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A Review of Emerging Energy-efficiency and CO₂ Emission-reduction Technologies for Cement and Concrete Production

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Abstract

Globally, the cement industry accounts for approximately 5 percent of current man-made carbon dioxide (CO₂) emissions. Development of new energy-efficiency and CO₂ emission-reduction technologies and their deployment in the market will be key for the cement industry's mid- and long-term climate change mitigation strategies. This paper is an initial effort to compile the available information on process description, energy savings, environmental and other benefits, costs, commercialization status, and references for emerging technologies to reduce the cement industry's energy use and CO₂ emissions. This paper consolidates available information on eighteen emerging technologies for the cement industry, with the goal of providing engineers, researchers, investors, cement companies, policy makers, and other interested parties with easy access to a well-structured database of information on these technologies.

1. Introduction

The cement industry accounts for approximately 5 percent of current man-made carbon dioxide (CO₂) emissions worldwide (WBCSD/IEA 2009a). World cement demand and production are increasing; annual world cement production is expected to grow from approximately 2,540 million tonnes (Mt) in 2006 to between 3,680 Mt (low estimate) and 4,380 Mt (high estimate) in 2050. The largest share of this growth will take place in China, India, and other developing countries on the Asian continent (WBCSD 2009b). This significant increase in cement production is associated with a significant increase in the cement industry's absolute energy use and CO₂ emissions.

Many studies from around the world have identified sector-specific (e.g., Worrell et al. 2008; APP 2009; CSI/ECRA 2009) and cross-cutting (e.g., U.S. DOE AMO 2011) energy-efficiency technologies for the cement industry that have already been commercialized. However, information is scarce and scattered regarding emerging or advanced energy-efficiency and low-carbon technologies for the cement industry that have not yet been commercialized. This paper consolidates available information on emerging technologies for the cement industry with the goal of giving engineers, researchers, investors, cement companies, policy makers, and other interested parties easy access to a well-structured database of information on this topic.

We also have provided the commercialization status of each technology along with resources for further information. The commercialization status for each technology is as of the writing of this paper and uses the following categories:

- Research stage: the technology has been studied, but no prototype has been developed
- Development stage: the technology is being studied in the laboratory, and a prototype has been developed
- Pilot stage: the technology is being tested at an industrial-scale pilot plant
- Demonstration stage: the technology is being demonstrated and tested at the industrial scale in more than one plant but has not yet been commercially proven
- Semi-commercial stage: the technology is proven and is being commercialized but has a very small market share

2. Emerging Energy-efficiency and CO₂ Emission-reduction Technologies

The subsections below describe emerging technologies to reduce energy consumption and CO₂ emissions in the different steps of the cement production process, as well as emerging alternative raw materials and products for the cement and concrete production.

2.1. Emerging Grinding Technologies

2.1.1. High-Activation Grinding

One strategy for conserving materials and reducing energy use in cement production is to increase the amounts of elements other than Portland cement in blended cement products. However, increased use of other elements can result in a final product that is slow to develop compressive strength. One solution that has been researched to improve compressive strength development is using high-energy milling to mechanically increase the reactivity of some of the blended constituents, i.e., fly ash and slag (Kumar et al. 2006). Mechanical activation or enhanced reactivity of fly ash or blast furnace slag in cement results from the combined effects of increased surface area and physiochemical changes produced by vibratory or attrition milling (Kumar et al. 2007).

The EMC Cement Company produces energetically modified cement (EMC) and pozzolana using a commercialized technology based on mechanical activation concepts. EMC's plant began operating near Jewett, Texas in September, 2004 with an initial production capacity of about 150,000 tonne/year, which can be increased to meet demand. Waste fly ash from a power plant is conveyed directly to the EMC production facility (EMC Cement 2011). Other Emerging Grinding Technologies are ultrasonic comminution and plasma comminution (Schneider et al. 2011; Schneider 2008).

2.2. Emerging Kiln Technologies

2.2.1. Fluidized Bed Kiln

A fluidized bed kiln (FBK) burns raw materials into powder with granules 1.5 to 2.5 millimeters (mm) in diameter. FBK uses a new technology known as granulation control/hot self-granulation (NEDO 2008), which agglutinates part of the raw material powder to form a core and attaches other raw material powder around the core. A FBK replaces the traditional rotary kiln with a stationary vertical cylindrical vessel (reactor) where the raw materials are calcined in a fluidized bed. An overflow at the top of the reactor regulates the transfer of clinker to the cooling zone. FBKs have improved heat recovery rates compared to conventional rotary kilns (burn to 1,400°C and cool to 100°C in a two-stage cooler) (European Commission 2010).

Table 1. Emerging grinding technology for the cement industry

| Technology Name | Energy/Environment/Other Benefits | Commercial Status | References |
|--------------------------|---|-------------------|---|
| High activation grinding | <ul style="list-style-type: none"> • No waste material; the grinding process does not pollute air or water. • Process is enclosed, with required dust protection features. • Energy consumption is 30 to 50 kWh per ton product. • For every tonne of clinker replaced by additives from mechanical activation grinding, the avoided energy uses are approximately: <ul style="list-style-type: none"> ○ thermal energy: 3.0 to 6.5 GJ/tonne clinker ○ electricity: 60 to 100 kWh/tonne clinker (European Commission 2010)¹ | Semi-commercial | Kumar et al. (2006, 2007, 2008); EMC Cement (2011); Schneider et al. (2011); Schneider (2008) |

The FBK's advantages are anticipated to be lower capital costs, lower operating temperatures, fewer NO_x emissions, lower overall energy use, and ability to accept a wide variety of fuels. However, it is difficult to scale up the current FBK demonstrations to the required 5,000 to 6,000 ton per day (tpd) clinker capacity (Worrell and Galitsky 2004). Early FBK technologies were not commercially successful because of high clinker recycling rates. Today, FBK development is in progress in Japan and the U.S. A FBK with a clinker capacity of more than 1,000 tpd was being erected in China in 2009 but it is not clear whether or not it is in operation now (CSI/ECRA 2009). Table 2 shows the energy and other benefits of this technology and its commercialization status.

2.3. Emerging Technologies for Alternative Raw Materials

Table 3 shows the energy, environmental and other benefits as well as commercialization status of emerging raw material technologies. The description of each technology is given below.

2.3.1. Use of Steel Slag as Raw Material for the Kiln - CemStar® Technology

For steel manufacturing, calcium oxide or lime (CaO) is added to molten steel at 1,650°C to remove impurities such as silica, magnesium, aluminum, and other oxides. These impurities float to the top and are poured away as slag (Perkins 2000). The CemStar® process was first developed in 1994 by Texas Industries (Midlothian, Texas). This process uses electric arc furnace slag as input to the cement kiln in place of limestone (Worrell et al. 2008). During the kiln pyroprocess, ¾-inch- to 1-inch-diameter slag is added to the feed end of the kiln as a component of the raw material mix. Because of its lower melting

point (1,260° C to 1,316° C), the slag does not require additional fuel in the kiln to form clinker with other raw feed components. Moreover, mineralizers already present in the slag help catalyze clinker formation. In addition, the exothermic reaction of converting dicalcium silicate into tricalcium silicate, which happens when slag is exposed to the high temperature, releases supplementary heat into kiln, resulting in even higher efficiency of the cement manufacturing process (Perkins 2000).

Table 2. Emerging kiln technology for the cement industry

| Technology Name | Energy/Environment/Other Benefits/Costs | Commercial Status | References |
|--------------------|---|---------------------|---|
| Fluidized bed kiln | <ul style="list-style-type: none"> • FBK energy use is expected to be 10 to 15 percent lower than that of conventional rotary kilns. • NO_x emissions are reduced to 0.77 kg/tonne clinker, compared to 2.1 to 2.6 kg/tonne clinker for conventional kilns, because of lower combustion temperatures in the FBK (Worrell and Galitsky 2004). • Future FBK fuel consumption is estimated at 2.66 to 3.1 GJ/tonne clinker. This might be less than that of conventional rotary kilns but not of modern precalciner rotary kilns, which have demonstrated fuel use of 2.7 to 2.8 GJ/tonne clinker (Worrell and Galitsky 2004). CSI/ECRA (2009) papers that the FBK reduces thermal energy use by up to 300 megajoules (MJ)/tonne clinker but increases the electricity used by approximately 9 kWh/tonne clinker (CSI/ECRA 2009). • An FBK needs less space and has greater flexibility with respect to raw material feed than conventional rotary kilns do (Worrell and Galitsky 2004). | Demonstration stage | Worrell and Galitsky (2004); NEDO (2008); CSI/ECRA (2009) |

Table 3. Emerging alternative raw material technologies for cement production

| Technology Name | Energy/Environment/Other Benefits/Costs | Commercial Status | References |
|--|---|-------------------|---------------------------------------|
| Use of steel slag as kiln raw material - CemStar® Technology | <ul style="list-style-type: none"> • CemStar® technology increases clinker production by up to 15 percent compared to the conventional process. • CemStar® technology allows replacement of 10 to 15 percent of clinker by electric arc furnace slag. • Using 10 percent slag would reduce energy consumption by 0.19 GJ/tonne, CO₂ emissions by roughly 11 percent, and NO_x emissions by 9 to 60 percent, depending on kiln type and plant specific conditions (Worrell et al. 2008; Perkins 2000). • Equipment costs are mainly for handling materials and vary from \$200,000 to \$500,000 per installation. Total investments are approximately double the equipment costs. CemStar® charges a royalty fee. • Cost savings result from increased income from additional clinker produced without increased operation and energy costs. • Cost savings also come from reduced iron ore purchases because the slag helps to meet iron needs in the clinker. • In 1999, the U.S. Environmental Protection Agency (U.S. EPA) awarded special recognition to the CemStar® process in the U.S. as part of the ClimateWise program (Worrell et al. 2008). | Semi-commercial | Worrell et al. (2008); Perkins (2000) |
| Non-carbonated raw | <ul style="list-style-type: none"> • The type and quality of the clinker produced by CCR are unchanged compared to clinker produced by traditional methods. • Using CCR will avoid significant CO₂ emissions. In a cement plant in Sichuan Province, | Semi-Commercial | UNFCCC (2008a, 2008b, |

| Technology Name | Energy/Environment/Other Benefits/Costs | Commercial Status | References |
|--|---|-------------------|------------|
| material for cement production – use of carbide slag | <p>China, CCR was used to produce 600,000 tons of clinker per year. The resulting annual CO₂ emissions reduction was papered to be equal to 224,540 tCO₂.</p> <ul style="list-style-type: none"> • When CCR is used instead of limestone, fuel consumption can be reduced because some chemical reactions that would take place if limestone was used will not take place if CCR is used. • The capital cost to implement this technology in two NSP kiln cement plants in China is papered to be between US\$2.9 and US\$4.3 Million (1 US\$= 6.83 Chinese yuan). • Use of CCR in the cement industry mitigates the risk of pollution to environments, especially water resources and surrounding landfills (UNFCCC 2008a, 2009). | | 2009) |

The CemStar[®] process eliminates the need to grind the slag because it allows the addition of 2-centimeter (cm) slag lumps directly to the kiln (using large lumps has traditionally led to poor clinker formation). Depending on the location of the slag injection the CemStar[®] process might also save heating energy (calcination energy is estimated to be 1.9 GJ/tonne clinker). Because there is already calcined lime in the slag, the CemStar[®] process results in reduced CO₂ emissions from calcination. The lower combustion energy conditions and flame temperatures also lead to a decrease in NO_x emissions (Worrell et al. 2008).

2.3.2. Non-carbonated Raw Material for Cement Production – Use of Carbide Slag

Carbide slag, also known as calcium carbide residue (CCR), is an unavoidable solid-waste byproduct of the industrial production of ethyne, polyvinyl chloride, polythene alcohol, and other products. A large amount of carbide slag from industrial production causes serious pollution in the surrounding environment, especially in water. Because there are no other appropriate disposal methods, carbide slag is currently disposed of in landfills.

In conventional cement production, limestone is decarbonated in the pyroprocessing stage (main reaction: $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$) to produce CaO (the main content of clinker) and CO₂; this accounts for more than half of the CO₂ emissions during clinker production. To decrease the CO₂ emissions, CCR can be used to partially replace limestone as a raw material. Calcium hydroxide [Ca(OH)₂], the main content of CCR, produces CaO and water (H₂O) during pyroprocessing (e.g., in a cement kiln) without CO₂ emissions (main reaction: $\text{Ca(OH)}_2 \rightarrow \text{CaO} + \text{H}_2\text{O}$). Thus, using CCR will substantially reduce CO₂ emissions from cement production (UNFCCC 2008a). Using CCR in cement kilns entails the following steps: 1) CCR dehydration and transportation, 2) Grinding and storage, 3) Raw material homogenization, 4) Clinker burning, 5) De-dusting (UNFCCC 2009)

2.4. Emerging Alternative Cement Products

Table 4 shows the energy, environmental and other benefits as well as commercialization status of emerging alternative cement products. The description of each technology is given below.

2.4.1. Cement/Concrete Based on Fly Ash and Recycled Materials

Fly ash is a byproduct of coal burning that can have cementitious characteristics similar to those of

Portland cement. The binding properties of fly ash depend on the type of coal burned and nature of the combustion process that produces the ash. Fly ash usually replaces no more than 25 percent of the Portland cement in concrete. Better understanding of the binding capacities of different types of fly ash might reveal additional possibilities. If the use of fly ash in concrete could be increased, the greenhouse gas footprint of concrete could be reduced. Increasing the amount of fly ash used in concrete would put to practical use large amounts of unused fly ash (39 million tons of fly ash is unused each year in the U.S. according to data from 2004). Ongoing research is focused on developing high-volume-fly-ash concretes. However, these products still use a significant amount of Portland cement.

In 2008, Montana State University/Western Transportation Institute performed research using 100-percent fly ash concrete with glass aggregate. This fly-ash-and-glass concrete was used successfully to construct both structural and nonstructural elements of a building. However, further research is required on this new material's fundamental engineering properties (Cross et al. 2005). The study identified 96 plants throughout the U.S. as potential sources of ash that could be used as the sole binder for concrete (Roskos et al. 2011).

Several existing companies produce cement or precast concrete and other building materials from recycled industrial wastes. One company is RecoCement, which has developed a technology to produce cement made entirely from recycled materials, primarily fly ash. (RecoCement 2011). CERATECH is another company that produces cement from fly ash (CERATECH 2012). CalStar Products, Inc. also has an innovative technology that uses recycled fly ash as a primary component in architectural facing bricks and durable pavers (CalStar Products 2012).

2.4.3. Geopolymer Cement

Geopolymer materials fit in the category of current innovative technology for the construction industry. In contrast to Portland cement, geopolymers rely on minimally processed natural materials or industrial byproducts as binding agents. Potential energy and CO₂ savings from the use of geopolymers are significant. Geopolymer cements that are used as binders are composed of a reactive solid component and an alkaline activator. Reaction with the alkaline agent causes a three-dimensional, inorganic, aluminosilicate polymer network to form, which contributes to the high compressive strength of the hardened product. Materials suitable for a geopolymeric polycondensation¹ are aluminosilicates, which can be found in nature (metakaolin, natural pozzolana) or industrial wastes (fly ash, GBFS) (CSI/ECRA 2009). Geopolymers are manufactured at relatively low temperatures, with calcining of aluminosilicates occurring at 750°C. However, no energy consumption data are available for this process (APP 2009).

Until now, geopolymers have been produced only for demonstration purposes and used only for non-structural applications such as paving (CSI/ECRA 2009). Other probable applications of geopolymers are bridges, and structural retrofits using geopolymer-fiber composites. Geopolymer technology is most advanced in precast applications, which can relatively easily handle sensitive materials such as high-alkali activating solutions and because of the controlled high-temperature curing environment that many

¹ Any condensation reaction, of a monomer having two functional groups, which leads to the formation of a polymer.

geopolymer systems require (U.S. DOT 2010).

Pyrament[®], a North-American geopolymer application with blended Portland-geopolymer cements, is used successfully for rapid pavement repair (U.S. DOT 2010). Blue World Crete Company produces a geopolymer that combines a proprietary binding agent with materials containing alumina silicate (Blue World Crete 2012).

Table 4. Emerging alternative cement products

| Technology Name | Energy/Environment/Other Benefits/Costs | Commercial Status | References |
|--|--|----------------------------------|---|
| Cement primarily of fly ash and recycled materials | <ul style="list-style-type: none"> • Recycling fly ash to produce concrete avoids the need for landfill disposal of this industrial byproduct. • Use of fly ash reduces or eliminates the need to mine virgin raw materials for Portland cement production and provides a constructive use for waste fly ash. • Increasing use of fly ash will significantly reduce the energy use needed for cement and concrete production. • Increasing use of fly ash can significantly reduce the greenhouse gas footprint of concrete production by eliminating CO₂ emissions from energy use and calcination in cement production. • Using recycled materials as aggregate in concrete diverts these materials from landfills and reduces the need for mined aggregate. Pulverized post-consumer glass is a recycled material that can be used as concrete aggregate. | Semi-commercial | Roskos et al. (2011); Cross et al. (2005); RecoCement (2011); CERATECH (2012) |
| Geopolymer cement | <ul style="list-style-type: none"> • Potential energy and CO₂ savings from the use of geopolymers are significant. • Expected CO₂ emissions for geopolymers are about 300 kg CO₂/tonne product. This estimate does not take into account emissions from production of the activators, such as sodium silicate, for which no data are available (CSI/ECRA 2009). • Major geopolymer systems rely on minimally processed natural materials or industrial byproducts as binding agents. • The use of industrial byproducts/wastes in the production of geopolymers creates a constructive use for these materials. | Demonstration stage ¹ | Geopolymer Institute (2012); CSI/ECRA (2009); Blue World Crete (2012) |

2.5. Emerging Carbon Capture Technologies for the Cement Industry

Table 5 shows the energy, environmental and other benefits as well as commercialization status of emerging carbon capture technologies for the cement industry. The description of each technology is given below.

2.5.1. Oxygen Enrichment and Oxy-fuel Technologies

The U.S. cement industry has used oxygen-enriched combustion since the 1960s. Using oxygen-enriched combustion air increases energy efficiency, production capacity, and allows fuels with low calorific value to be used in place of fossil fuels. This increases kiln flame temperatures while reducing CO₂ emissions. Short-term experiments have demonstrated a kiln capacity increase of 25 to 50 percent when

combustion air is enriched with 30 to 35 percent oxygen (by volume). Oxygen enrichment has not yet been applied for purposes of reducing CO₂ emissions. Enriched combustion air might reduce kiln fuel use and thus CO₂ emissions, but additional power is required to produce oxygen, so it is not clear whether there would be a net reduction in total energy use.

Oxy-fuel technology is another emerging candidate for CO₂ capture in new cement kilns. This technology is currently still being researched (ECRA 2007 and 2009). Oxy-fuel technology differs from oxygen enrichment in that oxygen enrichment does not replace air but injects oxygen into the combustion zone along with combustion air.

In contrast, oxy-fuel technology replaces the air with an oxygen stream, using pure oxygen instead of air for fuel burning. Because this eliminates the nitrogen that would normally be in the air that is traditionally used for fuel burning, fuel requirements and flue gas volumes are reduced. When the oxygen stream is fed to the kiln, the resulting kiln exhaust gas contains up to 80 percent of the CO₂ concentration from the fuel burning. This fraction of the exhaust stream is transported to a CO₂ separation, purification, and compression facility (U.S. EPA 2010).

Technical issues associated with use of oxy-combustion (oxy-fuel technology) at a cement plant include: the high flame temperatures (3,500°C) produced by this process which is too hot for proper operation of a cement kiln and the need for recycling a portion of the flue gases back to the combustion zone to provide the necessary dilution; heat-transfer characteristics that are influenced by changing the atmosphere within the combustion chamber; deterioration of kiln walls at higher oxygen levels; clinkering process chemistry under different atmospheres need further investigation; costly removal of contamination from the CO₂-rich exhaust gas resulting from excessive air infiltration; power consumption increases of 200 to 240 kWh/tonne O₂ for oxygen delivery using an air separation unit (see table 5) (Barker et al. 2009).

Table 5. Emerging carbon capture technologies for the cement industry

| Technology Name | Energy/Environment/Other Benefits/Costs | Commercial Status | References |
|---|--|--|---|
| Oxygen Enrichment and Oxy-fuel Technologies | <ul style="list-style-type: none"> • Oxygen enrichment technology reduces fuel use by 100 to 200 MJ/tonne clinker but increases electricity use by 10 to 35 kWh/tonne clinker compared to fuel and electricity use in conventional processes (CSI/ECRA 2009). • Short-term experiments have papered a 25- to 50-percent increase in kiln capacity with oxygen enrichment at 30 to 35 percent (volume) in combustion air (CSI/ECRA 2009). • With oxy-fuel technology, overall energy requirements drop by 75 to 84MJ/tonne cement despite an increase of 92 to 96 kWh/tonne cement that is attributable primarily to operation of the CO₂ separation, purification, and compression facility as well as the oxygen production (U.S. EPA 2010). • With oxy-fuel technology, reduction in CO₂ emissions from reduced fuel combustion ranges from 454 to 726 kg CO₂/tonne cement; | <p>Oxy-fuel technology: Pilot stage</p> <p>Oxygen enrichment: Commercial</p> | <p>ECRA (2007 and 2009); U.S. EPA (2010); Barker et al. (2009); CSI/ECRA (2009)</p> |

| Technology Name | Energy/Environment/Other Benefits/Costs | Commercial Status | References |
|-----------------|---|-------------------|------------|
| | <p>however, this would be partially offset by CO₂ emissions increasing by between 50 and 68 kg CO₂/tonne cement because of increased electricity use (U.S. EPA 2010).</p> <ul style="list-style-type: none"> • Using oxy-fuel technology only in the precalciner avoids approximately 61 percent of CO₂ emissions from the process. Using the technology in both precalciner and kiln could avoid almost 100 percent of CO₂ emissions although greater technical uncertainties are associated with this approach (Barker et al. 2009). • The additional investment costs for oxy-fuel technology in a new facility are estimated to range from \$495 to \$540 million, and operational costs would increase by \$10 to 13/tonne cement for a facility producing 2.2 million ton /yr. Costs related to transport and storage of CO₂ are not included (U.S. EPA 2010). | | |

2.5.2. Post-combustion Carbon Capture Using Absorption Technologies

Solvent scrubbing has been used to separate CO₂ in chemical industry exhaust streams (Bosoago et al. 2009). Post-combustion carbon capture takes advantage of this commercially mature technology and applies a common solvent, monoethanolamine (MEA), for CO₂ scrubbing. Because of the high cost of this solvent, it has to be regenerated and reused, an energy-consuming process that results in additional CO₂ emissions. SO₂, NO₂, and oxygen play an important role in solvent degradation mechanisms. Therefore, the SO₂, NO_x, and particulate matter concentrations in flue gases need to be reduced to a minimum before the flue gases go through the solvent scrubbing CO₂ capture system (CSI/ECRA 2009).

Barker et al. (2009) evaluated several technical issues associated with post-combustion amine scrubbing using MEA in a new cement plant. An extensive study by the International Energy Agency (IEA) proposes that cement plants make major changes to implement absorbent technologies. These changes include: addition of a solvent scrubber and regenerator as well as a compressor to increase the pressure of CO₂ emissions for transport by pipeline, high-efficiency flue gas desulphurization and de-NO_x to meet flue gas purity requirements, and a combined heat and power plant to provide steam for regeneration of the solvent. IEA performed a techno-economic analysis of these changes for a new dry-feed-process cement plant located in the UK, with a five-stage preheater and production capacity of 1.1 million tons of cement/yr. The analysis showed that total fuel consumption (coal) increased by 207.2 MW, and net power consumption from the grid decreased by 13.1 MW (because of onsite electricity generation) compared to fuel and power consumption of a similar cement process without the CO₂ capture system. This takes into account excess electricity generation of 2.9 MW by the combined heat and power plant. Avoided CO₂ emissions were 594,000 tons/yr, or 653,200 tons/yr, taking into account the import and export of electricity, which showed 74-percent and 77-percent reductions, respectively. Capital costs increased by \$443M, and operating costs, taking into account the export of excess electricity generation for the steam plant, increased \$95.7 M/yr (U.S. EPA 2010).

Absorption technologies are currently only being used at a pilot scale in the energy sector. Demonstration plants are in the planning phase (ECRA 2009), with the first industrial application

expected around 2020. With modifications, these technologies should then be available for the cement industry (CSI/ECRA 2009). Availability of a transport (pipeline) grid and storage sites are also important factors necessary to support this CO₂-capture technology (see table 5).

2.5.3. Calera Process

The Calera process captures power-plant CO₂ and stores it as a carbonaceous material. Using a process known as “mineralization via aqueous precipitation,” the Calera process converts gas into stable solids such as metastable calcium, magnesium carbonate, and bicarbonate minerals. The process requires a high pH and thus is most economic when power plants are located near sources of suitable brines, which are extracted from geologic formations, as well as alternative sources of alkalinity and minerals. Calera cement is similar to Portland cement and aggregate but can differ by site based on the inclusion of trace components. After processing, the solid materials produced by the Calera process can be used in various construction applications. Calera has another proprietary high-efficiency electrochemical process called “alkalinity based on low energy” uses only salt and electricity to produce NaOH and HCl ($\text{NaCl} + \text{H}_2\text{O} \rightarrow \text{NaOH} + \text{HCl}$) (Calera 2012).

Co-producing electricity with the Calera carbon capture process could reduce power plant emissions by up to 90 percent, with offsetting CO₂ emissions of 10 to 30 percent from the Calera process (CO₂ emissions associated with the energy use by Calera process). It is possible that Calera supplementary cementitious material could replace 20 percent of ordinary Portland cement in concrete, significantly decreasing concrete’s carbon footprint. Challenges associated with the Calera process include dependence on brines extracted from geologic deposits; the need for alternative natural alkalinity resources and/or minerals near the power plant; increase in energy use by Calera process (energy penalty); production of more calcareous material than needed in the current market; potential impact on water balances and hydrology from extraction and reinjection of brines; and the need for environmentally acceptable management of the brines and bicarbonate solutions that must be pumped from and returned to geologic formations as part of the process (Bren 2011).

Calera has a demonstration project at Moss Landing, California that is capable of capturing 30,000 tons per year of CO₂, which is equivalent to a 10-MW electric (MWe) natural gas power plant (Calera 2012). Other Calera demonstrations are planned in California and Wyoming in the USA as well as in China and Australia during the next few years.

2.5.4. Carbonate Looping Technology

Amine scrubbing carbon capture technology uses a significant amount of additional energy that can be reduced by using lime (CaO) as a regenerable sorbent. After reacting with CO₂ for a number of cycles, CaO loses its ability to react with CO₂ and usually becomes waste. However, the exhausted (spent) sorbent could partially replace the main raw material in cement manufacturing, CaCO₃. Because the spent sorbent would not need to be calcined in the kiln (releasing CO₂ to form CaO), using it as a replacement for limestone in cement would reduce CO₂ emissions from calcination, which accounts for more than 50 percent of total CO₂ emissions from the cement production process. This process is also

known as a “looping cycle” or “carbonate looping” technology (Dean et al. 2011).

Abanades (2008) describes the fundamentals of the carbonate looping process, and Pathi et al. (2011) created a model of a simple carbonate looping process based on the average conversion of calcined limestone. The model is used to study the influence of average conversions of limestone in the carbonator on the flow rates of various streams within the looping process, and to study the energy necessary for calciner reactivation. In addition, the model is used to study the carbonate looping process as implemented in the cement pyroprocess.

The European *Cement* Research Academy (*ECRA*) has estimated that modern anthracite- and lignite-fired power plants emit 750 or 950 grams(g) CO₂ /kWh, respectively. An 800-MWe power generation plant discharges approximately 620 or 780 tpd of degraded CaO sorbet (the sorbet has a lifetime of 30 cycles). For a mid-sized plant producing 3,000 tpd of clinker, use of precalcined CaO could meet approximately one-third of the raw material needs. This looping technology would be feasible if the cement plant and the power plant both function in close cooperation, ideally, next to each other in an operational link (see table 5) (Hollingshead and Venta 2009).

2.5.5. Industrial Recycling of Cement Process CO₂ Emissions into High-energy Algal Biomass

Concentrated CO₂ streams produced by cement or power plants could be used to cultivate algae. Due to algae’s sensitivity to impurities, the recycled CO₂ would have to undergo a cleaning process before being used for this purpose. Currently, closed algal cultivation systems for biofuel production have moved from the research phase to pilot and demonstration projects. Because of algae’s potential as a feedstock for biodiesel production, food products, and chemicals, several large global companies, including BP, Chevron, Virgin, and Royal Dutch Shell, have invested research funding in this area (APP 2008).

Commercial-scale systems range from 10 to 100 hectares and are estimated to absorb between 500 and 55,000 tonne CO₂ per system per year. Algae biomass fuels are predicted to become the largest biofuel class by 2022 when they will account for an estimated 37 percent of all biofuels produced. However, large land areas are required for algae cultivation, so the potential for this technology could be limited in areas with high land prices (Parsons Brinckerhoff and GCCSI 2011). Similar to existing agricultural systems, algal cultivation requires large quantities of nutrients, which makes it CO₂ intensive. The technical and reliability barriers to this technology are expected to be overcome within 3 to 5 years, and commercial deployment is expected in 5 to 10 years (APP 2008).

Pond Biofuels, a Canadian company, captures CO₂ and other emissions from a cement plant to create nutrient-rich algae slime. The algae are grown at a facility next to the cement plant to be harvested, dried, and then used as fuel in the plant (Pond Biofuels 2012). Algenol is a U.S. company planning to develop a \$850-million algae plant in the Sonora Desert. Approximately 6 million tons of CO₂ per year would be reused to produce 3.8 million cubic meters of ethanol. Solazyme is another company taking advantage of the microbial fermentation process, fermenting algae on a large scale without the need for sunlight, to produce algae oil. A third company, MBD Energy, uses algae to recycle captured industrial flue-gas

emissions and produce algae oils suitable for manufacture of high-grade plastics, transport fuel, and livestock feed (see table 5) (APP 2008).

3. Conclusions

This paper describes eleven emerging energy-efficiency and CO₂ emissions reduction technologies for cement and concrete production. The information presented for each technology was collected from various sources, including manufacturers. As can be seen from the information presented in this paper, most of the technologies have an energy penalty associated with their operation. Therefore, further research is needed to improve and optimized these technologies in order to minimize their energy penalty. In addition, for some technologies, there was not much information available except from the technology developer. Conducting independent studies and validation on the fundamentals, development, and operation of these emerging technologies can be helpful to private and public sectors as well as academia.

Shifting away from conventional processes and products will require a number of developments including: education of producers and consumers; new standards; aggressive research and development to address the issues and barriers confronting emerging technologies; government support and funding for development and deployment of emerging technologies; rules to address the intellectual property issues related to dissemination of new technologies; and financial incentives (e.g., through carbon trading mechanisms) to make emerging low-carbon technologies, which might have a higher initial costs, competitive with the conventional processes and products.

The purpose of this paper is solely informational. Neither the authors nor Lawrence Berkeley National Laboratory endorses or certifies any of the companies or technologies mentioned, nor do we take responsibility for any actions that readers might take in regard to these technologies.

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References

- Abanades, C. 2008. Calcium Sorbent Cycling for Simultaneous CO₂ Capture and Clinker Production. IPCC SRCCS 2005.
- Andersen, S.; Zaelke, D.; Young, O.; Ahmadzai, H.; Anderson, F.; Atkinson, M.; Carson, E.; Carson, R.; Christensen, S.; Van Deventer, J.; Hanford, S.; Hoenig, V.; Miller, A.; Molina, M.; Price, L.; Ramanathan, V.; Tope, H.; Wilkinson, J.; Yamabe, M., 2011. Scientific Synthesis of the Calera Sequestration of Carbon - Consensus Findings of the Scientific Synthesis Team.
- Asia Pacific Partnership on Clean Development and Climate (APP). 2008. Industrial Recycling of CO₂ from Cement Process into High-Energy Algal Biomass Coal Equivalent Fuel- Project Plan Summary.
- Asia Pacific Partnership on Clean Development and Climate (APP). 2009. Energy Efficiency and Resource Saving Technologies in Cement Industry. Available at http://www.asiapacificpartnership.org/english/cement_tf_docs.aspx
- Barker, D.J., S.A. Turner, P.A. Napier-Moore, M. Clark, J.E. Davison. 2009. CO₂ Capture in the Cement Industry. *Energy Procedia* Vol. 1:87–94.
- Blue World Crete. 2012. Technology. Available at www.greenworldcrete.com
- Bosoago, A., M. Ondrej, J.E. Oakey. 2009. CO₂ Capture Technologies for Cement Industry. *Energy Procedia*, Vol. 1:133-140.
- Calera. 2012. Calera process. Available at www.calera.com
- CalStar Products. 2012. Products. Available at <http://calstarproducts.com/products/>
- Cement Sustainability Initiative (CSI) and European Cement Research Academy (ECRA). 2009. Development of State-of-the-Art Techniques in Cement Manufacturing: Trying to Look Ahead (CSI/ECRA-Technology Papers). Available at <http://www.wbcdcement.org/pdf/technology/Technology%20papers.pdf>
- CERATECH. 2012. CERATECH's cement - Environmental Advantages. Available at <http://www.ceratechinc.com/environmental-advantages.asp>
- Cross, D., J. Stephens, J. Vollmer. 2005. Structural Applications of 100 Percent Fly Ash Concrete. 2005 World of Coal Ash (WOCA), Lexington, Kentucky, USA April 11-15, 2005, Lexington, Kentucky, USA. Available at www.flyash.info/2005/131cro.pdf
- Dean, C.C., D. Dugwell, P.S. Fennell. 2011. Investigation into potential synergy between power generation, cement manufacture and CO₂ abatement using the calcium looping cycle. *Energy Environ. Sci.*, 2011,4. DOI: 10.1039/c1ee01282g
- EMC Cement. 2011. Energetically Modified Cement. Available at <http://www.emccement.com/index.htm>
- European Commission. 2010. Integrated Pollution Prevention and Control (IPPC), Reference Document on Best Available Techniques in the Cement and Lime Manufacturing Industries. Available at <http://eippcb.jrc.es/reference/>
- European Cement Research Academy GmbH (ECRA). 2009. ECRA CCS Project - Paper about Phase II. Available at <http://www.cement.org/bookstore/profile.asp?id=16950>

- European Cement Research Academy GmbH (ECRA), 2007. Carbon Capture Technology - Options and Potentials for the Cement Industry. Available at <http://www.cement.org/bookstore/profile.asp?id=15360>
- Geopolymer Institute. 2012. Science - Chemical Structure and Applications. Available at <http://www.geopolymer.org/science/chemical-structure-and-applications>
- Hollingshead, A.F., G. J. Venta. 2009. Carbon Dioxide Reduction Technology Effectiveness Assessment – Initial Evaluation. Available at www.cement.org
- Kumar, S., R. Kumar, R., A. Bandopadhyay, T.C. Alex, B. Ravi Kumar, S.K. Das, S.P. Mehrotra. 2008. Mechanical activation of granulated blast furnace slag and its effect on the properties and structure of Portland slag cement. *Cement & Concrete Composites* 30: 679–685.
- Kumar, R., S. Kumar, S.P. Mehrotra., 2007. Towards sustainable solutions for fly ash through mechanical activation. *Resources, Conservation and Recycling* 52: 157–179.
- Kumar, S., R. Kumar, R., A. Bandopadhyay. 2006. Innovative methodologies for the utilization of wastes from metallurgical and allied industries. *Resources, Conservation and Recycling* 48: 301–314.
- New Energy and Industrial Technology Development (NEDO). 2008. Japanese Technologies for Energy Savings/GHG Emissions Reduction- 2008 Revised Edition. Available at www.nedo.go.jp/content/100107259.pdf
- Parsons Brinckerhoff and Global CCS Institute (GCCSI). 2011. Accelerating the uptake of CCS: Industrial use of captured carbon dioxide. Available at <http://www.globalccsinstitute.com/publications/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide>
- Pathi, S.K., M.F. Andersen, W. Lin, J.B. Illerup, K. Dam-johansen, K. Hjuler. 2011. Carbonate looping for decarbonization of cement plant. 13th International Congress on the Chemistry of Cement. Available at <http://www.mendeley.com/research/carbonate-looping-decarbonization-cement-plant/>
- Perkins, D. 2000. CemStarSM Technology Offers Increased Production and Environmental Benefits. World Cement, December 2000.
- Pond Biofuels. 2012. Pond Biofuels' Technology. Available at <http://www.pondbiofuels.com/Technology/Technology.html>
- RecoCement. 2012. RēcoCement™. Available at <http://recocement.com/>
- Roskos, C., D. Cross, M. Berry, J. Stephens. 2011. Identification and Verification of Self-Cementing Fly Ash Binders for “Green” Concrete. 2011 World of Coal Ash (WOCA) Conference – May 9-12, 2011 in Denver CO, USA. Available at www.flyash.info/2011/132-Berry-2011.pdf
- Schneider, M., M. Romer, M. Tschudin, H. Bolio. 2011. Sustainable cement production - present and future. *Cement and Concrete Research* 41: 642–650.
- Schneider, M. 2008. Innovation and optimization in cement grinding - European Cement Research Academy (ECRA). Available at bcsd.teri.res.in/documents/docs/event18_20/20martin1.pdf
- United Nations Framework Convention on Climate Change (UNFCCC). 2009. Sichuan Carbide Calcium Residues Based Cement Plant Project in Leshan City. CDM project design document. Available at <http://cdm.unfccc.int/Projects/DB/LRQA%20Ltd1218613946.27/view>

- United Nations Framework Convention on Climate Change (UNFCCC). 2008a. Nanning Shizuo Non-Carbonated Raw Material for Cement Production Renovation Project. CDM project design document. Available at <http://cdm.unfccc.int/Projects/DB/DNV-CUK1218618890.63/view>
- United Nations Framework Convention on Climate Change (UNFCCC). 2008b. Shanxi Carbide Calcium Residues Based Cement Plant Project in Linfen City. CDM project design document. Available at <http://cdm.unfccc.int/Projects/DB/LRQA%20Ltd1218656574.54/view>
- U.S. Department of Energy (U.S. DOE)'s Advance Manufacturing Office (AMO). 2011. Industries and Technologies. Available at http://www1.eere.energy.gov/industry/industries_technologies/index.html
- U.S. Department of Transportation (U.S. DOT). 2010. Geopolymer Concrete. <http://www.fhwa.dot.gov/pavement/concrete/pubs/hif10014/index.cfm>
- U.S. EPA. 2010. Available and Emerging Technologies for Reducing Greenhouse *Gas Emissions from the Portland Cement Industry*. Available at www.epa.gov/nsr/ghgdocs/cement.pdf
- World Business Council for Sustainable Development (WBCSD)/International Energy Agency (IEA). 2009a. Cement Technology Roadmap 2009 - Carbon emissions reductions up to 2050. Available at www.iea.org/papers/2009/Cement_Roadmap.pdf
- World Business Council for Sustainable Development (WBCSD)/International Energy Agency (IEA). 2009b. Cement roadmap targets. Available at www.iea.org/papers/2009/Cement_Roadmap_targets_viewing.pdf
- Worrell, E., C. Galitsky, L. Price. 2008. Energy Efficiency Improvement Opportunities for the Cement Industry. Berkeley CA: Lawrence Berkeley National Laboratory Paper LBNL-72E. <http://ies.lbl.gov/node/402>
- Worrell, E., C. Galitsky. 2004. Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making. An ENERGY STAR® Guide for Energy and Plant Managers. Available at www.energystar.gov/ia/business/industry/LBNL-54036.pdf