the control measures presented in the remainder of this document.

Total combustion and process-related GHG emissions from 2006 cement production, including methane (CH_4)and nitrous oxide (N_2O) emissions from fossil fuel combustion based on plant-specific characteristics were estimated to be 95.5 tons (86.8 million metric tons) of CO_2 equivalents (MTonne CO_2e). (EPA, 2007b) This is equivalent to 0.98 tons of CO_2e per ton of clinker, of which 0.46 tons are attributable to fuel combustion. Combustion emissions include CO_2, N_2O and CH_4 emissions that result from the combustion of carbon-based fuels in the cement kiln and other onsite combustion equipment. The cement kiln is the most significant of these combustion units and typically is fueled with coal. Other fossil fuels are generally too expensive to be used for kiln fuel; however carbon-based waste materials (e.g., solvents, oils, and waste tires) are commonly combusted in the kilns to dispose of the waste, and make use of their energy content. The other sources of CO2 emissions stemming from cement manufacturing operations include transportation equipment used in the mining and transport of raw and finished materials and the fuels required for operating the process. The direct CO_2 emission intensity of fuels depends on the carbon content of the fuel which varies by type of fuel and further may vary within a given fuel type. The emission intensity of coals, for example, will vary depending on its geologic source. Table 2 shows the CO_2 emission intensity in pounds per million British Thermal Units (lb/MMBtu) for fuels combusted at cement kilns in the United States.

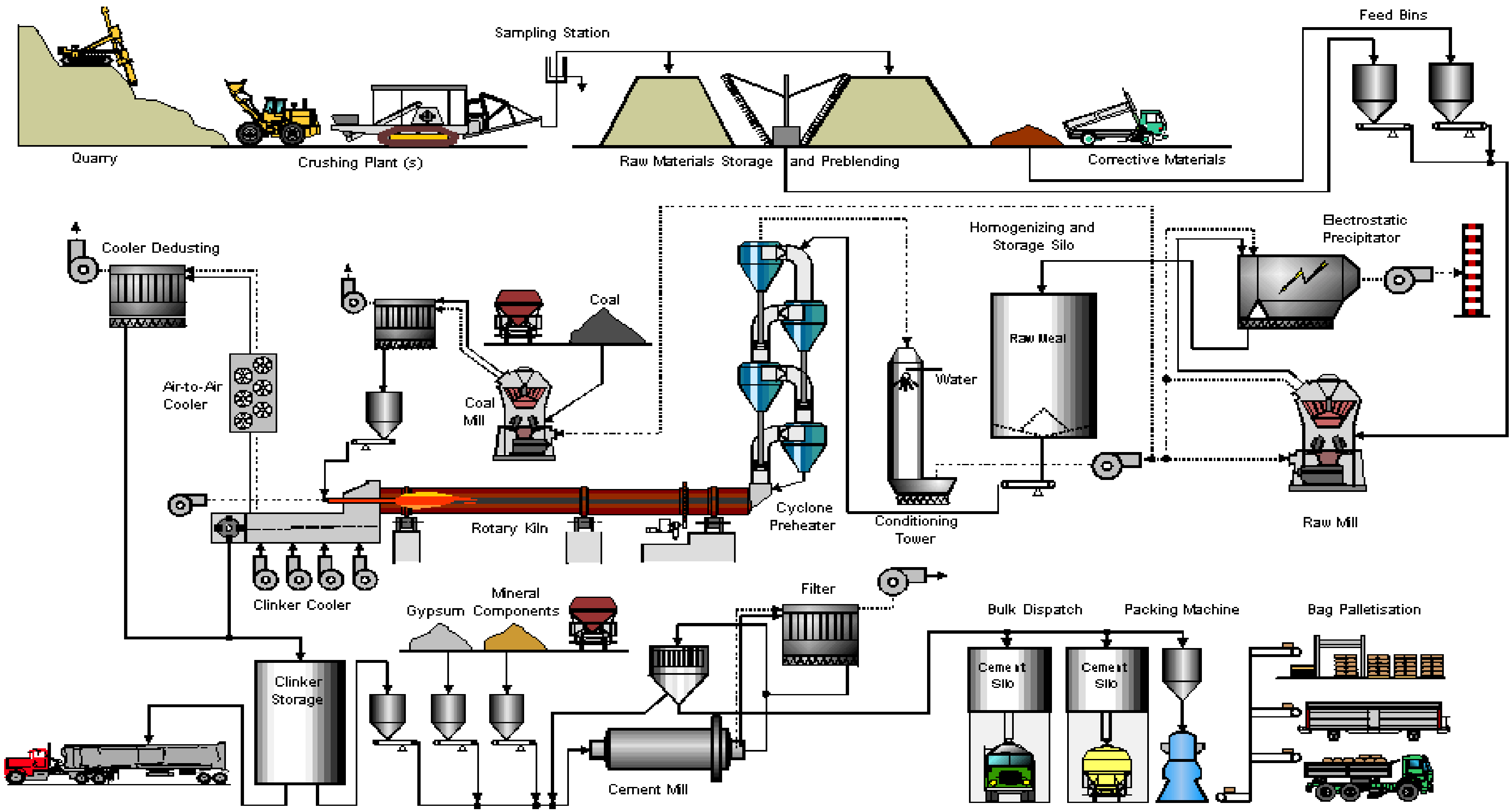

Figure 1. Diagram for Cement Manufacturing Preheater Process

Source: CEMBUREAU, 1999

Table 2. CO_2 Emission Intensity (lb CO_2/MMBtu) for Fuels Combusted at Cement Kilns

CO2 Emission Intensity (lb/MMBtu)					
Natural Gas	Heavy Fuel Oil	Western Sub-bituminous Coal[1]	Tires	Eastern Bituminous Coal[2]	Petroleum Coke
105.02	169.32	186.83	187.44	199.52	212.56

[1] Origin - Rosemont Powder River Basin
[2] Origin - Logan, West Virginia
Source: Staudt, 2008a

Process-related CO_2 emissions from cement production are the second largest source of industrial CO_2 emissions in the United States. (EPA, 2008) The cement production process comprises the following two steps: (i) clinker production and (ii) finish grinding. Essentially all GHG emissions from cement manufacturing are CO2 emissions from clinker production. There are no CO_2 emissions from the finish grinding process, during which clinker is ground finely with gypsum and other materials to produce cement. However, CO2 emissions are associated with the electric power consumed by plant equipment such as the grinders.

IV. Summary of Control Measures

This document addresses the cement manufacturing sector and summarizes readily available information on control techniques and measures to mitigate greenhouse gas emissions from this sector. Because the primary GHG emitted by the cement industry is CO2, the control technologies and measures presented here focus on this pollutant. In general, emissions of CO2 from the cement manufacturing sector can be reduced by:

- Improving the energy efficiency of the process,
- Shifting to a more energy efficient process (e.g. from wet and long dry to preheater/precalciner process),
- Replacing high carbon fuels with low carbon fuels,
- Applying lower clinker/cement ratio (increasing the ratio additives/cement): blended cements, and/or
- Removing CO_2 from the flue gases.

These options will be discussed in the remainder of this document.

Much of the original data used in this document were in different units. . To facilitate comparisons of costs and efficiencies for the various control measures, units were converted to English or International System of Units (SI_ units when possible. Also, many measures were expressed in units per ton of raw feed to the kiln, clinker production or cement production. Again for the sake of comparison, values were converted to values per short ton of cement. Conversions used in this process were as follows: 1.65 tons of raw feed/ton of clinker, 0.92 tons of clinker/ton of cement, and 1.52 tons of raw feed/ton of cement. Costs of control measures expressed in euros (€) were converted to dollars ($) assuming $1.50/€.

Table 3 summarizes the CO_2 control measures presented in this document. Where available, the table includes the emission reduction potential, energy savings, costs, and feasibility of each measure.

Table 3. Portland Cement Manufacturing Sector– Summary of Greenhouse Gas Control Measures[a, b]

Control Technology	Emission Reduction	Energy Savings	Capital Costs	Operating Costs	Applicability	Demonstrated in Practice?	Other factors
Energy Efficiency Improvements in Raw Material Preparation							
Switch from pneumatic to mechanical raw material transport	Calculated from energy savings	2.9 kWh/ton cement	$4.1/annual ton cement capacity	NA	New and Existing Facilities with LD, PH, PH/PC kilns	Yes	
Use of belt conveyors and bucket elevators instead of pneumatics	Calculated from energy savings	2.5 kWh/ton cement	$3.43/ton cement capacity	Reduction of $0.17/ton cement	New and Existing Facilities	Yes	
Convert raw meal blending silo to gravity-type homogenizing	Calculated from energy savings	1.4-3.5 kWh/ton cement	$5.0/ton cement Capacity (silo retrofit)	NA	New and Existing Facilities	Yes	
Improvements in raw material blending	Calculated from energy savings	1.0 kWh/ton cement	$2.5/ton cement capacity	Increase of $0.02/ton cement	New and Existing Facilities with LD, PH, PH/PC kilns	Yes	May increase production by up to 5%
Replace ball mills with high efficiency roller mills	Calculated from energy savings	9-11 kWh/ton cement	$7.6/ton cement capacity	NA	New and Existing Facilities	Yes	
Replace ball mills with vertical roller mills	14-22 lb CO_2/ton cement	11-15 kWh/ton cement	$33/ton cement capacity	Reduction of $0.17/ton cement	New and Existing Facilities	Yes	
High Efficiency Classifiers	4-6 lb CO_2/ton cement	3.8-5.2 kWh/ton cement	$3/annual ton cement capacity	NA	New and Existing Facilities	Yes	May increase grinding mill capacity

Control Technology	Emission Reduction	Energy Savings	Capital Costs	Operating Costs	Applicability	Demonstrated in Practice?	Other factors
Roller mill for fuel (coal) preparation instead of impact or tube mill	Calculated from energy savings	7-10 kWh/ton coal	Cost of roller mill is higher than impact or tube mill	Reduction of as much as 20-50%	New and Existing Facilities	Yes	
Energy Efficiency Improvements in Clinker Production							
Process control and management systems	7-33 lb CO_2/ton cement and 1.3 lb CO_2/ton cement from electricity usage reduction	2.5-5% or 42-167 MJ/ton cement and electricity savings of 1 kWh/ton cement	$0.3/annual ton cement capacity	NA	New and Existing Facilities. All kilns.	Yes	
Replacement of kiln seals	Calculated from energy savings	0.4% or 0.01 MMBtu/ton cement	NA	NA	New and Existing Facilities. All kilns.	Yes	
Kiln combustion system improvements	Calculated from energy savings	2-10% reduction in fuel usage	$0.8/annual ton cement capacity	NA	New and Existing Facilities. All kilns.	Yes	May result in up to 10% increase in kiln output
Fluxes and mineralizers to reduce energy demand	9-30 lb CO_2/ton cement and 0-2 lb/ton cement from electricity usage reduction	42-150 MJ/ton cement	NA	Fuel savings may be offset by cost of fluxes and mineralizers	New and Existing Facilities. All kilns.	Yes	
Kiln/preheater insulation (internal)	Calculated from energy savings	0.1-0.31 MMBtu/ton cement	$0.21/annual ton cement capacity	NA	New and Existing PH and PH/PC kilns	Yes	
Kiln/preheater insulation (external)	Calculated from energy savings	17 Btu/ton cement	$0.25/ton cement capacity	NA	New and Existing PH and PH/PC kilns	Yes	
Refractory material selection	Calculated from energy savings	49,800 Btu/ton cement	$0.50/ton cement capacity	NA	All kilns	Yes	

Control Technology	Emission Reduction	Energy Savings	Capital Costs	Operating Costs	Applicability	Demonstrated in Practice?	Other factors
Replacement of planetary and travelling grate cooler with reciprocating grate cooler	Reduction of17-52 lbCO_2/ton cement, but increase of 2-6 lb/ton cement from increased electricity use	Reduce energy consumption by 8% or 84-251 MJ/ton cement; increase electricity use by 1-5 kWh/ton cement	NA	NA	New and Existing kilns with capacity > 500 tonnes/day	Yes	
Heat recovery for power – cogeneration	Calculated from energy savings	Produce 7-20 kWh/ton cement	$2-4/annual ton cement capacity	$0.2-0.3/annual ton cement capacity	LD kilns	Yes	
Suspension preheater low pressure drop cyclones	Up to 2 lb CO_2/ton cement	0.5-0.6 kWh/ton cement per 50 mm water column pressure reduction	$2.5-2.9/annual ton cement capacity	NA	New and retrofitting PH and PH/PC kilns	Yes	May result in up to 3% production increase
Multistage preheater	Calculated from energy savings	0.4 MMBtu/ton cement	$12.8-34/annual ton cement capacity	NA	New and retrofitting PH and PH/PC kilns	Yes	May increase kiln capacity by up to 50%
Conversion from long dry kiln to preheater/ precalciner kiln	50-460 lb CO_2/ton cement	1.1 MMBtu/ton cement	$7.9-96/ annual ton cement capacity	Decrease by $0.08/ton cement	LD kilns	Yes	Actual values are highly site specific
Kiln drive efficiency improvements	Calculated from energy savings	0.5 kWh/ton cement	Increased by about 6%	Reduced power cost for kiln drive by 2-8%	New and Existing Facilities.	Yes	
Adjustable speed drive for kiln fan	Calculated from energy savings	5 kWh/ton cement	NA	NA	New and Existing Facilities.	Yes	

Control Technology	Emission Reduction	Energy Savings	Capital Costs	Operating Costs	Applicability	Demonstrated in Practice?	Other factors
Oxygen enrichment	18-37 lb CO_2/ton cement; however, this may be completely offset by increased electricity consumption	NA	NA	NA	All Kilns	Yes	May increase production by 3-7%. May increase NO_x emissions.
Mid kiln firing	Calculated from the emission factor of tires compared to fuel being replaced	NA	NA	NA	Existing Wet, LD kilns	Yes	Burning tires may result in lower NO_x emissions
Air mixing technology	Calculated from fuel reduction	Improves combustion efficiency reducing fuel use	$520,000	Increases electricity usage by 0.23 kWh/ton cement	TBD	Yes	Likely reduces CO, NO_x, and SO_2 emissions
Preheater riser duct firing					Ph and PH/PC kilns		
Energy Efficiency Improvements in Finish Grinding							
Improved ball mills	Calculated from energy savings	6-25 kWh/ton cement	$2.3-7.3/annual ton cement capacity; or $35/ton cement capacity for a vertical roller mill	May reduce by 30-40%, but vertical roller mill may increase costs by $0.17/ton cement	Existing and New Facilities. All kilns.	Yes	

Control Technology	Emission Reduction	Energy Savings	Capital Costs	Operating Costs	Applicability	Demonstrated in Practice?	Other factors
High efficiency classifiers	Calculated from energy savings	1.7-2.3 kWh/ton cement, but could be as high as 6 kWh/ton cement	$2/annual ton cement	$0.045/ton cement	Existing and New Facilities. All kilns.	Yes	May increase production by up to 25%
Energy Efficiency Improvements in Facility Operations							
High efficiency motors	Calculated from energy savings	5%, or about 5 kWh/ton clinker	$0.67/ton cement	No change	Existing and New Facilities. All kilns.	Yes	
Variable speed drives	3-10 lb CO_2/ton cement	3-8 kWh/ton cement	NA	NA	Existing and New Facilities. All kilns.	Yes	Capital and operating cost savings are highly site specific
High efficiency fans	Calculated from energy savings	0.9 kWh/ton cement	$0.46/ton cement	NA	Existing and New Facilities. All kilns.	Yes	
Optimization of compressed air systems	Calculated from energy savings	Up to 20%	NA	NA	Existing and New Facilities. All kilns.	Yes	
Lighting system efficiency improvements	Calculated from energy savings	12-50% depending on specific changes made	NA	NA	Existing and New Facilities. All kilns.	Yes	

Control Technology	Emission Reduction	Energy Savings	Capital Costs	Operating Costs	Applicability	Demonstrated in Practice?	Other factors
			Raw Material Substitution				
Decarbonated feedstocks (steel slag or fly ash)	0.02-0.51 ton CO_2/ton material	1.12 MMBtu/ton cement; or 0.07-1.59 MMBtu/ton material	$0.75/ton cement for steel slag fed into kiln without grinding	Increased by $0.08/ton cement for steel slag fed into kiln without grinding	All Facilities	Yes	Energy savings may be offset by 0.08 MBtu/ton to dry feedstock
Calcereous oil shale	0.009 lb CO_2/ton cement	0.07 MMBtu/ton cement	$1/ton cement when replacing 8% of raw meal	Increase by $0.08/ton cement when replacing 8% of raw meal	All Facilities	Yes	
			Blended Cements				
Cementitious materials	200-860 lb CO_2/ton cement for cement with 30-70% blast furnace slag	380-1710MJ/ton cement for cement with 30-70% blast furnace slag	NA	NA	All Facilities	Yes	In general, the use of 1 ton of material reduces emissions by the amount generated to produce 1 ton clinker
Pozzolanic materials	100-280 lb CO_2/ton cement	200-500 MJ/ton cement	NA	NA	All Facilities	Yes	Cost savings of cement replaced must be balanced against the cost of the material
			Carbon Capture				
Calera process	90%, but varies with specific application	Parasitic load of 10-20 of the power plant	$950/kW for coal-fired power plant	NA	TBD	Pilot testing	Pilot testing is on power plants

Control Technology	Emission Reduction	Energy Savings	Capital Costs	Operating Costs	Applicability	Demonstrated in Practice?	Other factors
Oxy-combustion	1000-1600 lb CO_2/ton cement, but increased electricity usage could generate 110-150 CO_2/ton cement	Overall energy requirements decrease by 75-84 MJ/ton cement, but electricity requirements increase by 92-96 kWh/ton cement	NA	NA	TBD	No	No installations at cement plants; many technical issues to overcome
Post-combustion solvent capture and stripping	Up to 95%	NA	NA	NA	TBD	Yes, but not at cement plants	
Post-combustion membranes	Up to 80%	NA	NA	NA	TBD	No, currently in research stage	
Superheated CaO	Up to 43%	NA	NA	NA	TBD	No, currently in research stage	
Other Control Measures							
Fuel switching	18% for switching from coal to heavy oil; 40% for switching from coal to natural gas	NA	NA	NA	All Facilities	Yes	Does not affect emissions from calcination reaction
Alternative fuels – biomass	Depends on emission factor of biomass compared to fuel being replaced	NA	NA	NA	All Facilities	Certain biomass materials have been used	

Control Technology	Emission Reduction	Energy Savings	Capital Costs	Operating Costs	Applicability	Demonstrated in Practice?	Other factors
Hybrid solar plants	Equivalent to emissions that would have been generated by fuel replaced	NA	NA	NA	TBD	No, currently in research stage	
Syngas co-production	Up to 650 lb CO_2/ton cement	NA	NA	NA	TBD	No, but has been applied to smaller streams	
Power plant/cement plant carbonate looping	830-1300 lb CO_2/ton cement	NA	NA	NA	TBD	No, currently in research stage	

[a] References for the information in this table are contained in the subsequent discussions of control measures.
[b] TBD = to be determined; NA = data not available at this time

V. Energy Efficiency Improvements to Reduce GHG Emissions

The cement manufacturing process is highly energy intensive. Thus, a primary option to reduce GHG emissions is to improve energy efficiency. Industrial energy efficiency can be greatly enhanced by effective management of the energy used by operations and processes. U.S. EPA's ENERGY STAR Program works with hundreds of U.S. manufacturers and has seen that companies and sites with stronger energy management programs gain greater improvements in energy efficiency than those that lack procedures and management practices focused on continuous improvement of energy performance.

Energy Management Systems (EMSs) provide a framework to manage energy and promote continuous improvement. The EMSs provides structure for an energy program. EMSs establish assessment, planning, and evaluation procedures which are critical for actually realizing and sustaining the potential energy efficiency gains of new technologies or operational changes. Approaches to implementing EnMS vary. EPA's ENERGY STAR Guidelines for Energy Management are available for public use on the web and provide extensive guidance (see: www.energystar.gov/guidelines). Alternatively, energy management standards are available for purchase from ANSI (ANSI MSE 2001:200) and in the future from ISO (ISO 50001).

For nearly 10 years, the U.S. EPA's ENERGY STAR Program has promoted an energy management system approach. The U.S. EPA's ENERGY STAR Program (www.energystar.gov/industry) and U.S. Department of Energy's (DOE's) Industrial Technology Program (www.energy.gov/energyefficiency) have led industry specific energy efficiency initiatives over the years. These programs have helped to create guidebooks of energy efficient technologies, profiles of industry energy use, and studies of future technology. Resources from these programs can help to identify technology that may help reduce GHG emissions generated by the cement manufacturing sector.

Cement plants can measure their improvements in energy efficiency either against themselves or against the performance of the entire industry. This type of plant energy benchmarking is typically done at a whole-facility, or site, level in order to capture the synergies of different technologies, operating practices, and operating conditions. Benchmarking enables companies to set informed and competitive goals for plant energy improvement and also helps companies prioritize investment to improve the performance of lowest performing processes while learning from the approaches used by the best performing processes.

When benchmarking is conducted across an industrial sector, a benchmark can be established that defines best-in-class energy performance. The U.S. EPA's ENERGY STAR Program has developed benchmarking tools that establish best in class for specific industrial sectors. These tools, known as Plant Energy Performance Indicators (EPI) are established for specific industrial sectors and are available for free at www.energystar.gov/industrybenchmarkingtools. Using several basic plant specific inputs, the EPIs calculate a plant's energy performance providing a score from 0-100. EPA defines the average plant within the industry nationally at the score of 50; energy-efficient plants score 75 or better. ENERGY STAR offers recognition for sites that score in the top quartile of energy efficiency for their sector using the EPI.

The remainder of this section summarizes available and emerging CO_2 control technologies and/or measures for the cement sector. For many of the control technologies and/or measures listed in this section, CO_2 emission reductions are not explicitly provided. Energy efficiency improvements lead to reduced fuel consumption in the kiln system, and/or reduce electricity demand. Thus, where CO_2 emission reductions are not provided, these reductions can be calculated from the reduction of fuel used by the kiln system. For facilities that produce their own electricity, emission reductions that result from reduced electricity usage can be calculated from the reduced amount of fuel consumed at their power plant (if fuel combustion rather than waste heat is used for this purpose).

The Portland Cement Association (PCA, 2008) provides a discussion on most of the efficiency measures presented in this section, particularly addressing technical feasibility.

Staudt (2009) provides a means of estimating the capital costs for the energy efficiency measures using the following equation:

$$\text{Capital Costs (\$2008)} = \text{Scale-Up Factor x (tons/yr cement capacity)}^{0.6}$$

The scale-up factors are provided in Table 1 of Staudt (2009) and cover a variety of different kiln types (see Appendix A).

A. Energy Efficiency Improvements in Raw Material Preparation

Transport System Efficiency Improvements

Pneumatic and mechanical conveyor systems are used throughout cement plants to convey kiln feed, kiln dust, finished cement, and fuel. Mechanical systems typically use less energy than pneumatic systems, and switching to mechanical conveyor systems can save 2.9 kWh/ton of cement. Installation costs for the mechanical conveyor systems are estimated to be $4.1/ton of cement. (Worrell and Galitsky, 2008)

Installation of belt conveyors and bucket elevators may result in investment costs of $3.43/ton cement and reduce operating costs by $0.17/ton cement. Additionally, power consumption may decrease by 2.5 kWh/ton cement. (Hollingshead and Venta, 2009)

New facilities should be able to use mechanical conveyors unless there is a design consideration that precludes their use or makes pneumatic systems a more viable choice. For existing facilities, the conversion from pneumatic systems to mechanical systems may be cost-effective due to increased reliability and reduced downtime. (Worrell and Galitsky, 2008)

Raw Meal Blending

The raw meal, or kiln feed material, is comprised of a number of ingredients. To optimize the clinker production process in the kiln, the raw meal must be mixed thoroughly to form a homogenous mixture. The mixing may occur in an air fluidized silo or a mechanical system that simultaneously withdraws material from several storage silos. Alternatively, gravity-type homogenizing silos may be used to reduce energy consumption. The gravity-type silos may reduce energy consumption by 1.4 – 3.5 kWh/ton cement. Silo retrofit costs have been estimated to be $5.0/ton cement. This estimate assumed a capital cost of $550,000 per silo having a capacity of 165,000 tons/yr. (Worrell and Galitsky, 2008)

Improvements in blending of raw materials may reduce energy requirements by16,700 Btu/ton cement and reduce power consumption by 1.0 kWh/ton cement. Production may increase by about 5 percent. Investment costs were estimated to be $2.50/ton cement and operating cost may increase by $0.02/ton cement. (Hollingshead and Venta, 2009)

Gravity-type silos appear to be most commonly used in new construction. Rather than constructing entirely new silos systems, modifications at existing facilities may be cost effective when the silo can be partitioned with air slides and divided into compartments which are sequentially agitated. (Worrell and Galitsky, 2008)

High Efficiency Roller Mills

Older facilities may use ball mills for grinding raw materials. Higher efficiency options for ball mills include high efficiency roller mills, ball mills combined with high pressure roller presses, or horizontal roller mills. The use of the more efficient grinding methods may reduce energy consumption by 9 – 11 kWh/ton cement. Retrofit costs are estimated to be $7.6/ton cement. (Worrell and Galitsky, 2008)

Replacing older ball mills with vertical roller mills or high pressure grinding rolls can reduce the electricity demand of the grinding operation from 11 – 15 kWh/ton cement, which may reduce CO_2 emissions related to the electricity generation from 14 – 22 lb/ton cement. (ECRA, 2009) Another study (Hollingshead and Venta, 2009) found that this option resulted in a power savings of 8.3 kWh/ton cement and reduced operating costs by $0.17/ton cement. Capital investment costs were estimated to be $33/ton cement capacity.

Additional energy savings can be realized by combining a raw material drying step with vertical roller mills by utilizing waste heat from kilns or clinker coolers. (Worrell and Galitsky, 2008)

High Efficiency Classifiers

After grinding, classifiers and separators are used to separate particles by size, with the larger particles being returned to the grinder for further processing. Classifiers that have lower efficiencies return an excess of smaller particles back to the grinder that should have been allowed to pass to the next operation. This extra load on the grinder results in an increase in energy consumption. Energy savings for using high efficiency classifiers is estimated to be 8 percent of the electricity usage of the grinder. (Worrell and Galitsky, 2008)

Case studies have shown that operations modified to include a high efficiency classifier realized an energy savings of 3.8 – 5.2 kWh/ton cement. The modification may also lead to increased grinding mill capacity and improved product quality. Modification costs are estimated to be $3/ton cement production. (Worrell and Galitsky, 2008)

Another study estimates the decrease in electricity demand as a result of installing high efficiency separators to be 4 kWh/ton cement, which may lead to CO_2 emission reductions of 4 – 6 lb/ton cement. The investment costs of installing high efficiency separators at a new facility or retrofitting an existing facility are about $3.75 million, with an operating cost decrease (excluding depreciation, interest, and inflation) of about $0.38/ton cement. (ECRA, 2009)

Fuel Preparation (Coal) – Roller Mills

Facilities that use coal as a fuel typically include fuel preparation steps to crush, grind, and dry the coal. As discussed above, roller mills are typically more efficient than other grinding methods. For coal operations, roller mills consume about 16-18 kWh/short ton coal processed, compared to 45-60 kWh/short ton for an impact mill and 25-26 kWh/short ton for a tube mill. Thus, a roller mill may save 7-10 kWh/short ton coal over the use of a tube mill and save 27 – 44 kWh/ton coal over the use of an impact mill. Although capital costs are higher for a roller mill, the operating costs may be as much as 20 percent lower than tube mill and 50 percent lower than an impact mill. (Worrell and Galitsky, 2008)

B. Energy Efficiency Improvements in Clinker Production

Process Control and Management Systems

Automated control systems can be used to maintain operating conditions in the kiln at optimum levels. Maintaining optimum kiln conditions leads to more efficient operation throughout the cement manufacturing process. Reported energy savings after installing such automated controls range from 2.5-10 percent, with typical results in the range of 2.5-5 percent. The cost to install an automated control system and to train operators at one facility was reported to be $0.3/annual ton cement. Payback periods are typically 2 years or less. (Worrell and Galitsky, 2008)

ECRA (2009) reported that energy savings related to control systems compared to a kiln without a control system may range from 42-167 megajoules (MJ)/ton cement, and reduce electricity consumption up to 1 kWh/ton cement. The kiln energy savings may reduce CO_2 emissions from 7 – 33 lb/CO_2/ton cement, with an additional 1.3 lb CO2/ton cement coming from the decrease in electricity usage.

There should be no barriers to installing control systems on new construction. Most existing facilities should be able to retrofit the clinker production operations to accommodate control systems.

Replacement of Kiln Seals

Kiln seals are used at the inlet and outlet of the kiln to reduce heat loss and air penetration. Leaking seals can result in increased heat loss which increases fuel use. Replacement of kiln seals has been reported to reduce fuel consumption by 0.4 percent (0.01 MMBtu/ton cement) at one facility. The payback period for improved kiln seal maintenance is estimated to be 6 months or less. (Worrell and Galitsky, 2008)

Improved kiln seal maintenance is generally applicable to existing facilities; however, the design of new facilities should consider the effectiveness and longevity of available kiln seals. All facilities should have a regular maintenance plan for the kiln seals.

Kiln Combustion System Improvements

As with any combustion system, inefficiencies may occur in the fuel combustion operation. Incomplete fuel burning, poor mixing of fuel with combustion air, and poorly adjusted firing can lead to increased fuel usage (as well as increased NO_x and CO emissions). Reported fuel savings of 2-10 percent have been reported at cement plants that have instituted combustion optimization methods. (Worrell and Galitsky, 2008)

A proprietary system called Gyro-Therm has been demonstrated at several cement plants to improve combustion and reduce fuel usage. The system is applicable to gas-fired and gas/coal-fired kilns and reportedly results in a 2.7-10 percent reduction in fuel usage and up to 10 percent increase in output of the kiln. Average costs of the system based on demonstration projects is $0.8/annual ton cement capacity (Worrell and Galitsky, 2008), and payback time is estimated to be less than one year. (FTC, 2009)

New construction should consider available technologies to optimize kiln combustion. Existing systems can typically be retrofitted to incorporate optimization techniques.

Use of Fluxes and Mineralizers to Reduce Energy Demand

The use of fluxes and mineralizers can reduce the temperature at which the clinker melt begins to form in the kiln, promote formation of clinker compounds, and reduce the lower temperature limit of the tricalcium silicate stability range. All of these factors can reduce the fuel energy demand of the kiln. (ECRA, 2009)

Fluorides are often used as a mineralizer and can reduce the sintering temperature by 190°F. Although there is a fuel savings, that savings may be offset by the high cost of the fluxing agent or mineralizer. (ECRA, 2009)

Fluxing agents and mineralizers can reduce energy consumption by 42-150 MJ/ton cement. Additional electricity requirements, if any, may be up to 1 kWh/ton cement. Potential reductions in CO_2 emissions range from 9-30 lb CO_2/ton cement at the kiln and increases due to increased electricity usage range from 0-2 lb CO_2/ton cement. (ECRA, 2009)

Kiln/Preheater Insulation

Due to the large size of cement kilns, the amount of outer surface area of the kiln is very high, and significant heat loss can occur through the kiln shell. Proper insulation is important to keep these losses to a minimum. The refractory material lining the kiln is the primary insulating material. High temperature insulating linings for the kiln may reduce fuel usage by 0.1-0.31 MMBtu/ton cement. Costs of the refractory material have been estimated to be $0.21/ton cement capacity. (Worrell and Galitsky, 2008)

The investment costs for external insulation on upper preheater vessels and on the cooler housing were estimated to be $0.25/ton cement and provide an energy savings of 17 Btu/ton cement. (Hollingshead and Venta, 2009)

When replacing refractory materials at existing plants, structural considerations must be taken into account to assure that the kiln can support the weight of the new refractory material. New construction can account for the weight of the refractory material in the kiln design.

Refractory Material Selection

The refractory bricks lining the combustion zone of the kiln protect the outer shell from the high combustion temperatures, as well as chemical and mechanical stresses. Although the choice of refractory materials is highly dependent on fuels, raw materials, and operating conditions, consideration should be given to refractory materials that provide the highest insulating capacity and have the longest life. Although energy savings are difficult to quantify due to the unique conditions at each facility, some benefit will be realized from higher quality refractory materials. (Worrell and Galitsky, 2008)

Investment costs of $0.50/ton cement for improved refractory materials in the kiln and preheater may reduce energy consumption by 49,800 Btu/ton cement. (Hollingshead and Venta, 2009)

Grate Cooler Conversion

Grate coolers are used to cool the clinker immediately after it exits the kiln. The grate cooler is integral to heat recovery from the clinker, so grate coolers that operate with higher efficiencies will lead to less wasted heat and reduce fuel usage elsewhere in the process. Both planetary and travelling grate coolers can be replaced with reciprocating grate coolers. (Worrell and Galitsky, 2008)

Replacement of a planetary cooler with a reciprocating grate cooler can reduce kiln fuel consumption by as much as 8 percent, even though the reciprocating grate cooler has an increased power consumption of about 2.5 kWh/ton cement. However, the cost of the reciprocating cooler may be prohibitive for facilities with a capacity less than 550 tons/day. Planetary coolers do not allow tertiary heat recovery, which is required if a precalciner is used.

The conversion to a reciprocating grate cooler may be more economical for units that have or will have a precalciner installed as well. (Worrell and Galitsky, 2008)

Another study also estimated the energy savings at the kiln to be about 8 percent, or 84 – 251 MJ/ton cement. The grate coolers, however, require an increase in electrical consumption of about 1 – 5 kWh/ton cement. The cost for conversion from a planetary cooler to a reciprocating grate cooler with a capacity of 6,600 tons/day is estimated to be $22.5-30 million. The actual costs can vary significantly based on site specific conditions. Retrofitting an older grate cooler to a modern reciprocating grate cooler is estimated to be $1.5-4.5 million. (ECRA, 2009)

Hollingshead and Venta (2009) estimated that installing a complete new grate cooler would have an investment cost of $8/ton cement and reduce energy consumption by 0.22 MMBtu/ton cement. Power consumption would increase by 3 kWh/ton cement and operating costs would increase by $0.17/ton/cement. Production would increase by about 20 percent.

Emission reductions of CO_2 due to the lower kiln fuel requirements may range from 17 – 52 lb/CO_2/ton cement. The increase in electrical power usage could result in an increase in CO_2 emissions from power generation operations. The associated increase due to electrical usage may range from 2 – 6 lb CO_2/ton cement. (ECRA, 2009)

Heat Recovery for Power – Cogeneration

There are several exhaust streams in the cement manufacturing operation that contain significant amounts of heat energy, including the kiln exhaust, clinker cooler, and kiln preheater and precalciner. In certain cases, it may be cost effective to recover a portion of the heat in these exhaust streams for power generation. Power generation can be based on a steam cycle or an organic Rankin cycle (i.e., the conversion of heat into work). In each case, a pressurized working fluid (water for the steam cycle or an organic compound for the organic Rankin cycle) is vaporized by the hot exhaust gases in a heat recovery boiler, or heater, and then expanded through a turbine that drives a generator. Based on the heat recovery system and the kiln technology, 7-8 kWh/ton cement can be produced from hot air from the clinker cooler, and 8-10kWh/ton cement from the kiln exhaust. (ECRA, 2009) Total power generation can range from 7-20 kWh/ton cement. Steam turbine heat recovery systems were developed and first implemented in Japan and are being widely adopted in Europe and China. Installation costs for steam systems range from $2-4/annual ton cement capacity with operating costs ranging from $0.2-0.3/annual ton cement capacity. (Worrell and Galitsky, 2008; ECRA, 2009)

Generally, only long dry kilns produce exhaust gases with temperatures high enough to make heat recovery for power economical. Heat recovery installations in Europe and China have included long dry kilns with preheaters. Heat recovery for power may not be possible at facilities with in-line raw mills where the waste heat is used to extensively dry the raw materials; it is usually more economic and efficient to use the exhaust heat to reduce the moisture content of raw materials with very high moisture. (Worrell and Galitsky, 2008)

It is possible to meet 25-30 percent of the plants total electrical needs through this type of cogeneration. As an example, a 4,100 ton/day cement plant in India, installed a waste heat recovery power plant using the exhaust from the preheaters and clinker cooler. The power plant was rated at 8 megawatts (MW). Capital investment was $18.7 million, and CO_2 emission reductions were reported to be 49,000/yr. (PCA, 2008)

Suspension Preheater Low Pressure Drop Cyclones

Cyclones are used to preheat the raw meal prior to the kiln. Exhaust gases from the kiln or clinker cooler are routed to the cyclone and provide the heat to preheat the raw meal suspended or residing in the cyclone. The larger the pressure drop losses in the cyclone, the greater the energy requirements for the kiln or clinker cooler exhaust fan. One study estimated that the energy savings resulting from installing low pressure drop cyclones is 0.5 – 0.6 kWh/ton cement for each 50 mm water column the pressure drop is reduced. One facility realized a savings of 4 kWh/ton cement, but a total savings of 0.6 – 0.9 kWh/ton cement may be more typical. (Worrell and Galitsky, 2008)

At existing facilities, retrofit to include the cyclones may also require rebuilding of the preheater tower, which may significantly increases the cost of the project. Additionally, new cyclones may increase overall dust loading and increase dust carryover from the preheater tower. Capital costs have been estimated to be $2.50/annual ton cement capacity. There should be no barriers to installing low pressure drop cyclones at new facilities. (Worrell and Galitsky, 2008)

One study (Hollingshead and Venta, 2009) estimated the investment cost for this option to be $2.90/ton cement based on replacing the inlet and outlet cyclone ducting. Electricity requirements may decrease by 3 kWh/ton cement and production increase by 3 percent.

Another study (ECRA, 2009) stated that retrofitting the preheat system with low pressure drop cyclones may be economically reasonable when the foundation and tower of the preheater can be reused without rebuilding. The reduced power consumption of the fan system may range from 0.5 – 1.3 kWh/ton cement. The reduced electricity generation may reduce CO_2 emissions by up to 2 lb CO_2/ton cement.

Conversion to Multistage Preheater

Modern cement manufacturing facilities incorporate multi-stage preheaters (four- or five-stage) prior to the kiln. (These preheater cyclones may or may not be low pressure drop cyclones as discussed above.) However, older kilns may preheat only prior to the combustion zone of the kiln or employ single- or two-stage preheaters. Some older kilns may not preheat at all. Multi-stage preheaters allow higher energy transfer efficiency and lower fuel requirements. Improved preheating may increase productivity of the kiln as a result of a higher degree of precalcination. Although the energy savings are highly site-specific, one retrofit project at an older kiln resulted in a decrease in energy usage of 0.4 MMBtu/ton cement, while increasing capacity by over 50 percent. The capital cost of the conversion was $33-34/annual ton cement capacity. Another study estimated the cost of installing suspension preheaters to be $23/ton cement capacity. (Worrell and Galitsky, 2008)

Adding a preheater stage will lead to additional heat capture from the exit gases. These savings were estimated to be 108,200 Btu/ton cement with a 3 percent production increase for adding one preheater stage. Electricity usage will increase by 1 kWh/ton cement. Investment costs were estimated to be $12.80/ton cement, which includes exit duct modifications and structural improvements to handle the additional stage. (Hollingshead and Venta, 2009)

New construction typically employs multistage preheaters. Retrofit of existing facilities may be cost effective when the kiln needs to be replaced. (Worrell and Galitsky, 2008)

In order to demonstrate the energy efficiency obtained with multistage preheaters, one study (ECRA, 2009) investigated the theoretical yearly average fuel energy requirements for cement kilns using multistage preheat systems and reported the following data:

- 3 cyclone stages: 2,800 to 3,200 MJ/ton cement
- 4 cyclone stages: 2,700 to 3,000 MJ/ton cement
- 5 cyclone stages: 2,600 to 2,900 MJ/ton cement
- 6 cyclone stages: 2,500 to 2,800 MJ/ton cement

Conversion of Long Dry Kiln to Preheater/Precalciner Kiln

Long dry kilns without preheater capacity or with only a single-stage preheater can be upgraded to a multi-stage PH/PC kiln. The conversion can reduce energy consumption by 1.1 MMBtu/ton cement based on studies done in Canada and the conversion of an Italian facility. While one study estimated the capital cost of such a conversion to be $7.9/ton cement capacity, another estimated the cost to be $19 – 24/ton cement. (Worrell and Galitsky, 2008)

According to another study, the cost of upgrading a long dry kiln to a multistage preheater kiln is about $33 – 34/ton cement (in 1993 dollars). Capital costs can also be estimated using the following equation (Staudt, 2008b):

$$\text{Capital Costs (2005\$)} = \$6545 \times (\text{tons/yr cement})^{0.6}$$

The conversion of a long dry kiln to a preheater/precalciner kiln can be estimated using the following equation (Staudt, 2008b):

$$\text{Capital Costs (2005\$)} = \$8084 \times (\text{tons/yr cement})^{0.6}$$

Fixed costs for either conversion are estimated to be 4 percent of capital costs. Variable costs are primarily related to fuel usage and will be reduced according to the specific fuel reduction at each facility. (Staudt, 2008b)

Converting to a PH will require a new pyro line (except perhaps for half the kiln) and minor improvements for raw grinding equipment. Production may increase by 25 percent with a reduction in energy consumption of 1.2MM Btu/ton cement and no net increase in electricity consumption. Investment costs were estimated to be $88/annual ton cement capacity, and operating and maintenance costs were projected to decrease by $0.08/ton cement. (Hollingshead and Venta, 2009)

Converting to a PH/PC kiln may increase production by 40 percent and may require more extensive upgrades in the raw grinding and clinker cooling areas to handle the increased production. The PH/PC kiln may reduce energy consumption by 0.7 MMBtu/ton cement and require no net increase in electricity consumption. Investment costs were estimated to be $96/annual ton of cement capacity, and operating and maintenance costs were projected to decease by $0.08/ton cement. (Hollingshead and Venta, 2009)

One report (ECRA, 2009) stated that the energy savings realized for a retrofit depend highly on the process being replaced. Energy savings range from 800 MJ/ton cement when converting a long dry kiln to as much as 2,300 MJ/ton cement when converting a long wet kiln with a modern preheater/precalciner kiln and a modern clinker cooler. Electricity consumption in either case may be reduced up to 4kWh/ton cement. Emission reduction potential for CO_2 ranges from 150-460 lb CO_2/ton cement for direct emissions from the cement plant, and indirect reductions due to reduced consumption of electricity range from 0-6.5 lb CO_2/ton cement.

Kiln Drive Efficiency Improvement

Due to the large size of the kiln, a substantial amount of power is required to rotate the kiln. When direct current motors are used, the efficiency of the motors is maximized by using a single pinion drive with an air clutch and a synchronous motor. This combination may reduce kiln drive electricity requirements by 2-3 percent, which equates to about 0.5 kWh/ton cement. However, the higher efficiency system increases capital costs by about 6 percent. (Worrell and Galitsky, 2008)

The use of alternating current motors may result in slightly higher efficiencies than direct current motors. Alternating current motors may achieve a 0.5-1 percent reduction in electricity usage over direct current motors and also have a lower capital cost.

New construction should consider high efficiency motors as part of an overall energy efficiency strategy. Existing facilities should consider replacing older motors with either alternating current or direct current high efficiency motors rather than re-winding the old motors, which could reduce power costs for the kiln drive by 2-8 percent. (Worrell and Galitsky, 2008)

Adjustable Speed Drive for Kiln Fan

Replacing the damper on the kiln fan system can reduce energy consumption of the kiln fan. One cement facility realized a nearly 40 percent reduction in electricity usage after making this modification on a 1,000 hp fan motor. Another facility that installed adjustable speed drives saw a reduction in electricity use of 5 kWh/ton cement. Installing adjustable speed drives for the kiln fan is applicable to both new and existing facilities.

Oxygen Enrichment

Oxygen enrichment is the process of injecting oxygen (as opposed to air) directly into the combustion zone (or as an adjunct to the combustion air stream) to increase combustion efficiency, reduce exhaust gas volume, and reduce the available nitrogen that may form NO_x pollutants. One study (Staudt, 2009) reported on four US cement plants that installed oxygen enrichment systems. These plants experience an increase in clinker production between 3.1 percent and 10 percent. One of the facilities reported a 3-5 percent decrease in fuel usage. If the oxygen enrichment process is not carefully managed, increased thermal NO_x emissions can occur due to increased flame temperatures associated with highly efficient oxygen combustion. (Worrell and Galitsky, 2008)

Staudt (2009) reported that the capital cost of an oxygen enrichment system can be estimated using the following equation:

$$\text{Capital Costs (\$2009)} = \$1511 \times (\text{tons/yr cement capacity})^{0.6}$$

This same report estimated fixed operating costs to be 4 percent of capital costs and variable operating costs to be 40 kWh/short ton of additional clinker times the cost of power, since electricity accounts for virtually all of the variable costs.

ECRA (2009) reported that some experimentation showed that an increase of 25-50 percent in kiln capacity was possible with oxygen enrichment of 30-35 percent by volume of the combustion air. The thermal efficiency increase can reduce kiln energy requirements from 84-167 MJ/ton cement. The increase in kiln production may lead to an increased electricity demand of 8-29 kWh/ton cement. While the reduced fuel usage in the kiln may reduce CO_2 emissions by 18-37 lb CO_2/ton cement, the increased electricity consumption could increase CO_2 emissions by 28-46 lb CO_2/ton cement.

Oxygen enrichment is applicable to both new and existing facilities. However, a source of oxygen is required.

Mid Kiln Firing

Mid kiln firing, which is the practice of adding fuel (often scrap tires) at a point near the middle of the kiln, can result in reduced fuel usage thereby potentially reducing overall CO_2 emissions. This practice is most often used with long wet or long dry kilns. The burning of tires emits slightly less CO_2 per MMBtu than bituminous coal, but more CO_2 per MMBtu than natural gas. Burning tires may also result in lower NO_x emissions.

Air Mixing Technology

Mixing air is the practice of injecting a high pressure air stream into a kiln to break up and mix stratified layers of gases within the kiln. Mixing the air improves the combustion efficiency. Due to the increased efficiency, less fuel is required, leading to lower CO_2 emissions. (Staudt, 2008b)

Capital costs of an air mixing system are approximately $520,000. Staudt (2008b) provides an equation to estimate capital costs based on tons per year (tpy) of clinker. Fixed annual costs are expected to be similar to that of a low NO_x burner. Variable costs will be incurred by an air mixing system for electricity usage and is estimated to be 0.23 kWh/ton cement.

Air mixing technology will likely reduce CO, NO_x, and SO_2 emissions. Staudt (2008b) reports that the concentration of CO in the kiln exhaust stream is reduced from 228 ppm down to 121 ppm, while SO_2 was reduced from 359 ppm down to 10 ppm and NO_x was reduced from 599 ppm down to 313 ppm.

Preheater Riser Duct Firing

The operation of cement manufacturing operations that include a preheater prior to the kiln can be improved by firing a portion of the fuel in the riser duct to increase the degree of calcination in the preheater. When tires are used as the fuel, CO_2 emissions may be reduced because the burning of tires emits slightly less CO_2 per MMBtu than bituminous coal, but more CO_2 per MMBtu than natural gas.

C. Energy Efficiency Improvements in Finish Grinding

Improved Ball Mills

Several technologies exist that reduce the power consumption of the finish grinding operation, such as roller presses, roller mills, and roller presses used for pre-grinding in combination with a ball mill. The electricity savings when replacing an older ball mill with a new finish grinding mill may be 25 kWh/ton cement. The addition of a pre-grinding system to an existing ball mill can reduce electricity consumption by 6-22 kWh/ton cement. Capital cost estimates for installing a new roller press vary widely, from a low of $2.3/annual ton cement capacity to a high of $7.3/annual ton cement capacity. Additionally, new grinding technologies may reduce operating costs by as much as 30-40 percent. (Worrell and Galitsky, 2008)

Replacing ball mills with vertical roller mills is estimated to require an investment cost of $35/ton cement capacity and increase operating costs by $0.17/ton cement to account for more frequent maintenance. Power savings were estimated to be 9 kWh/ton cement. (Hollingshead and Venta, 2009)

Retrofitting of existing facilities most often involves the use of high-pressure roller presses. All types of finish grinding systems applicable to the specific facility should be evaluated for new construction.

High Efficiency Classifiers

Classifiers are used to separate fine particles from coarse particles in the grinding operation. Low efficiency classifiers do a poorer job of separating out the fine particles and send an excess of fine particles back to the grinder. This increases the load on the grinder and increases energy usage. High efficiency classifiers reduce the amount of fine particles returned to the grinder. In one study, the installation of high efficiency classifiers reduced electricity use by 6 kWh/ton cement and increased production by 25 percent. Other studies have shown the reduction in electricity use to be 1.7-2.3 kWh/ton cement. Capital costs were $2/annual ton finished material. (Worrell and Galitsky, 2008)

Another study (Hollingshead and Venta, 2009) assumed that this conversion would require, in addition to the high efficiency classifier, a product dust collector and a new fan. Investment costs were estimated to be $2/ton cement with operating costs increasing by $0.04/ton cement. However, production may increase by 10 percent and power consumption may decrease by 2.1 kWh/ton cement.

Retrofitting existing facilities with high efficiency classifiers should be considered where the physical layout of the finish grinding system allows it. New construction should consider the most efficient classifiers.

D. Energy Efficiency Improvements in Facility Operations

High Efficiency Motors

Due to the high number of motors at a cement manufacturing facility, a systems approach to energy efficiency may be considered. Such an approach would look for energy efficiency opportunities for all motor systems (motors, drives, pumps, fans, compressors, controls). An evaluation of energy supply and energy demand would be performed to optimize overall performance. A systems approach includes a motor management plan that considers at least the following factors (Worrell and Galitsky, 2008):

- Strategic motor selection
- Maintenance
- Proper size
- Adjustable speed drives
- Power factor correction
- Minimize voltage unbalances

One cement facility recently retrofitted the motors on the blowers and pumping systems as part of a motor system improvement project. Replacing older, less efficient motors with new, high efficiency motors reduced electricity use by about 2.1 million kWh/yr and saved about $168,000/yr in energy costs and $30,000/yr in maintenance costs. (PCA, 2008)

The cost of replacing all older motors with high efficiency motors was estimated to be $0.67/ton cement with no increase in operating costs. Power consumption may decrease by about 5 percent, or 4 kWh/ton cement. (Hollingshead and Venta, 2009)

Motor management plans and other efficiency improvements can be implemented at existing facilities and should be considered in the design of new construction.

Variable Speed Drives

A typical cement plant may include 500-700 motors, most of which are fixed speed AC models. Since load conditions vary during production, decreasing throttling using variable speed drives can reduce energy consumption by 3-8 kWh/ton cement. This may lead to a reduction of CO_2 emissions of 3-10 CO_2/ton cement. The cost of retrofitting is highly site specific, but may range from $0.38-0.53 million. Operational savings from reduced electricity usage may range from $0.41-0.96/ton cement. (ECRA, 2009)

High Efficiency Fans

Fan technology has improved greatly since many older plants were constructed. If older fans are still in use, upgrading them to modern high efficiency fans may reduce power consumption by 0.9 kWh/ton cement with an investment cost of $0.46/ton cement. (Hollingshead and Venta, 2009)

Optimization of Compressed Air Systems

Compressed air systems provide compressed air that is used throughout the plant. Although the total energy used by compressed air systems is small compared to the facility as a whole, there are opportunities for efficiency improvements that will save energy. Efficiency improvements are primarily obtained by implementing a comprehensive maintenance plan for the compressed air systems. Worrell and Galitsky (2008) listed the following elements of a proper maintenance plan:

- Keep the surfaces of the compressor and intercooling surfaces clean
- Keep motors properly lubricated and cleaned
- Inspect drain traps
- Maintain the coolers
- Check belts for wear
- Replace air lubricant separators as recommended
- Check water cooling systems

In addition to the maintenance plan, reducing leaks in the system can reduce energy consumption by 20 percent. Reducing the air inlet temperature will reduce energy usage. The most effective means of reducing inlet air temperatures is by routing the air intake to a location that is outside and does not draw plant heat into the inlet air. Rerouting the inlet air can have a payback period as little as 2-5 years. Control systems can reduce energy consumption by as much as 12 percent. Properly sized pipes can reduce energy consumption by 3 percent. Since as much as 93 percent of the electrical energy used by air compressor systems is lost as heat, recovery of this heat can be used for space heating, water heating, and similar applications. (Worrell and Galitsky, 2008)

Air compressor system maintenance plans and other efficiency improvements can be implemented at existing facilities and should be considered in the design of new construction.

Lighting System Efficiency Improvements

Similar to air compressor systems, the energy used for lighting at cement manufacturing facilities represent a small portion of the overall energy usage. However, there are opportunities for cost effective energy efficiency improvements. Automated lighting controls that shut off lights when not needed may have payback periods of less than 2 years. Replacing T-12 lights with T-8 lights can reduce energy use by half, as can replacing mercury lights with metal halide or high pressure sodium lights. Substituting electronic ballasts for magnetic ballasts can reduce energy consumption by12-25 percent as well as reducing noise and heat from the ballasts.

Lighting system improvements can be implemented at existing facilities and should be considered in the design of new construction.

VI. Raw Material Substitution to Reduce GHG Emissions

Decarbonated Feedstocks (Steel Slag or Fly Ash)

Certain steel slag and fly ash materials may be introduced into the raw material feed or the clinker grinding process (see Blended Cements below) to reduce the amount of raw material needed to produce a given amount of clinker. Reduction in the amount of raw feed materials needed for clinker production can result in energy savings of 1.12 MMBtu/ton cement. This is slightly offset by the need to dry the slag or fly ash, which may consume 0.07 MMBtu/ton cement. However, where a low alkali cement product is desired, the use of steel slag or fly ash reduces the alkali content of the finished product. This may save 0.16 MMBtu/ton cement for reducing the need to bypass kiln exit gases to remove alkali-rich dust. (Worrell and Galitsky, 2008) Another study estimated that when the steel slag is used to increase production (rather than simply reduce raw material usage); the increased load on the finish grinders is 2.0 kW/ton cement. (Staudt, 2008b)

Another study quantified the CO_2 emission reduction as approximately the same on a ton CO_2/ton clinker basis as the percent of slag added. Thus, if slag is substituted for 5 percent of the clinker output, then the CO_2 emissions on a ton CO_2/ton clinker basis will be reduced by about the same percentage. (Staudt, 2008b)

In a separate report, Staudt (2009) reported the following values for estimating the CO_2 emissions avoided and heat input reduced by using decarbonated kiln feedstocks (see Table 4).

Table 4. CO_2 Emissions Avoided and Heat Input Reduced by Using Decarbonated Kiln Feedstocks

Decarbonated Feedstock Material	CO_2 Avoided (tons calcined CO_2/ton material)	Heat Input Reduced (MMBtu/short ton material)
Blast Furnace Slag	0.35	1.10
Steel Slag	0.51	1.59
Class C Fly Ash	0.20	0.61
Class F Fly Ash	0.02	0.07

One study (ECRA, 2009) reported that for a 15 percent replacement of raw materials by granulated blast furnace slag the decrease in kiln energy consumption may range from 84-335MJ/ton cement, but that electricity consumption may increase by as much as 2 kWh/ton cement. The potential CO_2 emission reductions from reduced fuel consumption may range from 0-216 lb CO_2/ton cement and 0-4 lb CO_2/ton cement emissions increase may occur due to the increased electricity requirements. The study cautioned that the high CO_2 reduction potential may be very site specific and may not represent overall emission reduction potentials for the industry.

Another study reported that 172 lb of steel slag used as a raw material feed could provide as much calcium as 200 lb of limestone, which reduced CO_2 emissions by 88 lb. Thus, each ton of steel slag used to replace an equivalent amount of limestone reduced CO_2 emissions by 0.466 tons. (PCA, 2008)

According to Hollingshead and Venta (2009), steel slag can be fed directly into the kiln without grinding. In this case, the only equipment upgrades are a slag hopper with a regulated withdrawal system and conveyors to the feed point of the kiln. Investment costs were estimated to be $0.75/ton cement and operating costs were estimated to increase by $0.08/ton cement. Production may increase by 5 percent with a corresponding energy savings of 15 kcal/kg clinker 54,100 Btu/ton cement and power savings of 3 kWh/ton cement. (Hollingshead and Venta, 2009)

The costs associated with implementing feedstock substitutions will vary at each location because of specific equipment modifications needed at each site. Primary capital costs are related to storage and handling systems for the materials. When the materials must first be dried, the kiln exhaust can generally be used to provide the necessary energy. Capital costs have been estimated to be $0.65/short ton cement capacity. Operating costs will depend on the costs of the substitute materials compared to the original raw materials, including transportation and mining, increased energy usage for grinding, and reduced electricity and fuel usage for the kiln. (Worrell and Galitsky, 2008)

Cemstar, a proprietary slag injection process, has a total capital investment of about $1.5 million (as expressed in 2005 dollars) for a 45 ton/hr wet kiln. Fixed annual costs are expected to be low and one estimate put them at 4 percent of capital costs. Variable costs will depend on how the kiln is operated after the modification. First there will be a cost reduction because steel slag ($5-15/ton) costs less than clinker ($73/ton). Second, there may be a reduction in cost due to less limestone used as raw material if the kiln output remains the same. If the kiln output is simply increased, then there will be no net savings in the limestone cost. (Staudt, 2008b)

The use of steel slag or fly ash can be considered for existing facilities due to the relatively minor modification required, and should be considered in the design of new construction when sources of steel slag or fly ash are located close enough to the plant site to make their use feasible.

Calcereous Oil Shale

Calcerous oil shale has been used in cement plants in Germany and Russia as an alternate feed stock. Oil shale can also be used as a fuel substitute, and one facility uses the resulting ash as an additive in the finish grinding operation. (PCA, 2008)

Some oil shale deposits may be partially decarbonated and their use would lead to reduced CO_2 emissions from the calcination process. Additionally, they may have a caloric value that will contribute to the energy requirements of the preheater and kiln. If the shale is burned separately, the ash may be used as a raw material. Assuming that 8 percent of the raw meal is replaced with oil shale, an investment of $1/ton cement would be required for installation of a feed system, and operating costs would increase by $0.08/ton cement (assuming that the source of the shale is close to the facility). This modification could reduce energy requirements by 0.07 MMBtu/ton cement and reduce CO_2 emissions by 0.009 lb/ton cement. (Hollingshead and Venta, 2009)

Reductions in CO_2 emissions will be directly related to the amount of limestone feed stock replaced. However, processing of the oil shale may result in some CO_2 emissions that would have to be taken into account and are not estimated here.

VII. Blended Cements to Reduce GHG Emissions

Blended cements contain supplementary cementitious materials that replace a portion of the clinker used to make Portland cement. These materials are broadly divided into cementitious materials and pozzolans. Cementitious materials exhibit characteristics of cement. Granulated blast furnace slag is a commonly used cementitious material in cement manufacturing. A pozzolan is a material that when mixed with calcium hydroxide will exhibit cementitious properties. Example pozzolans used in cement manufacture include diatomite, calcined clay, calcined shale, metakaolin, silica fume, and fly ash from coal combustion. (Staudt, 2009)

Whether supplementary cementitious materials can be used in cement depends on a number of factors including availability, properties of the material, price, intended application of the cement, quality and elemental constituents of the pozzolans, national standards, and market acceptance. (ECRA, 2009) Primary among these is availability, as the cement kiln must be located near the source of the material. The use of blast furnace slag requires the location of a blast furnace for pig-iron production near the kiln, as well as availability of the slag from that facility. Deposits of natural pozzolans suitable for cement production are located in very limited areas.

In general, investment costs for the equipment needed to receive, store, and meter supplementary materials to the cement product were estimated to be $3.40/ton cement. Operating costs and power consumption will decrease in proportion to the replacement rate of the clinker. (Hollingshead and Venta, 2009)

Cementitious Materials

Granulated blast furnace slag will offset emissions from the cement manufacturing process on a one-for-one basis. In other words, the use of one ton of slag will reduce all emissions from the cement manufacturing process by the amount of emissions that would be generated to produce one ton of clinker. (Staudt, 2009)

The cost of granulated slag averages about $80/ton (in 2006 dollars). This may not include shipping costs, which may drive up the final cost to prohibitive levels if the source of the slag is not close to the cement facility. (Staudt, 2008b)

The reduction in kiln energy requirements will be directly related to the reduced amount of clinker production resulting from blending another material in the finish grinding process. For a cement product with 30-70 percent by mass of granulated blast furnace slag, the reduced energy requirements will range from 380-1710 MJ/ton cement. The resulting CO_2 emission reductions may range from 200-860 lb CO_2/ton cement. Retrofitting a facility to allow blending in the finish grinding process may require investment costs ranging from about $7.5-15 million. (ECRA, 2009)

Pozzolanic Materials

Fly ash from coal combustion is the most widely used pozzolanic material for blended cement use. However, the use of fly ash may be limited by quality and consistency. Fly ash used for concrete blending must meet stringent quality specifications and have a good consistency. Local market factors may also play a part in the use of fly ash, as shipping costs are high due to fly ash weight. (Staudt, 2009)

Natural pozzolans are available in limited areas. Facilities using natural pozzolans must be located in proximity to the source of the pozzolans.

Fly ash of sufficient quality for cement blending costs $25-$30 per ton while displacing an equivalent weight of cement at about $70-$80/ton (in 1997 dollars). These prices do not include transportation costs, which may range from $0.10-$0.13/ton-mile (in 1997 dollars). Diatomite, one of the more widely used natural pozzolans in blended cements, cost $9.00 per ton (FOB plant) (in 2009 dollars). Clay and shale cost about $11/ton (FOB plant) (in 2009 dollars). (Staudt, 2009)

The use of fly ash as a blending material may reduce the energy requirements of the kiln by 200-500 MJ/ton cement for a cement with a fly ash content of 25-35 percent by mass. The resulting CO_2 emission reductions may range from 100-280 lb CO_2/ton cement. Retrofitting a facility to allow blending in the finish grinding process may require investment costs ranging from$12-18 million. (ECRA, 2009)

Natural pozzolans may require additional drying, crushing and grinding prior to use. Depending on the extent of drying necessary, the energy requirements of the kiln may be reduced by 0-500 MJ/ton cement for a cement with a natural pozzolan content of 15-35 percent by mass. The resulting CO_2 emission reductions may range from 0-280 lb CO_2/ton cement. Retrofitting a facility to allow blending in the finish grinding process may require investment costs ranging from $12-18 million. (ECRA, 2009)

VIII. Carbon Capture and Storage

Carbon capture and storage (CCS) involves separation and capture of CO_2 from the flue gas, pressurization of the captured CO_2, transportation of the CO_2 via pipeline, and finally injection and long-term geologic storage of the captured CO_2. Several different technologies, at varying stages of development, have the potential to separate and capture CO_2. Some have been demonstrated at the slip-stream or pilot-scale, while many others are still at the bench-top or laboratory stage of development.

In 2010, an Interagency Task Force on Carbon Capture and Storage was established to develop a comprehensive and coordinated Federal strategy to speed the commercial development and deployment of clean coal technologies. The Task Force was specifically charged with proposing a plan to overcome the barriers to the widespread, cost-effective deployment of CCS within 10 years, with a goal of bringing 5 to 10 commercial demonstration projects online by 2016. As part of its work, the Task Force prepared a report that summarizes the state of CCS and identified technical and non-technical barriers to implementation. The development status of CCS technologies is thoroughly discussed in the Task Force report. For additional information on the Task Force and its findings on CCS as a CO_2 control technology, go to: http://www.epa.gov/climatechange/policy/ccs_task_force.html.

The post-combustion technologies listed below are generally end-of-pipe measures and would not require fundamental changes in the clinker burning process.

Calera Process

Calera has recently developed a process to capture CO_2 emissions and chemically convert the captured CO_2 to carbonates. The process employs a scrubber with high pH water containing calcium, magnesium, sodium, and chloride as the scrubbing liquid. The CO_2 is absorbed by the water, converting it to a dissolved carbonic acid species. At higher pH values, the carbonic acid dissociates and produces bicarbonate and CO_3^{2-} ions. The CO_3^{2-} then reacts with Ca^{2+} and Mg^{2+} to form carbonate minerals. These minerals can then be precipitated from the solution and dried, and then used to make blended cement or other building materials. The remaining water can then be further treated to remove sodium chloride to produce potable water. Thus, the process can take seawater or brackish natural water from wells and produce potable water as a byproduct. Further, the process can be expanded using a low voltage chemical process to convert the removed sodium chloride to produce sodium hydroxide or sodium bicarbonate. The sodium hydroxide can then be used to raise the pH of the scrubber water. The process can be configured such that no industrial waste is discharged into the environment.

Results at a pilot plant installed at a 10MW coal-fired power plant have shown capture efficiency greater than 90 percent for CO_2. When the carbonate materials are used in blended cements, the overall carbon footprint can be negative. This is because the carbon emissions avoided from the cement manufacturing process may be greater than those of the baseline CO_2 emissions from the power plant. (Calera, 2009) This process is still being researched for its use in the cement industry.

Oxy-combustion

Some researchers have reported that oxy-combustion may be feasible for cement plants, although no systems have been installed. Oxy-combustion is the process of burning a fuel in the presence of pure or nearly pure oxygen instead of air. (Oxygen enrichment, as discussed earlier, differs from oxy-combustion in that oxygen enrichment does not replace air but injects oxygen into the combustion zone along with combustion air.) Fuel requirements for oxy-combustion are reduced because there is no nitrogen component to be heated, and the resulting flue gas volumes are significantly reduced. (Barker et al., 2009)

The process uses an air separation unit to remove the nitrogen component from air. The oxygen-rich stream is then fed to the kiln, and the resulting kiln exhaust gas contains a higher concentration of CO_2, as much as 80 percent. A portion of the exhaust stream is discharged to a CO_2 separation, purification, and compression facility. This technology is still in the research stage for the cement industry. (ECRA, 2009)

Technical issues related to using oxy-combustion at a cement plant identified by Barker et al. (2009) include:

- Flame Temperatures and Dilution. Flame temperatures in excess of 3500°C can be achieved using oxy-combustion, which is too hot for proper operation of a cement kiln. Therefore, a portion of the flue gases are recycled back to the combustion zone to provide the necessary dilution.
- Heat Transfer Characteristics. Changing the atmosphere within the combustion chamber will have a significant effect on the heat transfer characteristics.
- Feed Lifting. Nitrogen ballast in the exhaust gases from the kiln plays an important role in lifting the feed between the cyclone stages in the suspension preheater. CO_2 is a denser gas than nitrogen and should be more effective in this feed lifting role.
- Wear and Tear. Due to higher temperatures, kiln wall deterioration may increase at higher oxygen concentrations, leading to more frequent replacement of the kiln lining.
- Process Chemistry. Research is still on-going to determine whether the clinker formation in a different atmosphere will still generate a useful product.

- Air Dilution. Excessive air in-leaks will result in contamination of the CO_2-rich exhaust gas. These contaminates will require removal which will increase costs.
- Flue Gas Cleanup. Depending on the final storage location of the CO_2, the gas will require some clean-up to remove water vapor, nitrogen, argon, NO_x, and SO_x.
- Air Separation Unit (ASU). An ASU will be required to deliver oxygen to the process, which will increased electricity demand.
- Reducing Conditions. The oxygen concentration in the clinker production process should be maintained >2 percent (w/w).

The ECRA (2009) study indicated that the overall energy requirements would decrease by 75-84MJ/ton cement. Electricity requirements would increase by 92-96 kWh/ton cement, primarily to operate the CO_2 separation, purification, and compression facility. Potential CO_2 emission reductions would range from1000-1600 lb CO_2/ton cement as a result of reduced fuel combustion, but increase by 110-150 lb CO_2/ton cement as a result of the increased electricity demand.

The ECRA (2009) study estimated that additional investment costs for a new facility would range from $495-540 million, and operational costs would increase by $10-13/ton cement based on a 2.2 million ton /yr facility. Costs related to transport and storage of CO_2 were not included. The study cautioned that these costs are highly uncertain because the technology has not yet been developed, and that the initial facilities employing the technology would likely incur much higher costs.

IEA GHG performed a study in 2008 that involved a very extensive analysis of the technical, economic, and retrofitting issues related to oxy-combustion. The analysis was performed based on a new cement plant located in the United Kingdom (UK) producing 1.1 million tons/year of cement, using a dry feed process with a five stage preheater. Additionally, the analysis focused on a plant configuration where oxy-combustion was used for the precalciner, but air combustion was used for kiln. This configuration minimized the possible impact of a high CO_2 atmosphere on the clinker production process. This was compared to a base case of the same plant without oxy-combustion. Total energy consumed from fuel, assuming coal as the fuel, was an increase of 1.0 MW. Net power consumption increased by 11.8 MW. (IEA GHG, 2008)

CO_2 emissions avoided at the cement plant were 490,200 tons/yr, or 436,500 tons/yr when taking into account the import and export of electricity, which equated to 61 and 52 percent reductions, respectively. (IEA GHG, 2008)

Capital costs were an increase of $96 M over the base case. Total operating costs, taking into account the import of electricity, was an increase of $24 M/y. (IEA GHG, 2008)

Post-Combustion Solvent Capture and Stripping

Post-combustion capture using solvent scrubbing, typically using monoethanolamine (MEA) as the solvent, is a commercially mature technology. Solvent scrubbing has been used in chemical industry for separation of CO_2 in exhaust streams. (Bosoaga et al., 2009)

While post-combustion capture of CO_2 has been studied extensively for combustion sources at gas-fired power stations, there has been little work to address feasibility at cement plants. One study (Barker et al., 2009) performed an initial evaluation of solvent capture for new cement plants. This study evaluated post-combustion amine scrubbing using MEA. The following technical issues were raised in this study:

- Sulfur Dioxide (SO_2). The concentration of SO_2 in the flue gas from the cement process is important for post-combustion capture with amines because amines react with acidic compounds to form salts that will not dissociate in the amine stripping system.
- Nitrogen Dioxide (NO_2). NO_x within the flue gas is problematic for MEA absorption as this result in solvent degradation.
- Dust. The presence of dust reduces the efficiency of the amine absorption process. The dust level must be kept below 15 mg/Nm^3.
- Additional Steam Requirements. One of the major issues with using MEA CO_2 capture is the large steam requirement for solvent regeneration.
- Reducing Conditions. The clinker must not be generated in reducing conditions and an excess of oxygen must be maintained in the process.
- Heat Reduction for MEA Absorption. The flue gas must be cooled from about 110°C to about 50°C to meet the ideal temperature for CO_2 absorption with MEA.
- Other Gases. The presence of any acidic components will reduce the efficiency of the MEA absorption process.

ECRA (2009) estimated that 95 percent of the CO_2 in the exhaust stream could be captured using MEA absorption. Similar to Barker et al. (2009), this study stated that absorption technologies are only in the pilot stage in the energy sector and actual demonstration facilities are many years in the future. Initial cost estimates place the investment costs at $130-380 million and operating costs at $13-63/ton cement. These are rough estimates only and exclude CO_2 transport and storage costs. However, Bosoaga et al. (2009) pointed out that an advantage of cement plants over power plants is the higher concentration of CO_2 in the flue gas. This directly impacts absorber unit size, and the power requirements for CO_2 compression will be lower compared to the power demand for a power plant.

One study that performed a very extensive analysis of the technical, economic, and retrofitting issues related to post-combustion solvent capture was completed by IEA GHG (2008). Based on this analysis, the major additions to a cement plant to incorporate this technology include:

- A CO_2 capture plant which includes a solvent scrubber and regenerator
- A compressor to increase the pressure of the CO_2 product for transport by pipeline
- High efficiency flue gas desulfurization and De-NO_x (a NO_x removal process) to satisfy the flue gas purity requirements of the CO_2 capture process
- A plant to provide the steam required for regeneration of the CO_2 capture solvent.

The technical and cost analysis was performed based on a new cement plant located in the UK producing 1.1 million tons/year of cement, using a dry feed process with a five stage preheater. This was compared to a base case of the same plant without the post-combustion control. Total energy consumed from fuel, assuming coal as the fuel, increased by 207.2 MW. Net power consumption decreased by 13.1 MW, including excess electricity generation of 2.9 MW. (IEA GHG, 2008)

CO_2 emissions avoided at the cement plant were 594,000 tons/yr, or 653,200 tons/yr when taking into account the import and export of electricity, which equated to 74 and 77 percent reductions, respectively. (IEA GHG, 2008)

Capital costs were an increase of $443 M over the base case. Total operating costs, taking into account the export of excess electricity generation for the steam plant, was an increase of $95.7 M/y. (IEA GHG, 2008)

Post-Combustion Membranes

Membrane technology may be used to separate or adsorb CO_2 in the kiln exhaust. It has been estimated that 80 percent of the CO_2 could be captured using this technology. The captured CO_2 would then be purified and compressed for transport. This technology is still primarily in the research stage, with industrial application at least 10 years away. There are significant problems to overcome designing membrane reactors large enough to handle the kiln exhaust. Positive aspects of membrane systems include ability to be positioned either horizontally or vertically and very low maintenance since regeneration is not required). Although the technology is too immature to estimate energy requirements, potential CO_2 emission reductions are at least 1300 lb CO_2/ton cement. (ECRA, 2009)

Superheated Calcium Oxide (CaO)

A typical modern cement plant operates by feeding limestone (primarily $CaCO_3$) to a precalciner that dissociates CO_2 from the $CaCO_3$ to produce CaO. Fuel is burned in the precalciner to provide the heat necessary to drive this reaction. Thus, the exhaust stream contains CO_2 from the calcination of $CaCO_3$ and combustion of the fuel, as well as other products of combustion and excess combustion air. As a result, the total CO_2 produced in the precalciner is diluted by a larger exhaust steam, making capture of the CO_2 more difficult.

The superheated CaO process separates the calcination and combustion reactions into independent chambers. The heat necessary to run the calciner is provided by circulating a stream of superheated CaO particles between a fluidized bed combustor and a fluidized bed calciner. Thus, the exhaust stream from the calciner consists primarily of CO_2. The CO_2 can then be collected and compressed in preparation for disposal.   Theoretically, up to 53 percent of the CO_2 released in the cement manufacturing process could be captured, avoiding 43 percent of the CO_2 emitted by the traditional cement plant. (Rodriguez et al., 2009)

Although simulations using Aspen Hysys have shown that the superheated CaO process is theoretically feasible, the system remains theoretical with no systems yet built. New construction is most amenable to this system, although retrofitting existing facilities is possible. Retrofits would involve removal of existing preheaters and precalciners (if present) and construction of the fluidized beds, cyclones, heat exchangers, and compressors associated with the process. Rodriguez et al. (2009) did not provide cost information.

IX. Other Measures to Reduce GHG Emissions

Fuel Switching

Switching from coal as the primary fuel to oil or gas will reduce the fuel combustion portion of overall CO_2 emissions, but will not affect the emissions from the calcination reaction. The CO_2 reduction potential of switching from coal to heavy oil is about 18 percent (210 lb CO_2/gigajoule (GJ) versus 170 lb CO_2/GJ). Switching to natural gas will reduce fuel combustion CO_2 emissions by about 40 percent (210 lb CO_2/GJ versus 124 lb CO_2/GJ). However, any fuel switching scenario will have to consider whether other pollutants, such as NO_x increase as a result of the switch. (ECRA, 2009)

The investment cost to retrofit a cement plant to switch from coal to oil fuel has been estimated to range from $7.5-22.5 million, with an increase in operating costs (excluding depreciation, interest, and inflation) ranging from $10-20/ton cement. (ECRA, 2009)

Alternative Fuels – Biomass

The potential on site reduction in CO_2 emissions that may be realized by switching from a traditional fossil fuel to a biomass fuel is based on the specific emission factor for the fuel as related to its caloric value. Pure biomass fuels include animal meal, waste wood products and sawdust, and sewage sludge. It may also be possible to use biomass materials that are specifically cultivated for fuel use, such as wood, grasses, green algae, and other quick growing species. (ECRA, 2009)

ECRA (2009) identified a number of issues related to the use of biomass fuels:

- Caloric Value. Although cement kilns can theoretically use 100 percent biomass fuels, the caloric content must be taken into consideration. Most organic materials have a caloric content of 9-16 GJ/ton cement, while the main firing of a cement kiln requires at least 18-20 GJ/ton cement. Thus, biomass would have to blend with other fuels if used in the kiln. The lower process temperatures in the precalciner allow the use of lower caloric value fuels. Up to 60 percent of the precalciner fuel can be biomass.
- Trace Compounds. The biomass fuel, particularly waste products, may contain trace elements such as heavy metals or may contain compounds that are detrimental such as chlorine. These substances could result in other air emission issues or produce compounds in the combustion process that may be detrimental to equipment or clinker quality.
- Technical Experience. Because cement kilns operate differently when alternate fuels are used, technical expertise to operate the process when using the alternate fuels is required.
- Waste Regulations. The regulation of wastes that may be used for fuel affects the use of those wastes as fuel. For example, if there are no impediments to land filling the waste, then there may be little of the waste available for fuel use.

- Social Acceptance. The use of waste fuels in a given area may be driven by social acceptance of burning the fuel in the community.
- Agricultural Areas. For crops grown for biomass purposes, sufficient agricultural areas in proximity to the cement kiln are required.

Hybrid Solar Plants and Wind Turbines

Initial research is being performed on a system that uses sunlight collected by heliostat mirrors and focused by a parabolic reflector into the kiln as an energy source. Such a system may be feasible in generally sunny areas where small cement plants could be constructed to meet local needs. Due to the immaturity of this technology, no cost information is available. Emission reductions of CO_2 are equivalent to the emissions that would be generated by fuel combustion, since the solar system would replace fuel in the clinker forming process. However, CO_2 emissions from the calcination process would be unaffected. (PCA, 2008)

At least one cement plant has installed wind turbines capable of meeting one-third of their plant electric demand. No cost information is available. Emission reductions of CO_2 are equivalent to the emissions that would be produced by the fuel being replaced. Emissions of CO_2 from calcinations would not be affected.

Syngas Co-Production

Pre-combustion technologies such as reforming or gasification/partial oxidation can be used to produce fuels (mainly hydrogen) that are mostly carbon-free, or to reduce the carbon content of hydrocarbon fuels. Syngas is a mixture of predominantly H_2, CO, and CO_2 that is generated as an intermediate step from fossil fuels such as coal or gas. The CO is then oxidized to CO_2 in a shift reactor. The subsequent separation of the CO_2 from the H_2 is the primary function of pre-combustion capture.

The resulting H_2 is too explosive to use directly in the kiln, but may be diluted with other gaseous fuels or inert gas such as nitrogen or steam. Even when diluted, the combustion and radiation properties of hydrogen differ significantly from traditional fuels, requiring extensive modifications to the kiln and perhaps new developments in burner technology.

The potential CO_2 emission reductions are up to 650 lb CO_2/ton cement depending on how much of the carbon in the fuel can be removed. Since this technology has been applied only to much smaller streams than required for a cement kiln, estimates of investment and operating costs for a system sized for a cement kiln have not yet been developed.

Power Plant/Cement Plant Carbonate Looping (Solid Sorbent Process)

Carbonate looping is a subset of mineral carbonation based on the equilibrium of calcium carbonate to calcium oxide and CO_2 at various temperatures and pressures. The combustion gases are placed in contact with calcium oxide, forming calcium carbonate from the CO_2. The sorbent is sent to a calciner for regeneration. The gas stream exiting the calciner has an increased CO_2 concentration and is suitable for subsequent processing for transport and storage. (ECRA, 2009)

Due to the immaturity of this technology, energy requirements and costs have not been estimated. Potential CO_2 emission reductions range from about 830-1300 lb CO_2/ton cement. (ECRA, 2009)

Chemical Looping

Chemical looping is a combustion technology with inherent separation of CO_2. A metal oxide is used as an oxygen carrier which transfers oxygen from combustion air to the fuel. Direct contact between air and fuel is avoided, and a concentrated stream of CO_2 is generated. Although direct application to clinker production appears unlikely, the technology may be applicable to H_2 production that can subsequently be used as fuel. (PCA, 2008)

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Appendix A

Scale-up Factors for Use with Equation 1 of Staudt (2009)

Energy Saving Method	Capital Cost	From Payback Calculation				From Reported Capital Costs			
		Wet Process	Long Dry	Pre-heater	Precal-ciner	Wet Pro-cess	Long Dry	Pre-heater	Precal -ciner
Raw Material Preparation									
Efficient Transport System	Min		392	392	392		787	787	787
Raw Material Blending	Avg		1181	1181	1181		1181	1181	1181
Process Control Vertical Mill	Avg		19	19	19				
High Efficiency Roller Mill	Min		1352	1352	1352		1458	1458	1458
Slurry Blending and Homogenization	Max	1546							
Wash Mills w/Closed Circuit Classifier	Min	1136							
High Efficiency Classifiers	Min	553	714	714	714	451	584	584	583
Clinker Making									
Energy Management and Control System	Avg-wet Max-dry	207	220	220	220				
Seal Replacement	Max	6	8	8	8				
Combustion System Improvement	Avg	370	334	334	334	188	244	244	243
Indirect Firing	Avg		1986	1986	1986	1394	1802	1802	1802
Shell Heat Loss Reduction	Avg	66	88	88	88	47	60	61	60
Optimize Grate Cooler	Avg	48	78	78	78				
Conversion to Grate Cooler	Avg	83	101	101	101	38	50	50	49
Heat Recovery for Power Generation	Avg		604						
Conversion to Semi-Dry Process Kiln	Min	2455							
Efficient Mill Drives	Avg	194	30	30	30				
Finish Grinding									
Energy Management and Process Control	Max	16	20	20	20				
Improved Grinding Media in Ball Mills	Avg	178	230	230	230				

Energy Saving Method	Capital Cost	From Payback Calculation				From Reported Capital Costs			
		Wet Process	Long Dry	Pre-heater	Precal-ciner	Wet Pro-cess	Long Dry	Pre-heater	Precal -ciner
High Pressure Roller Press	Min	1515	1958	1958	1958	903	1166	1166	1166
High Efficiency Classifiers	Min	389	545	545	545	451	584	584	583
Plant-Wide Measures									
Preventative Maintenance	Max	40	51	51	51				
High Efficiency Motors	Max	29	37	37	37				
Adjustable Speed Drives	Avg	158	213	213	213	70	91	91	90
Optimization of Compressed Air Systems	Max	86	44	44	44				
Product Changes									
Blended Cement	Max	294	294	294	294				
Limestone Portland Cement	Max	153	153	153	153				