Title
Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Cement Sector

Author
Sathaye, J.

Publication Date
2011-03-31

Ernest Orlando Lawrence Berkeley National Laboratory

LBNL Report

Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Cement Sector

Jayant Sathaye
Tengfang Xu
Christie Galitsky

Environmental Energy Technologies Division

August 2010

This work was supported by the Climate Economics Branch, Climate Change Division, U.S. Environmental Protection Agency through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Disclaimer

LBNL Final Report

Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Cement Sector

Jayant Sathaye
Tengfang Xu
Christie Galitsky

Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory
Berkeley, CA

Prepared for
Eric Smith
Climate Economics Branch
Climate Change Division
US Environmental Protection Agency

This work was supported by the Climate Economics Branch, Climate Change Division, U.S. Environmental Protection Agency through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Table of Contents

Appendices

Table of Tables

Table of Figures

General Acronyms

Greenhouse gas (GHG)
Carbon dioxide (CO2)
Energy-climate (EC) models
Integrated assessment models (IAM)
Cost of conserved energy (CCE)
Cost of carbon reduction (CCR), or Cost of reduced carbon (CRC)
Conservation supply curve (CSC)
Computational general equilibrium model (CGE)
Operation and maintenance (O&M)
Gross Domestic Product (GDP)
Environmental Protection Agency (EPA)
Bureau of Economic Analysis (BEA).
International Energy Agency (IEA)
United States Geological Survey (USGS)
Department of Energy (DOE)
Department of State (DOS)
Portland Cement Association (PCA)
Energy Information Administration (EIA)
Manufacturing Energy Consumption Survey (MECS)
Model Acronyms
ADAGE - Applied Dynamic Analysis of the Global Economy Model
AIM- The Asian-Pacific Integrated Model
AMIGA - All-Modular Industry Growth Assessment Model
BEAR - Berkeley Energy and Resources
COBRA - Cost-Optimized Burden-Sharing and Regional emission Allocation
MARKAL - MARKet ALlocation
MESSAGE - Model for Energy Supply Strategy Alternatives and their General Environmental Impact

Units

Energy (in petajoules -PJ, or in gigajoules - GJ)
Cost of conserved energy (CCE, $/GJ)
Energy savings per production (GJ/Tonne)
Million metric ton, or million tonne (Mt)
Million tonne of carbon (MtC)
Cost of carbon reduction (CCR, $/MtC)
Capital cost ($)
Capital recovery factor (yr-1)
Annual change in O&M costs ($/yr)
Annual total of productivity benefits ($/yr)
Annual energy savings (GJ/yr)
Lifetime of the mitigation option (years)
Annual carbon savings (tC/yr)

Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Cement Sector

Executive Summary

Adoption of efficient end-use technologies is one of the key measures for reducing greenhouse gas (GHG) emissions. How to effectively analyze and manage the costs associated with GHG reductions becomes extremely important for the industry and policy makers around the world.

Energy-climate (EC) models are often used for analyzing the costs of reducing GHG emissions for various emission-reduction measures, because an accurate estimation of these costs is critical for identifying and choosing optimal emission reduction measures, and for developing related policy options to accelerate market adoption and technology implementation. However, accuracies of assessing of GHG-emission reduction costs by taking into account the adoption of energy efficiency technologies will depend on how well these end-use technologies are represented in integrated assessment models (IAM) and other energy-climate models.

In this report, we first conduct a brief review of different representations of end-use technologies (mitigation measures) in various energy-climate models, followed by the problem statement, and a description of the basic concepts of quantifying the cost of conserved energy including integrating no-regrets options. According to IPCC (2001), no-regrets opportunities for GHG emissions reduction are the options whose benefits such as reduced energy costs and reduced emissions of local or regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change. In this report, a no-regrets option is defined as a GHG reduction option (i.e., via energy efficiency measure) that is cost effective over the lifetime of the technology compared with a given energy price, without considering benefits of avoided climate change. There are two types of treatments of no-regrets options: 1) options that include other benefits, e.g., reduced operational and maintenance costs and productivity benefits; and 2) options that exclude other benefits. Although existence of no-regret options is not entirely acknowledged by some economists, a number of cost-effective measures in the U.S. cement sector were identified and studied in this report, regardless whether or not other benefits are included. There are many factors including market barriers and knowledge gap that contribute to slower adoption of such measures in the markets.

Based upon reviews of literature and technologies, we develop information on costs of mitigation measures and technological change. These serve as the basis for collating the data on energy savings and costs for their future use in integrated assessment models. In addition to descriptions of the cement making processes, and the mitigation measures identified in this study, the report includes tabulated databases on costs of measure implementation, energy savings, carbon-emission reduction, and lifetimes.

Through characterizing energy-efficiency technology costs and improvement potentials, we have developed and presented energy and carbon reduction cost curves for energy efficiency measures applicable to the U.S. cement industry for the years 1994 and 2004. The cost curves can change significantly under various scenarios: the baseline year, discount rate, energy intensity, cement production, industry structure (e.g., blended vs. non-blended cement making, wet kiln conversion

to dry cement making), efficiency measures, share of cement production to which the individual measures can be applied, and inclusion of other non-energy benefits. Based upon limited data available for quantifying other benefits of individual mitigation measures, we have found that inclusion of other benefits from implementing some mitigation measures can change the actual costs of conserved energy. In addition, costs of conserved energy (CCE) for individual mitigation measures increase with the increases in discount rates, resulting in a general increase in total cost of mitigation measures for implementation and operation with a higher discount rate. In this study, all the cost data (U.S. dollars) are obtained and presented in the currency values for the respective reference years (i.e., 1994, 2004). A direct comparison of costs (U.S. dollars), when desired, can be made by converting the existing reference-year data (i.e., 1994, 2004 in this study) to a preferred reference year (e.g., 2007). The conversions can be accomplished by multiplying the existing cost in a reference year by a Gross Domestic Product (GDP)-based inflation index for the preferred year (BEA 2009).

In this study, we included 31 mitigation measures for year 1994 and 36 mitigation measures for year 2004 in the analysis based upon availability of such data for each year, respectively. We also estimated potential energy savings and carbon-emission reduction corresponding to the mitigation measures for each year (1994 and 2004), respectively. In addition, we have developed and defined the concept for cost of carbon reduction (CCR) associated with the mitigation measures; therefore, the cost of carbon reduction for each mitigation measure can be established and estimated based upon available information. Main findings are included in the following.

We evaluated final energy use in the U.S. cement making sector, and estimated that 366 petajoules (PJ) final energy was used in 1994, and 465 PJ final energy was used in 2004. We calculated that from 1994 to 2004 the cement production energy intensity has decreased from 6 GJ/t to 5.1 GJ/t (a reduction of 15%) in wet-cement production, indicating efficiency technology uptakes in wet-cement production over the period of time. During the same period, the cement production energy intensity remained stable at the level of 4.5-4.6 GJ/t for dry-cement production, indicating no significance change in efficiency technology uptakes. In addition, there was a production expansion in less energy intensive dry-cement in 2004. As a result, the overall cement production energy intensity decreased from 4.9 GJ/t to 4.7 GJ/t (a reduction of 4%) from 1994 to 2004.

The potential savings of final energy use from applying 31 measures was 42 PJ for blended cement and 39 PJ for non-blended cement in 1994, while the potential savings of final energy use resulting from applying 36 mitigations measures was 54 PJ for blended cement and 72 PJ for non-blended cement in 2004. Therefore, the technical potential of energy savings was approximately 22% in 1994 and 27% in 2004.

We have identified a number of cost-effective mitigation measures in this study. Furthermore, inclusion of other benefits from implementing mitigation measures can reduce the costs of conserved energy significantly, making more measures cost-effective. We estimated that the potential savings of final energy use resulting from cost-effective mitigations measures was 53 PJ in 1994 and 89 PJ in 2004, corresponding to 15% and 19% of total annual final energy use in the U.S. cement industry in 1994 and 2004, respectively. Implementing cost effective measures can result in significant energy savings relative to the total annual energy use in the sector, and more even so when compared to the technical energy savings potential.

The total carbon emissions associated with the U.S. cement sector consists of two categories: 1) energy use for cement production, and 2) the direct emissions from cement-making processes. We estimated that total carbon emissions from the cement sector in the U.S. were approximately 18.9 million ton of carbon (MtC) in 1994 and 24.2 MtC in 2004. We estimated that the potential reduction of carbon emissions resulting from the applicable mitigation measures was 4.2 MtC (2.2 MtC blended, and 2.0 MtC non-blended) in 1994 and 6.5 MtC (2.8 MtC blended, and 3.7 MtC non-blended) in 2004, corresponding to 22% and 27% of annual total carbon emissions in 1994 and 2004, respectively. We have found that applying cost-effective measures would reduce carbon emissions by 2.8 MtC in 1994 and by approximately 4.7 MtC in 2004, corresponding to 15% and 19% of annual total carbon emissions in 1994 and 2004, respectively. Implementing cost effective measures can result in significant carbon-emission reduction relative to the total carbon emissions in the sector, and more even so when compared to the technical potential in carbon-emission reduction.

We have also concluded that based upon the cost curves derived from available information on mitigation measures for both years, the rate of change in the energy-savings or carbon-reduction potential at a given cost can be evaluated and be used to estimate future rates of change for input in energy-climate models. Accuracies of such estimation of the rate change may be improved as more comprehensive information on characterizing the mitigation measures becomes available. Implementing existing cost effective measures can result in significant energy savings and carbon-emission reduction for both years relative to their technical potential in energy savings and carbon-emission reduction. In addition, total costs of conserved energy increase with the increases in discount rates. The outcomes from this research provide information on initial technology database that can be accessible to integrated assessment modeling groups seeking to enhance their empirical descriptions of technologies.

While many energy efficiency technologies have become cost-effective to mitigate long-term climate change, it is important and necessary to continue to incorporate new information on technology characteristics, and their evolution and response to energy and carbon price into various integrated assessment models to enhance empirical descriptions of the technologies, e.g., econometric models, service demand models, discrete choice models, or computational general equilibrium (CGE) models.

There appears to be a need to develop and refine sectoral algorithms and produce databases that can be used to match the needs of different integrated assessment modeling of climate policies. New algorithms should allow transformation of information on behavioral responses, technology costs, energy savings, other benefits, and policy costs into meaningful and functional data forms. Developing such algorithms may require customization and automation of database functions that would account for many variables. Furthermore, the desired data-model linking effort will require close interfaces between modelers and the developers of the cost-curve databases on energy efficiency measures. Future efforts should also include additional business sectors.

1 Background

According to International Energy Agency (IEA 2007), over one-third of the world's energy consumption and 36% of carbon dioxide (CO_2) emissions are attributable to manufacturing industries worldwide. According to the United States Geological Survey (USGS), in 2007 the cement sector produced approximately 2.6 billion tonnes of cement (Van Oss 2008). Used as a binding agent in concrete, it is an essential element for building infrastructure, and therefore world's total production is increasing, especially in recent years in developing countries including India and China.

Energy constitutes a significant portion of the cost of cement production and accounts for a large portion of industrial sector energy use and carbon dioxide emissions worldwide. The aggregate amount of carbon dioxide (CO_2) emitted from the global cement industry has reached about 1.5 billion tonnes, accounting for approximately 5% of global anthropogenic CO_2 emissions (US DOS 2006).

The U.S. cement industry is made of portland cement plants that produce clinker in either wet or dry kilns and then grind the clinker to make finished cement, or clinker-grinding plants that intergrind clinker obtained elsewhere. Clinker is produced through a controlled high-temperature burn in a kiln of a measured blend of calcareous rocks (usually limestone) and lesser quantities of siliceous, aluminous, and ferrous materials. The kiln feed blend (also called raw meal or raw mix) is adjusted depending on the chemical composition of the raw materials and the type of cement desired. Portland and masonry cements are the chief types produced in the United States. More than 95% of the cement produced in the U.S. in 2007 was portland cement, while masonry cement accounted for rest of the U.S. cement output in 2007 (USGS 2008). Dry cement plants accounted for 82% and wet plants for 13% of cement production in 2006. Wet plants in 2006 averaged about 6.5 GJ per ton of clinker, about 3% lower than the ratio in 2005, and dry kiln plants averaged about 4.1 GJ per ton of clinker, unchanged from the ratio in 2005 (Van Oss 2008). Combination plants (operating both wet and dry kilns) averaged 4.9 GJ per ton in 2006, also unchanged.

In 2007, there were 113 operating cement plants in 37 states in the U.S. producing between 0.5 and 3.1 million tonnes per year, for a total U.S. production of 95 million tonnes (Van Oss 2008). Approximately 560 PJ of primary energy was used for producing the cement in the United States (EIA, 2001). The total carbon emissions from the U.S. cement industry is the sum of carbon emissions associated with total energy (fuel) use for cement production and the direct carbon emissions from process (e.g., the carbon directly emitted from the calcinations of limestone to make clinker). In 1999 the U.S. cement industry was responsible for a total of 22.3 MtC emissions, which was approximately 5% of all industrial carbon emissions, and about 2% of the total anthropogenic carbon emissions in the United States (Worrell and Galitsky, 2004).

Based upon the available data, we estimate that the total annual carbon emissions from the U.S. cement sector was 18.9 MtC (sum of direct emissions from processes and emissions associated with energy use in the sector) in 1994 and 24.2 MtC in the 2004. In order to understand the impact of energy efficiency measures on the sector and cost and potential of carbon-emission reduction, we evaluate a list of mitigation technologies for increasing energy efficiency and reducing carbon emissions from the U.S. cement sector for 1994 and 2004 in this study, for which cost and energy-savings data on mitigation measures are available.

2 Introduction

Adoption of efficient end-use technologies is one of the key measures for reducing GHG emissions. In many cases, implementing energy efficiency measures is among one of the most cost effective investments that the industry could make in improving efficiency and productivity while reducing CO_2 emissions. With ambitious energy and carbon policies being implemented globally, effectively analyzing and managing the costs associated with GHG reductions becomes extremely important for industry and policy makers.

Energy-climate (EC) models are often used for analyzing the costs of reducing GHG emissions (e.g., carbon emission) for various emission-reduction measures, because an accurate estimation of these costs is critical for identifying and choosing optimal emission reduction measures, and for developing related policy options to accelerate market adoption and technology implementation. However, accuracies of assessing of GHG-emission reduction costs by taking into account the adoption of energy efficiency technologies will depend on how well these end-use technologies are represented in integrated assessment (IA) models and other energy-climate models. For example, if the models do not include end-use technologies with an appropriate level of detail in their modeling framework, it will be difficult to estimate, with confidence, the costs and benefits of reducing GHG emissions by adopting efficient end-use technologies.

In this report, we will first conduct a brief review of different representation of end-use technologies in various energy-climate models; then we will elaborate the statement of the problems upon which the purpose of this study will be defined. The report will then describe the basic concepts of quantifying the cost of conserved energy and carbon reduction including integrating non-regrets options. According to IPCC (2001), no-regrets opportunities for GHG emissions reduction are the options whose benefits such as reduced energy costs and reduced emissions of local or regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change. In this report, a no-regrets option is defined as a GHG reduction option (i.e., via energy efficiency measure) that is cost effective over the lifetime of the technology compared with a given energy price, without considering benefits of avoided climate change. Although existence of no-regret options is not entirely acknowledged by some economists, a number of cost-effective measures in the U.S. cement sector were identified and studied in this report, regardless whether or not other benefits are included. There are many factors including market barriers and knowledge gap that contribute to slower adoption of such measures in the markets.

We will develop information on costs of mitigation measures and technological change. These serve as the basis for collating the data on energy savings and costs for their future use in IA models. The concept description is then followed by a section on developing energy efficiency cost curves for the cement industry in the U.S. The cost curve data on mitigation measures are available over time, which allows an estimation of technological change over a decade-long historical period. . In particular, the report will address technological change in energy-climate modeling, e.g., assessing the changes in costs and savings potentials between two or more historical conservation supply curves.

The last section summarizes the conclusions and recommendations for future work. In addition, the report includes tabulated databases on costs of implementation, energy savings, carbon-emission reduction, and lifetimes as exhibited in Appendix A. Finally, Appendix B of this report includes descriptions of cement-making processes, and the mitigation measures noted in Appendix A.

2.1 Representation of End-use Technologies in Existing Energy-climate Models

Many existing integrated assessment models originally emerged primarily from economic and energy modeling approaches that were for the most part developed for, and applied to, industrialized economies (Sanstad and Greening, 1998). Increasingly, however, these models have been enhanced and extended over time, and in many cases created, to encompass the global economy at various levels of regional and sectoral disaggregation.

Factoring technological changes in both energy supply and end-use technologies may significantly affect the outcomes of estimated GHG emissions associated with energy systems in such energy-climate models. A majority of energy-climate models can handle, to various extents, the input of technological changes. In exogenous modeling of technological change, the rate of technological changes (improvement) is specified exogenously by the modelers, not the model itself. In endogenous modeling of technological change, various approaches exist, such as modeling technological changes via "learning by doing." In this case, the costs of new technologies decline overtime and their technical characteristics improve with increased market adoption. Improvement in efficiency, cost, and market adoption (e.g., cumulative installed capacity) are included as input to the model. Both exogenous and endogenous modeling of technological changes can benefit from historical data. In this study, we focus particularly on two issues related to the representation of end-use technologies in energy climate models: treatment of technological change, and treatment of no-regrets options. There are two types of treatments of no-regrets options: 1) options that include other benefits, e.g., reduced operational and maintenance costs and productivity benefits; and 2) options that exclude other benefits.

To improve the representation of end-use technologies in energy-climate models, it is necessary to understand how end-use technologies are represented in common models. Table 1 summarizes a review of how end-use technologies are represented in seven energy-climate models included for this study. End-use technologies are represented in five of the seven models. Four out of the seven models explicitly take both no-regrets options and technological change in end-use technologies into consideration.

Pending the availability of information, or body of knowledge about what is known (or even knowable), modelers commonly made one choice over another when establishing input assumptions, and methodologies for their desired models. In all of the selected models reviewed in this study, except for the MARKet ALlocation (MARKAL) model, the technological change is considered in an exogenous manner. Among the six models with exogenous treatment of technological changes, only four of them include end-use technology representation, as well as concurrent no-regrets options. In addition, the levels of detail in handling technological change and no-regrets options also vary across the models. For example, in All-Modular Industry Growth Assessment (AMIGA) modeling, end-use technologies in residential and commercial sectors and some industries are represented to date. In Berkeley Energy and Resources (BEAR) modeling, end-use technologies are represented only for the cement industry. Energy savings due to overall improvements in end-use energy efficiency are represented for different sectors. However, specific technologies associated with these savings are not identified. In Cost-

Optimized Burden-Sharing and Regional emission Allocation (COBRA) modeling, end-use technologies and no-regrets treatment are considered for some key energy consuming industries. However, the cost of policies and programs to promote no-regrets options are not included.

Table 1. A review on different representation of end-use technologies in common energy-climate models

Model	Representation of End-Use Technologies	Treatment of No-regrets Options	Treatment of Technological Change	Treatment of Technological Change in End-Use Technologies
ADAGE - Applied Dynamic Analysis of the Global Economy, by Research Triangle Institute	No	No	Exogenous	No
AIM - The Asian-Pacific Integrated Model, by a collaborative international team led by Japan's National Institute for Environmental Studies	Yes	Yes	Exogenous	Yes
AMIGA - All-Modular Industry Growth Assessment, by Argonne National Laboratory (ANL)	Some	Yes	Exogenous	Yes
BEAR - Berkeley Energy and Resources, by UC Berkeley	Some	Yes	Exogenous	Yes
COBRA - -Optimized Burden-Sharing and Regional emission Allocation, by Lawrence Berkeley National Laboratory	Some	Yes	Exogenous	Yes
MARKAL - MARKet Allocation, by Brookhaven National Laboratory	Some	No	Endo-genous	Yes, exogenous.
MESSAGE Model for Energy Supply Strategy Alternatives and their General Environmental Impact, by Austria's International Institute for Applied Systems Analysis (IIASA)	No	No	Exogenous	No

Note: CGE models are included in many IAMs, except AMIGA, COBRA, MARKAL, or MESSAGE.

Apparently, there are opportunities to improve technology representation in the selected models and many others, which can provide more accurate estimation of the costs of reducing GHG emissions due to technological changes and associated benefits.

2.2 Statement of Problem

Information on costs and saving potentials of energy efficiency measures and ways that these end-use technologies are represented in energy-climate models vary greatly from model to model. Many energy-climate models are not created to represent technology-specific costs, energy savings or GHG-emission reductions; instead they are often restricted to evaluation of carbon prices or cap-and-trade programs without adequate consideration of issues on mitigation technologies. The difference in cost estimates can be attributed to various assumptions in economic growth, resource endowment, selection of policy instrument, treatments of no-regrets options (e.g., including or excluding other benefits), and cost and availability of supply- or demand-side technologies.

An often-debated issue is the integration of end-use technologies in large bottom-up energy-climate models. The extent of including representation of such technologies in large energy-climate models varies greatly: e.g., some without technological representation, some with representation if any being limited to certain sectors such as electric power generation, or some with detailed end-use technological representation. Therefore, a major challenge is to determine the appropriate interfaces for the use of bottom-up technology or sector-specific data in energy-climate models.

Often many IA models ignore policy and programmatic costs of measure implementation; on the other hand, other non-energy benefits are also often not included or accounted for in model input. Therefore, such modeling is often inadequate to accurately estimate the real costs of reducing GHG emissions. For example, exclusion of other benefits (as one way of treating no-regret options) in models is largely because modelers either lack sufficient data or because their current model structure is not suitable for representing these options. As a result, the way in which most of these models are calibrated tends to force a prediction of positive mitigation costs. In addition, although some models that represent end-use technologies model technological change over time, none of them represents technological change in end-use technologies endogenously. This approach has limited their ability to analyze the effect of policies that promote early adoption of efficient end-use technologies to reduce their future costs.

Integrated assessment modeling of climate policy uses various top-down models that describe the general economy and its interactions, and the effects of price changes. Many of these models include a sectoral representation of the economy. The existing empirical basis for modeling of sector-based technologies is often weak, and often largely arises from literature at the sectoral level rather than technology level. There is a need to investigate and improve the representation of end-use technologies in energy-climate models, in coordination with energy-climate modelers who will stand to benefit from this research.

Given the growing importance of technological improvement (e.g., energy efficiency) as an avenue to mitigate climate change, it is critical that technology characteristics, their evolution and response to energy and carbon price be understood better than has been the case to date. This is also particularly true of developing countries where obsolete technologies are likely to see a more rapid transformation as their markets integrate into the global economy, while newer technologies are likely to be adopted faster due to evolving global markets and availed policy support.

2.3 Project Purpose

The overarching goal of this research is to characterize technology costs and potentials for improvement in energy efficiency in several U.S. industrial sectors. The purpose of this project is to develop a technology database and modules that will be accessible to IAM groups seeking to enhance their empirical descriptions of technologies for modeling. In this report, we will describe concepts of cost of conserved energy (CCE) and cost of carbon reduction (CCR), and develop and present the cost curves of mitigation options based upon available historical data, with a focus on the U.S. cement sector. Effect of technological change on savings potential will be analyzed, which may become useful input for estimating future savings potential in energy-climate models.

3 Concepts for Cost Curves of Conserved Energy and Carbon Reduction

3.1 Cost of Conserved Energy Curves – with and without Other Benefits

Conservation Supply Curves (CSCs) were developed in the 1970s as a way to rank energy conservation investment along with energy supply investment in order to identify the least cost approach. CSCs can be used to show how much energy-conservation would be supplied corresponding to a specific energy price, and have long been a primary analytical tool for evaluating the economic benefits of energy efficiency. These have been constructed for the major energy demand sectors, and the energy savings have been translated into corresponding GHG emissions reductions in many countries.

A CSC plots the marginal cost of conserved energy by a mitigation option (mitigation capital cost) against the total amount of energy conserved. Equation 1 shows the parameters used in estimating the marginal cost of conserved energy (CCE). By calculating and ranking CCE value for each efficiency measure, a CSC curve can be developed by plotting the ranked CCE values consecutively on the y-axis against cumulative energy savings along the x-axis.

$$CCE = \frac{I \cdot q}{ES}, \text{ Equation 1}$$

$$q = \frac{d}{(1-(1+d)^{-n})}, \text{ Equation 2}$$

Where:

CCE = Cost of conserved energy for a mitigation option, in $/kWh

I = Capital cost ($)

q = Capital recovery factor (yr^{-1})

ES= Annual energy savings (kWh/yr)

d = discount rate

n = lifetime of the option (years)

Earlier analyses of energy efficiency options typically ignored other effects of their implementation. Modification of Equation 1 to Equation 3 includes other benefits: These effects include changes in operation and maintenance (O&M), which may lead to a reduction in “M” value; as well as reduced capital cost, which may correspond to a lowered “I” value in the equation. The effects can also include additional monetizable productivity benefits, noted as "B" in Equation 3.

The contributing factors to productivity benefits include additional labor, material, and other resource requirements that are often monetizable, and other benefits such as reduced pollution due to decreased use of electricity and other fuels that may be more difficult to quantify, and in particular more difficult to attribute to a single mitigation measure (e.g., as shown in Table 2). In principle, adding monetizable non-energy effects that are attributable to an energy efficiency option can decrease the cost of conserved energy. These may be expressed as shown in Equation 3 (Worrell et al. 2003).

$$CCE = \frac{I \cdot q + (M - B)}{ES}, \text{ Equation 3}$$

Where

CCE = Cost of conserved energy for an energy-efficiency measure (or mitigation option), in \$/GJ

I = Capital cost (\$)

q = Capital recovery factor (yr^{-1})

M = Annual change in O&M costs (\$/yr)

B = Annual total of productivity benefits (\$/yr)

ES = Annual energy savings (GJ/yr)

Accounting for such "hidden benefits" requires that bottom-up models look beyond the energy markets and examine the cost considerations in light of their impact on other resource markets.

Using the primary energy price of \$2.14/GJ in 1994, Worrell et al. (2003) reported cost effective annual primary energy savings of 1.9 GJ/tonne for the U.S. iron and steel industry in 1994 (Figure 1). Corresponding to the implementation of an array of 47 measures, the cost of supplied energy conservation is generally reduced when productivity benefits associated with labor and material cost savings are included in the calculation during the operation of an efficient iron and steel plant (Table 2). Inclusion of such productivity benefits has however, increased the savings potential due to cost-effective measures to 3.8 GJ/tonne at the same unit price of primary energy (\$2.14/GJ in 1994).

When including productivity benefits, the CCE ranking of technologies changes dramatically. Inclusion of all resource benefits thus is crucial to understanding the full cost impacts of a technology. This may be particularly relevant to end-use energy efficiency technologies whose main goal often is not only providing energy savings but also providing some other form of services related to the production of an industrial product.

Table 2. Non-energy benefits from efficiency improvements in U.S. iron and steel industry (Worrell et al. 2003)

Waste	Emissions	Operation & Maintenance
Use of waste fuels, heat, gas	Reduced dust emissions	Reduced need for engineering controls
Reduced product waste	Reduced CO, CO2, NOx, Sox emissions	Lower cooling requirements
Reduced waste water		Increased facility reliability
Reduced hazardous waste		Reduced wear and tear on equipment/machinery
Materials reduction		Reductions in labor requirements
Production	**Working Environment**	**Other**
Increased product output/yields	Reduced need for personal protective equipment	Decreased liability
Improved equipment performance	Improved lighting	Improved public image
Shorter process cycle times	Reduced noise levels	Delaying or Reducing capital expenditures
Improved product quality/purity	Improved temperature control	Additional space
Increased reliability in Production	Improved air quality	Improved worker morale

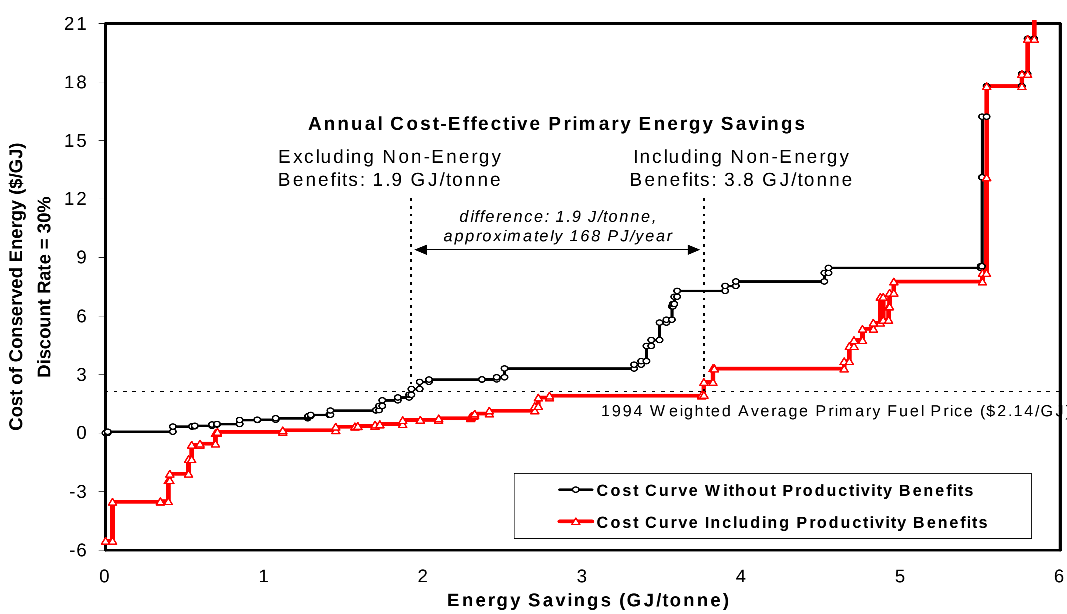

Figure 1. Conservation supply curves with and without including non-energy benefits, U.S. steel industry (Worrell et al. 2003)

3.2 Calculation of cost of carbon reduction related to energy savings

Adopting energy efficiency options can reduce carbon emissions associated with energy use in the industry. In this study, we define cost of carbon reduction (CCR) associated with mitigation measures in the cement sector, which has included the other benefits monetized for the changes in operation and maintenance. The cost of energy-related carbon reduction is treated to be the same as the cost of mitigation measures, which is normalized by the quantity of carbon reduction corresponding to each mitigation measure.

Mitigation cost of carbon reduction (CCR) for a mitigation measure may be expressed in Equation 4.

$$CCR = \frac{I \cdot q + (M - B)}{\Delta(C)}, \text{ Equation 4}$$

Where:

CCR = Cost of carbon reduction for an energy-efficiency measure (or mitigation option), in \$/tC (carbon tonne)

I = Capital cost (\$)

q = Capital recovery factor (yr^{-1})

M = Annual change in monetizable other benefits (\$/yr)

B = Annual total of productivity benefits (\$/yr)

ΔC= Annual carbon savings (tC/yr)

4 Treatment of Technological Change in Climate Modeling

An important issue related to the representation of both supply and end-use technologies is how the technological change that results in mitigation improvement is taken into account in energy-climate modeling. Assumptions about technological change may include determination of efficiency levels of energy supply and end-use technologies into the near future. Therefore, the treatment of technological change is an important factor that will influence the mitigation costs and reductions in future emissions in energy-climate models. As discussed earlier, there are two common methods of including technological change in energy-climate models: exogenous modeling and endogenous modeling.

In exogenous modeling, the rate of improvement in technology is specified exogenously by the modelers and is not determined or simulated within the exogenous model.

In endogenous modeling, various approaches are implemented to model endogenous technological change. For example, one of the popular approaches is to model technological change as learning-by-doing where the costs of technologies decline and their technical characteristics improve with increased adoption of technologies. In this case, the external input to the model includes learning rates that specify the relationship between improvements in technology characteristics (primarily technology cost and efficiency) and the technology's cumulative installed capacity.

Overall, the input parameters required for modeling technological change in exogenous or endogenous models can be based upon estimates from analyzing historical trends. For example, Nakicenovic et al. (2000) have published curves showing the decline in costs of electricity-supply technologies over time. These time trends are typically used for exogenously specifying technological change. Sathaye et al. (2006) developed a simplified global energy supply and carbon cycle model, the Cost-Optimized Burden-Sharing and Regional Emission Allocation in the energy sector (COBRA-Energy). It is driven by exogenous energy demand projections and implements a scheme for international burden sharing for the 21st century, which takes into account the regional amounts of cumulative, anthropogenic emissions. Some efficiency technologies were represented in the COBRA model using the historical data and changes over time. Other studies estimated learning rates (Manne and Barreto, 2002) and used them in endogenous modeling of technological change.

To date, there has been limited representation of demand-side technological change in the energy-climate models reviewed in this report, in part because of a lack of such information. In this study, we develop a new approach of treating technological change in energy-climate modeling (Xu et al. 2010). The new approach is based on quantifying changes in costs and savings potentials between two or more historical conservation supply curves. With this approach, cost curves of mitigation technologies are first developed for two historic periods, respectively; followed by calculating the rate of change of the savings potential at a given cost, which can then be the basis for estimating future rates of change and the input into energy-climate models.

5 Development of Cost Curves and Estimate of Technological Changes for the Cement Sector

The U.S. cement production consists of wet-cement and dry-cement production, of which processes includes raw materials preparation, clinker production, and finish grinding. The energy efficiency of an operating cement plant is significantly affected by several elements, such as type of products, technologies, plant size, and quality of raw materials. Dry cement making tends to be less energy intensive than wet cement making.

Table 3 shows that in 1994, wet-cement plants produced 21.2 Mt cement and dry-cement plants produced 53.1 Mt dry cement, for a total of 74.3 Mt cement production in the United States. In 2004 wet-cement plants produced 20.2 Mt cement and dry-cement plants produced 78.8 Mt cement, for a total of 99 Mt cement production in the United States. We analyzed final energy use in the U.S. cement making sector, and estimated that 366 Peta-joules (PJ) final energy was used in 1994, and 465 PJ final energy was used in 2004.

Table 3. Final energy, associated carbon emissions, and production in 1994 and 2004.

		Wet-cement	Dry-cement	Total
1994	Energy Use (PJ)	127	239	366
2004	Energy Use (PJ)	102	363	465
1994	Carbon Emissions (MtC)	3.2	6.2	9.4
2004	Carbon Emissions (MtC)	2.6	9.5	12.1
1994	Production (Mt)	21.2	53.1	74.3
2004	Production (Mt)	20.2	78.8	99
1994	Energy Intensity (PJ/Mt)	6.0	4.5	4.9
2004	Energy Intensity (PJ/Mt)	5.1	4.6	4.7

From 1994 to 2004, the final energy intensity for cement production has decreased from 6.0 GJ/t to 5.1 GJ/t (a 15% reduction) in wet-cement production, indicating efficiency technology uptakes in wet-cement production over the period of time. During the same period, the cement production energy intensity remained stable at the level of 4.5-4.6 GJ/t for dry-cement production, indicating no significance change in efficiency technology uptakes. In addition, there was a production expansion in less energy intensive dry-cement in 2004. As a result, the overall cement production energy intensity decreased from 4.9 GJ/t to 4.7 GJ/t (a 4% reduction) from 1994 to 2004.

The total carbon emissions associated with energy use in cement making were 9.4 MtC in 1994, and were 12.1 MtC in 2004.

In this paper, we analyze the potential of energy savings and carbon reduction of energy efficiency measures and their annualized costs based upon the available data for years 1994 and 2004, respectively. The analysis was accomplished by developing cost curves of energy savings and carbon reductions. The sensitivities of cost curves to their determinants are then discussed and evaluated.

Based upon the cost curves, the rate of change in the savings potential at a given cost can be evaluated and be used to estimate future rates of change that can be the input for energy-climate models.

5.1 Development of Cost Curves for Mitigation Measures

In order to develop cost curves for mitigations measures, we adopted the methodology discussed in the previous section to evaluate applicable measures for 1994 and 2004. For example, cost curves for 31 measures for improving energy efficiency in the cement sector were evaluated for the year 1994, and cost curves of 36 measures were developed for the year 2004. The data on costs of implementation, energy savings and lifetimes were collected from a variety of sources, including information and data from the Portland Cement Association, case studies and experts from around the world. These data are included in Appendix A1 (1999) and Appendix A2 (2004). In addition, Appendix B includes descriptions of the mitigation measures noted in Appendices A1 and A2.

In addition to energy savings, some of the measures had identifiable and quantifiable additional benefits, such as reduced labor and maintenance or increased yields. In order to highlight these benefits associated with the mitigation measures, Table 3 enlists the technologies for the cement industry that have these additional benefits.

Table 4. Mitigation Technologies for the Cement Industry that Have Other Benefits as well as Energy Benefits (and the process – wet or dry – to which they apply) (Martin et al., 1999; Worrell and Galitsky, 2004)

Measure	Wet/ Dry	Benefit
Raw materials preparation		
Mechanical transport systems	Both	Increased reliability and decreased downtime
Use of high efficiency roller mills	Dry	Increased throughput, flexibility, and raw meal fineness.
Raw meal process control	Dry	Increased throughput
High Efficiency Classifiers	Dry	Increased grinding mill capacity and improved product quality due to more uniform particle size
Fuel Preparation		
Roller mills	Both	Greater variety of coal sizes and throughput available
Clinker Production – wet cement		
Process control & management	Wet	Improved product quality and grindability, increased cooler throughput, reduced free lime and NOx and increased refractory life.
Kiln combustion system improvements	Wet	Increased output
Indirect firing	Wet	Reduced NOx emissions, better operation with varying fuel mixtures and longer lifetime of kiln refractory
Kiln shell heat loss reduction	Wet	Improved reliability of the kiln and reduced downtime
Use of waste fuels	Wet	Reduced disposal costs and emissions
Conversion to semi-dry process	Wet	Increased capacity
Optimize heat recovery of clinker cooler (grate)	Wet	Increased product quality and reduced maintenance
Clinker production - dry cement		
Kiln combustion system improvements	Dry	Increased output
Kiln shell heat loss reduction	Dry	Improved reliability of the kiln and reduced downtime
Use of waste fuels	Dry	Reduced disposal costs and emissions
Low pressure drop cyclones for suspension pre-heaters	Dry	Increased overall dust loading and increased dust carryover
Conversion from dry to multi-stage pre-heater kilns	Dry	Increased clinker production capacity

Conversion from multi-stage pre-heater to pre-calciner kiln	Dry	Increased productivity and reduced NOx emissions
Optimize heat recovery of clinker cooler (grate)	Dry	Increased kiln capacity and reduced maintenance of grate
Finished Grinding		
Improved grinding media	Both	Reduced wear
High pressure roller press-pre grinding	Both	Increased productivity
Roller press/horomill system	Both	Increased productivity
High efficiency classifiers	Both	Increased productivity
General Measures		
Energy management and process control system	Both	Increased productivity
Preventative maintenance	Both	Increased plant utilization ratio

After each mitigation technology is characterized individually, its applicability to the U.S. cement industry as a whole was then assessed as well. In principle, in order to estimate the potential for future uptake of each energy efficiency and GHG-emission reduction measure, each measure was characterized by the degree to which implementation of the measure can be applied in the U.S. cement industry. The potential degree of implementation depends on a number of factors, such as technical limitations on the implementation of the measure in specific processes and the degrees of application of competing technologies.

The key sources for the cement sector were the statistics published by the United States Geological Survey, the list of plants published by the Portland Cement Association (PCA), and the Labor and Energy Survey of the PCA (USGS, various years; PCA 1990 and PCA 1996). In addition, reference information on equipment suppliers (e.g. F.L. Smith, Polysius, Pavilion Technologies) and news articles (e.g., Cement Americas, International Cement Review and World Cement) were used: Anonymous 1994; Bösche 1993; Conroy 1997; Crosilla and Häutle 1997; Grydgaard 1998; Haspel and Henderson 1993; Hrizuk 1999; Martin and McGarel 2001a and 2001b; Patzelt 1993; Rajbhandari 1995; Steuch and Riley 1993; Su 1997).

In general, overall data availability limits the accuracies of estimating the potential degree of implementation. For some measures, it is easier to find data than other measures. For example, the Energy Information Administration reports the uptake of some energy efficiency measures in the Manufacturing Energy Consumption Survey (MECS), such as crosscutting technologies like process controls, building controls, waste heat recovery or adjustable speed drives (EIA 1997; 2001; 2005).

In this report, we focus on years 1994 and 2004, largely because the data available for both years were more complete than other years. All the cost data (U.S. dollars) are obtained and presented as the currency values for the respective reference years (i.e., 1994, 2004). A direct comparison of costs (U.S. dollars), when desired, can be easily made by converting the existing reference-year data (i.e., 1994, 2004 in this study) to a preferred reference year (e.g., 2007). The conversions can be accomplished by multiplying the existing cost in a reference year by a GDP-based inflation index for the preferred year (BEA 2009).

5.2 Energy Cost Curves with and without Other Benefits in the U.S. Cement Industry in 1994 and 2004

Two different curves of conserved energy (in U.S. dollar per GJ energy used) of mitigation measures can be plotted against the specific final energy savings (GJ per tonne of cement) of two scenarios: with and without inclusions of other non-energy benefits (e.g., productivity benefits) for the U.S. cement industry in 1994 and 2004, as shown

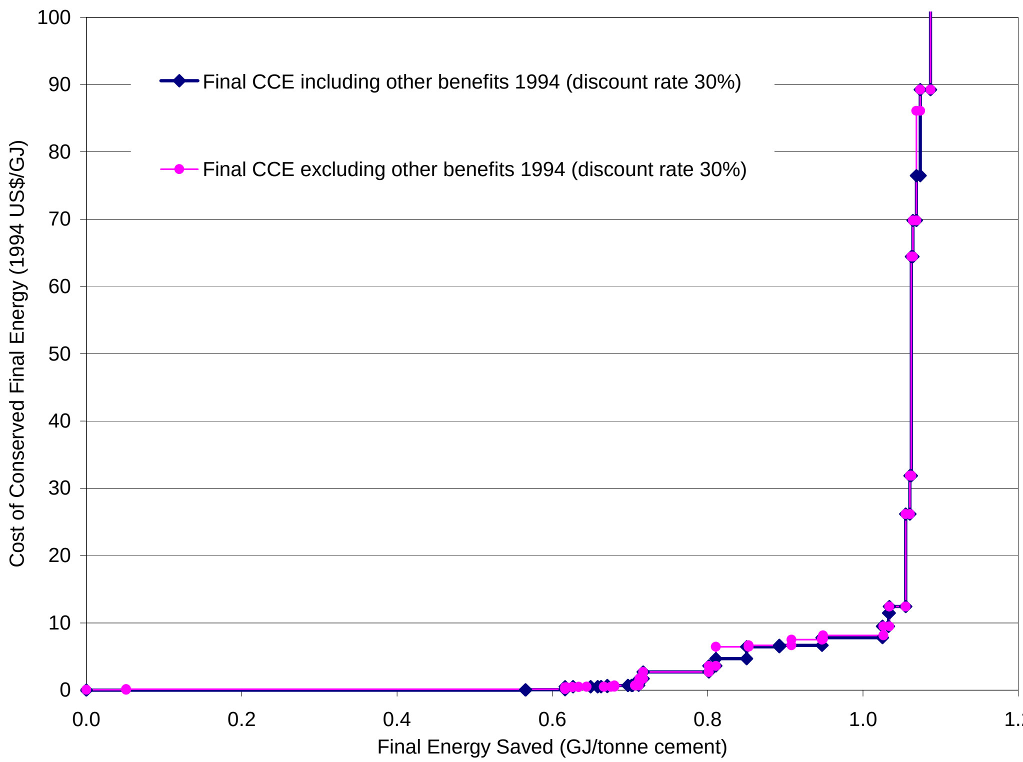

Figure 2 (1994) and

Figure 3 (2004). . The scale of ordinate y-axis in

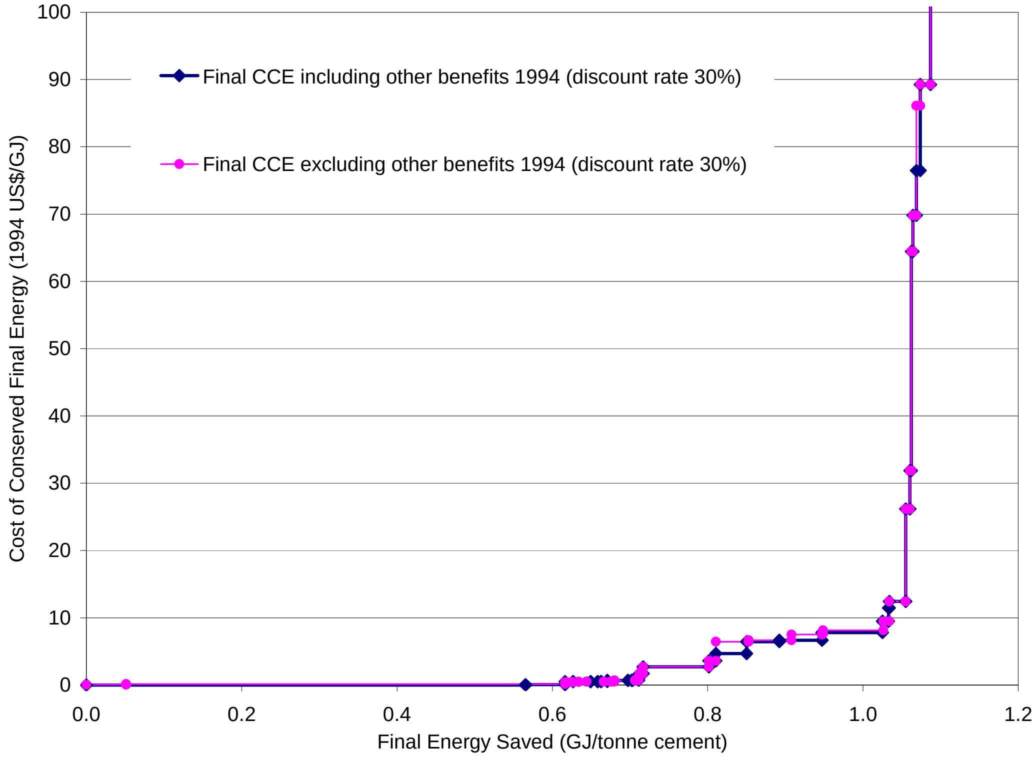

Figure 2 and

Figure 3 is truncated to highlight the major potential of final energy savings (in fact only the last measure is excluded for each plot).

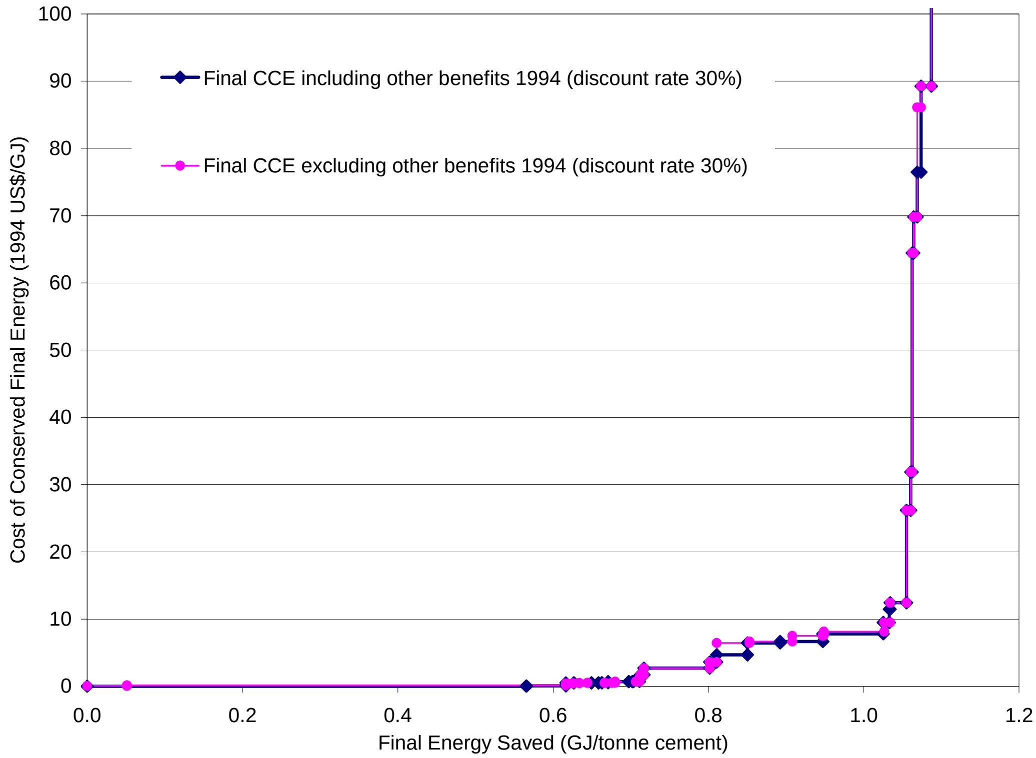

Figure 2. Cost curves for inclusion and exclusion of other benefits in U.S. cement industry in 1994

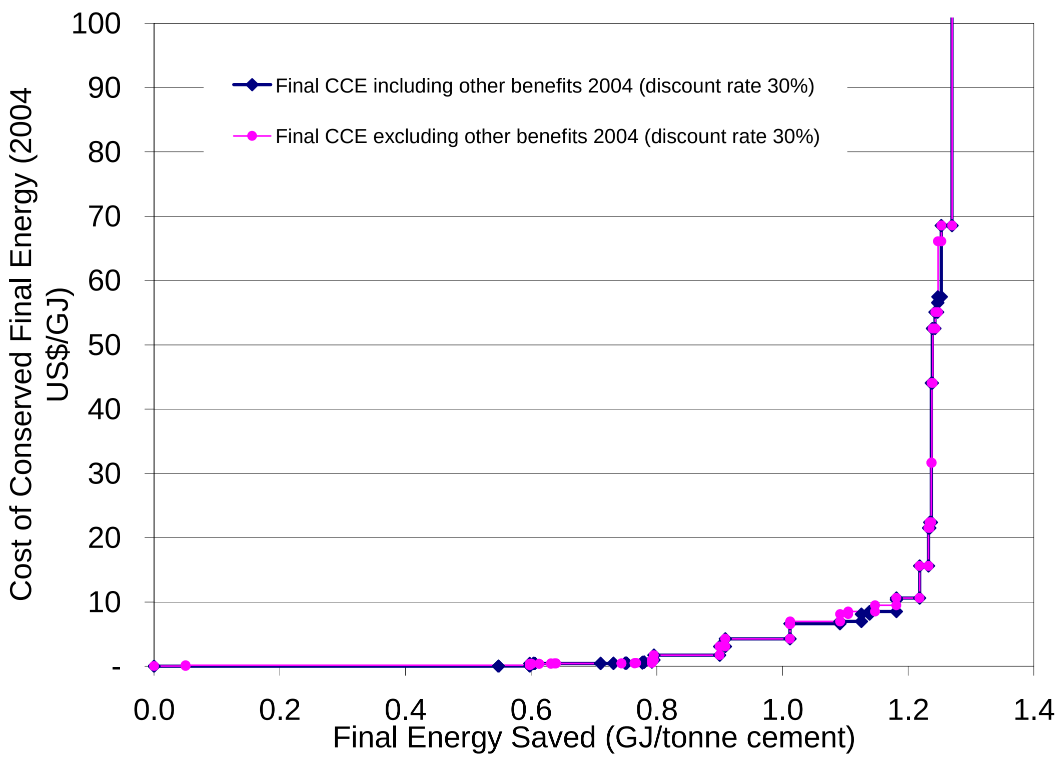

Figure 3. Cost curves for inclusion and exclusion of other benefits in U.S. cement industry in 2004

For calculating the CCE values, we assumed that a real discount rate of 30% is applied, in part reflecting the industry's capital constraints and preference for short payback periods and high internal rates of return. In general, the assumption of higher discount rates (e.g., 30%) can also indirectly account for program costs and various barriers against the adoption of cost-effective energy efficient technologies. It is also clear that such an assumption would mathematically lead to a prediction with higher (e.g., positive) annualized costs of GHG mitigation measures. An energy-climate model that assumes a high discount rate or constrains market penetration of efficient technologies may represent two likely scenarios – the first being that market failures and indirect costs are a reality for implementing efficiency measures; or the second being that cost-effective policies are not implemented while the costs of efficiency measures are positive. In the latter case, however, implementing these policies could possibly lead to negative-costs of GHG mitigation measures and improved market.

As shown in both figures, the CCE of some measures becomes different when other non-energy benefits are excluded from calculation. Changes in cost ranking, the CCE (final energy) and cost-effectiveness due to the exclusion or inclusion of other benefits are shown in Table 4 for measures in 2004. A difference in ranking was exhibited when other benefits are taken into account.

Table 5. The effect of non-energy benefits on the cost-effectiveness of conservation measures in cement sector (30% discount rate)

	Final CCE excluding other benefits			Final CCE including other benefit		
Measure -2004 Cement	(US$/GJ)	Rank of 35	cost effective	(US$/GJ)	Rank of 35	cost effective
Preventative maintenance	0.05	1	y	0.05	2	y
Blended cements	0.16	2	y	0.01	1	y
conversion to grate clinker cooler (w)	0.36	3	y	0.64	10	y
conversion to grate clinker cooler (d)	0.36	4	y	0.64	11	y
conversion to semi-wet kilns (w)	0.37	5	y	0.48	7	y
Use of waste fuels (w)	0.43	6	y	0.43	3	y
Kiln shell heat loss reduction (w)	0.43	7	y	0.43	4	y
Use of waste fuels (d)	0.43	8	y	0.43	5	y
Kiln shell heat loss reduction (d)	0.43	9	y	0.43	6	y
Optimize heat recovery of clinker cooler (grate) (w)	0.50	10	y	0.50	8	y
Optimize heat recovery of clinker cooler (grate) (d)	0.50	11	y	0.50	9	y
Kiln combustion system improvements (w)	0.82	12	y	0.82	12	y
Process control & management (w)	0.96	13	y	0.96	13	y
Energy Management and Process Control system	1.74	14	y	1.74	14	y
High efficiency motors	3.07	15	no	3.07	15	no
conversion from dry to pre-heater, pre-calciner kilns (d)	4.25	16	no	4.25	16	no
heat recovery for cogeneration (d)	6.53	17	no	10.34	21	no
conversion to dry multi-stage pre-heater, pre-calciner kilns (w	6.96	18	no	6.63	17	no
Variable speed drives	8.11	19	no	8.11	19	no
conversion from dry to multi-stage pre-heater kilns (d)	8.50	20	no	8.50	20	no
conversion from multi-stage pre-heater to pre-calciner kiln (d)	9.48	21	no	6.95	18	no
Roller press/horomill system	10.61	22	no	10.61	22	no
conversion to semi-dry process (w)	15.61	23	no	15.61	23	no
Improved Grinding Media	21.51	24	no	21.51	24	no
High pressure roller press-pre grinding	22.38	25	no	22.38	25	no
roller mills (w)	31.64	26	no	56.56	29	no
roller mills (d)	31.64	27	no	358.51	35	no
Raw meal process control (d)	44.06	28	no	44.06	26	no
High Efficiency Classifiers	52.51	29	no	52.51	27	no
Low pressure drop cyclones for suspension pre-heaters (d)	55.08	30	no	55.08	28	no
High Efficiency Classifiers (d)	66.10	31	no	57.47	30	no
Use of High Efficiency Roller Mills (d)	68.53	32	no	68.53	31	no
Mechanical Transport Systems (d)	112.45	33	no	112.45	32	no
Slurry Blending and Homogenizing (w)	307.86	34	no	307.86	33	no
Raw meal blending systems (d)	331.54	35	no	331.54	34	no

As shown in the table, the measures for which changes in CCE and therefore rank are most dramatic include conversion to grate clinker coolers (wet and dry), and conversion to semi-wet kilns in 2004. The CCE values of the majority of the other measures remain unchanged or only changed slightly whether or not to include other benefits, when 30% discount rate is assumed in the estimation.

One would expect that at a lower discount rate (e.g., 10%), including non-energy benefits for all measures in the cost curve should decrease the total cost of conserved energy for all measures.

By changing the discount rates for the estimation, we confirmed this hypothesis with CCE value comparisons for the U.S. cement industry in 2004. Figure 4 shows different costs of conserved final energy including other benefits with various discount rates for year 2004. The Y-axis is truncated at \$100/GJ saved in order to exhibit the cost difference corresponding to the majority of the efficiency measures.

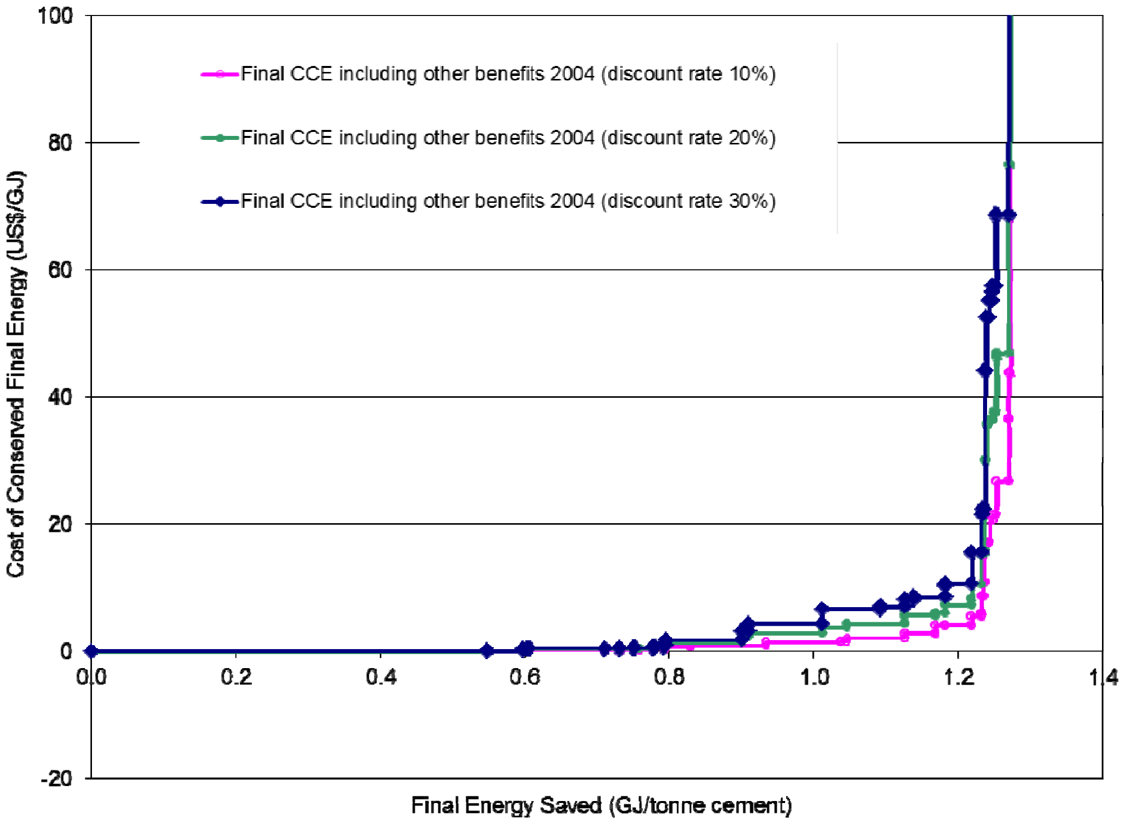

Figure 4. Cost of conserved final energy including other benefits with various discount rates

Assuming with a discount rate of 30%, we calculated that the total cost of conserved final energy from 31 measures was approximately \$68/GJ to achieve the total energy savings of 1.27 GJ/tonne cement; while the other five measures appeared to be more expensive, collectively contributing to an additional energy savings of 0.003 GJ/tonne cement. All measures when implemented would contribute to a total energy savings of 1.273 GJ/tonne cement, and collectively cost \$439/GJ.

With a discount rate of 20%, the total cost of conserved final energy from 31 measures was approximately \$47/GJ to achieve the total energy savings of 1.27 GJ/tonne cement; while the other five measures appeared to be more expensive, collectively contributing to an additional energy savings of 0.003 GJ/tonne cement. All measures when implemented would contribute to a total energy savings of 1.273 GJ/tonne cement, and collectively cost \$349/GJ.

With a discount rate of 10%, the total cost of conserved final energy from 31 measures was approximately \$37/GJ to achieve the total energy savings of 1.27 GJ/tonne cement; while the other five measures appeared to be more expensive, collectively contributing to an additional energy savings of 0.003 GJ/tonne cement. All measures when implemented would contribute to a total energy savings of 1.273 GJ/tonne cement, and collectively cost $338/GJ.

In summary, the calculated costs of conserved final energy increase with the increase in discounted rates. Furthermore, the spread in the costs of conserved energy corresponding to the same discount rate difference (e.g. a difference of 10%) become less sensitive when discount rates are lower (e.g., ranging from 10% to 20%); and become more sensitive when discount rates are higher (e.g., ranging from 20% to 30%).

5.3 Estimating Technological Change (Uptake) between 1994 and 2004

Many factors affect the changes seen in the cost curves: discount rates, energy intensity, production, industry structure (e.g., shares of wet kiln conversion versus dry cement making), shares of U.S. production to which the individual measures are applied, additional technologies and measures becoming available from 1994 to 2004, and data availability of the costs, savings, and other benefits. We have identified 31 measures for 1994, and 36 measures for 2004. Not all measures have other benefits or information available for monetizing the other benefits if any.

Figure 5 shows two cost curves, one that was developed for 1994 and the other for 2004 for the entire U.S. cement sector. Each of the two curves shows the costs of conserved energy versus energy-savings potential for each year. In general, energy-savings potential in 2004 was larger than that in 1994 when given the same cost of conserved energy (i.e., exhibited by a same Y-value in the chart). Quantifying or comparing historic changes in the magnitudes of savings potential can be useful for predicting future trend for energy climate modeling. In this case, we quantified the rate of change in energy-savings potential at a given cost over this decade (2004 vs. 1994) using 1994 as the baseline. For instance, at the cost of $40/GJ, the energy-savings potential increased from 1.06 GJ/tonne to 1.24 GJ/tonne (by approximately 15%) over this decade. This shift may be used to estimate future rates of change. For all measures, the technical potential of energy savings would be 1.09 GJ/tonne in 1994 and 1.27 GJ/tonne in 2004, indicating a shift of 16.5% using 1994 as the baseline.

There are a number of reasons for which the observed technical potential increased from 1994 to 2004. These included 1) technology uptakes, especially in wet-cement making process that had in fact become less energy intensive in 2004; 2) cement industry's production and structure change, e.g., higher dry-cement production in 2004 (in terms of the actual production and its share of the total cement production); and 3) more mitigation measures in 2004 - more technologies were available and applicable to the cement sector. The changes (e.g., structural changes, technological uptakes, additional mitigation measures) had also collectively affected the percentage applicability of each measure to the whole U.S. cement industry, thus the total potential of applicable energy savings.

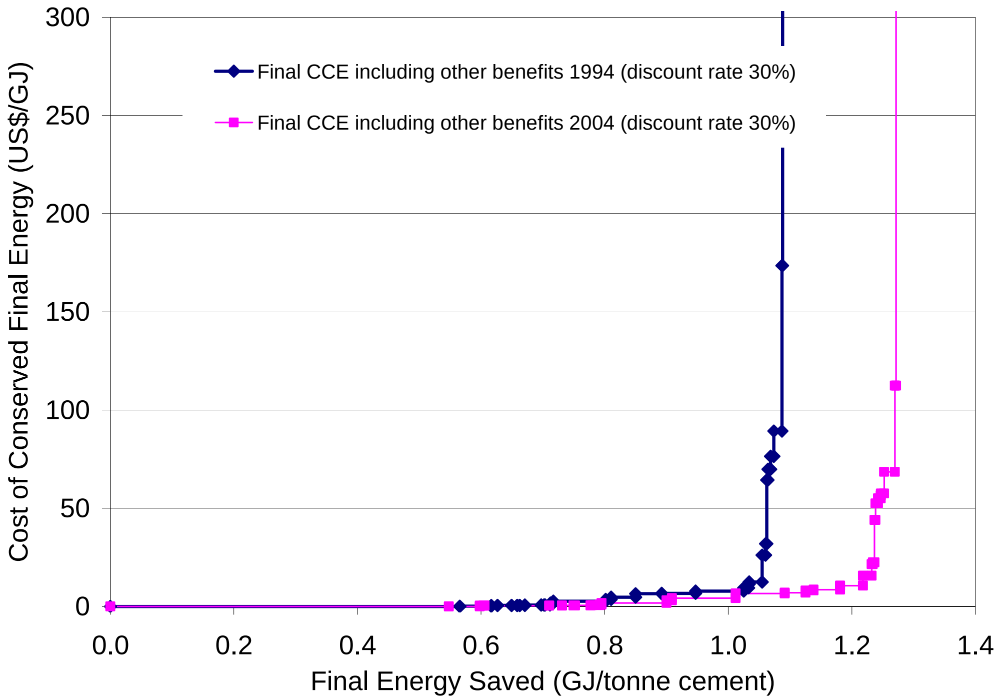

Figure 5. U.S. cement sector: Changes in energy savings potential between 1994 and 2004 due to technological uptake, structure change, and mitigation measures (30% discount rate with other benefits).

The technical potential for energy savings are calculated and presented in Table 6. The potential technical savings was 54 PJ from blended cement measure and 72 PJ from non-blended cement measures in 2004, while it was 42 PJ for blended cement and 39 PJ for non-blended cement measures in 1994. We evaluated overall cement making, and estimated that 465 PJ final energy was used in 2004, and 366 PJ final energy was used in 1994. Therefore, the technical potential of energy savings was approximately 22% in 1994 and 27% in 2004.

Table 6. Technical potential for applied final energy savings in 1994 and 2004.

	Applied Final Energy Savings (PJ)			
Year	Blended	Non-blended	Total	Max Applied Technical (%)
1994	42	39	81	22%
2004	54	72	126	27%

Furthermore, based upon the unit energy prices, we can identify cost effective measures from the pool of mitigation measures. For example, when using final energy price of $2.00/GJ for 1994 and 2004 to select cost-effective measures, we have found blended cement measure to be a major cost-effective measure, as potential energy savings from implementing all cost-effective measures are shown in Table 7.

Table 7. Technical potential for cost-effective final energy savings in 1994 and 2004.

	Cost-effective Final Energy Savings (PJ)			
Year	Blended	Non-blended	Total	Energy Savings (%)
1994	42	11	53	15%
2004	54	35	89	19%

We estimated that the potential savings of final energy use resulting from cost-effective mitigations measures was 53 PJ in 1994 and 89 PJ in 2004, corresponding to 15% and 19% of total annual final energy use in the U.S. cement industry in 1994 and 2004, respectively.

This is an important finding in that implementing existing cost effective measures can result in significant energy savings for both years (and future years) relative to the total annual final energy use, and more so compared to their technical potential in energy savings.

Based upon the cost curves derived from available information, the rate of change in the savings potential at a given cost can be evaluated and be used to estimate future rates of change that can be the input for energy-climate models. For example, from the cost curves, we can quantify the rate of change in energy-savings potential at a given cost over this decade (2002 vs. 1994) using 1994 as the baseline.

6 Estimation of Carbon Reduction and its Costs

The total carbon emissions associated with the U.S. cement sector consist of two categories: 1) energy use for cement production (9.4 MtC in 1994, 12.1 MtC in 2004), and 2) direct emissions from cement-making processes (9.5 MtC in 1994, 12.2 MtC in 2004). We estimated that the total carbon emissions from the cement sector in the U.S. were approximately 18.9 MtC in 1994 and 24.2 MtC in 2004.

Associated with the energy savings from implementing mitigations measures is the mitigation cost and carbon reduction. We consider cost of carbon reduction as the cost of the mitigation measures, taking other benefits (whenever monetized data is available for this study).

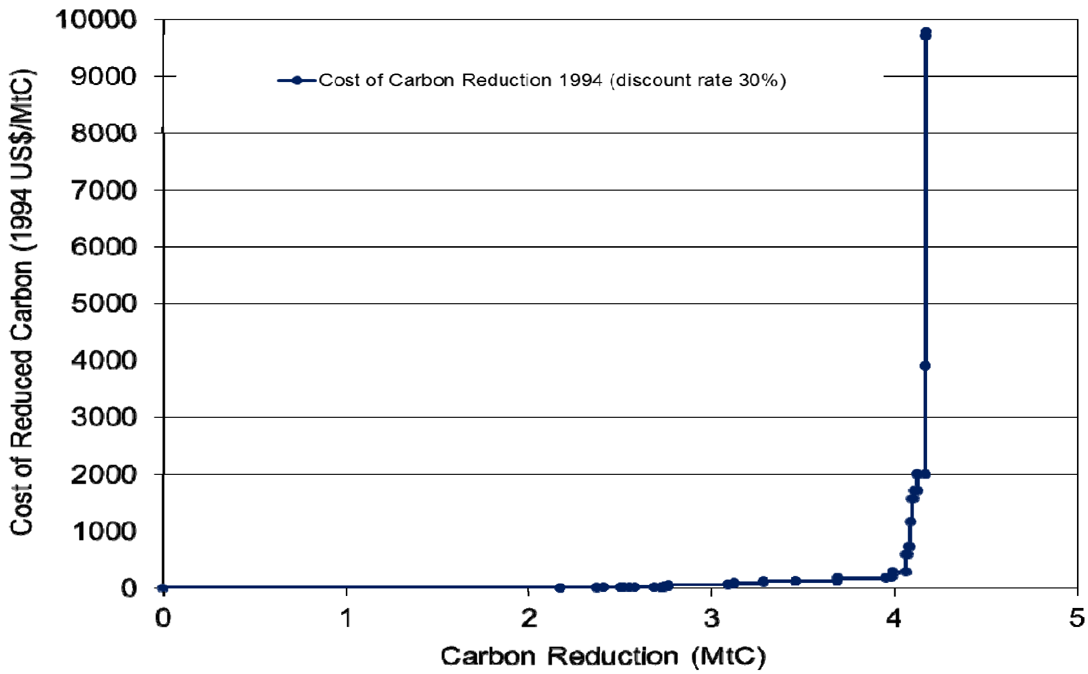

Figure 6 shows cost curve of conserved carbon (in U.S. dollar per MtC) of mitigation measures against the carbon reduction (in MtC) with discount rate of 30% and with inclusion of other benefits for the U.S. cement industry in 1994.

Figure 7 shows cost curve of conserved carbon (in U.S. dollar per MtC) of mitigation measures against the carbon reduction (in MtC) with discount rate of 30% and with inclusion of other benefits for the U.S. cement industry in 2004

.

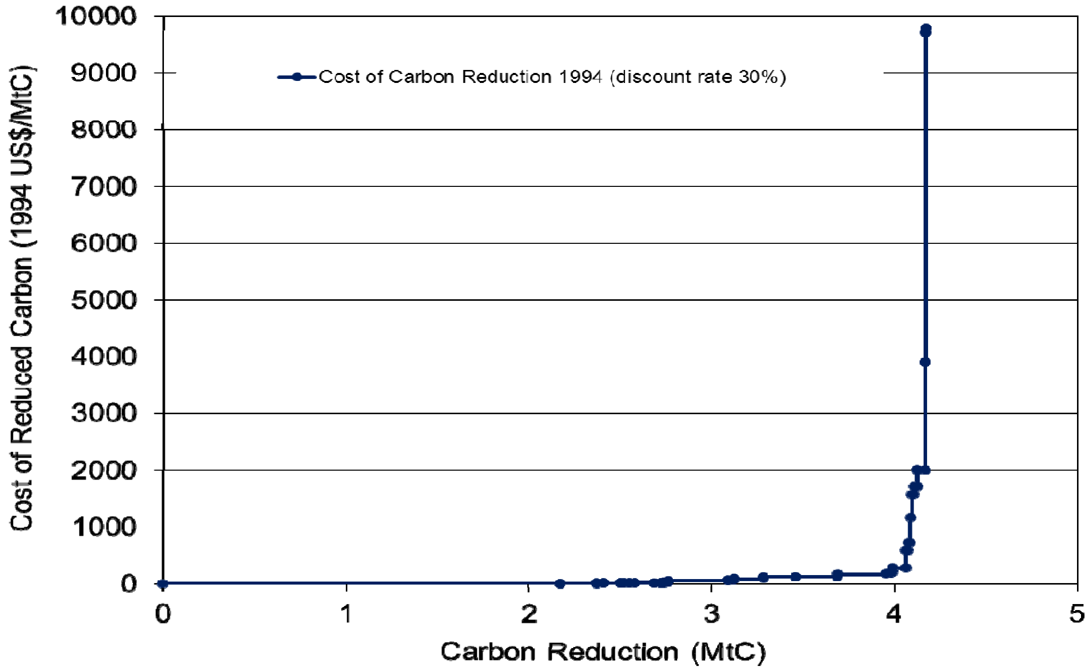

Figure 6. Carbon reduction cost curve for the U.S. cement sector, 30% discount rate, with other benefits 1994

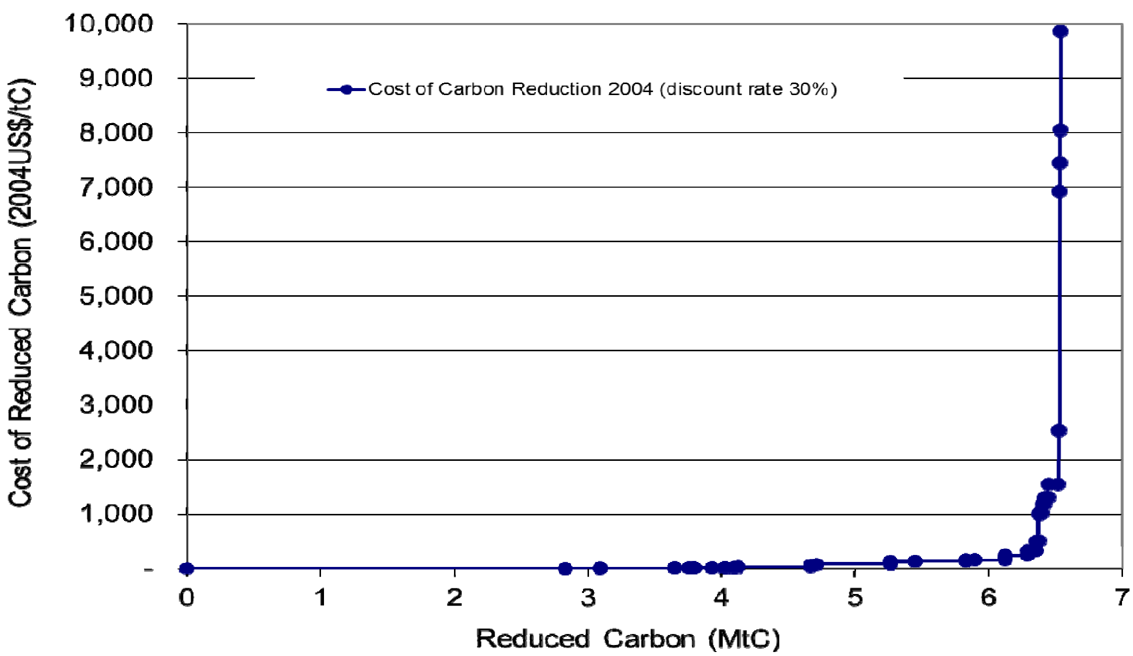

Figure 7. Carbon reduction cost curve for the U.S. cement sector, 30% discount rate, with other benefits, 2004

In addition, Table 8 shows the aggregated numbers for potential carbon reductions grouped by blended and non-blended cement making. The technical potential of carbon-emission reduction is corresponding well to the technical potential of energy savings associated with the mitigation measures. We estimated that the potential reduction of carbon emissions resulting from applicable mitigations measures was 4.2 MtC (2.2 MtC blended, and 2.0 MtC non-blended) in 1994 and 6.5 MtC (2.8 MtC blended, and 3.7 MtC non-blended) in 2004, corresponding to 22% and 27% of total annual carbon emissions in the U.S. cement industry in 1994 and 2004, respectively.

Table 8. Technical potential for carbon reductions in 1994 and 2004.

	Applied Total Carbon Reduction (MtC)			
	Blended	Non-blended	Total	Max Applied Carbon Reduction (%)
1994	2.2	2.0	4.2	22%
2004	2.8	3.7	6.5	27%

Table 9 shows the potential carbon reductions from cost-effective measures grouped by blended and non-blended cement making. The technical potential of carbon-emission reduction is also corresponding well to the technical potential of energy savings associated with the cost-effective mitigation measures. We estimated that the potential reduction of carbon emissions resulting from applicable mitigations measures was 2.8 MtC (2.2 MtC blended, and 0.6 MtC non-blended) in 1994 and approximately 4.7 MtC (2.8 MtC blended, and 1.8 MtC non-blended) in 2004, corresponding to 15% and 19% of the total annual carbon emissions associated with energy use in the U.S. cement industry in 1994 and 2004, respectively. This is an important finding in that implementing existing cost effective measures can result in significant reduction in carbon emissions for each year relative to the total annual carbon emissions in the sector, and more even so when compared to the technical potential reduction in carbon emissions associated with energy use.

Table 9. Technical potential for cost-effective carbon reductions in 1994 and 2004.

	Cost-effective Carbon Reduction (MtC)			
	Blended	Non-blended	Total	Carbon Reduction (%)
1994	2.2	0.6	2.8	15%
2004	2.8	1.8	4.7*	19%

Note: * The number presented is rounded-off.

Finally, we performed a parallel analysis to examine the effects of discount rates on the magnitudes of costs of conserved energy and savings potential for individual mitigation measures.

Figure 8 and Figure 9 show the cost curves with various discount rates (10%, 20%, and 30%) in 1994 and 2004. respectively. For each year, we have found no changes in the magnitudes of total savings potential for all rates, while the cumulative costs of conserved energy increase greatly with the increase in discount rates. In addition, the costs of conserved energy corresponding to individual measures also tend to increase with the increase in discount rates. The sensitivities of such increases to discount rates are different across specific measures, however. The higher discount rates result in an overall increase in the total cost of mitigation measures for implementation and operation.

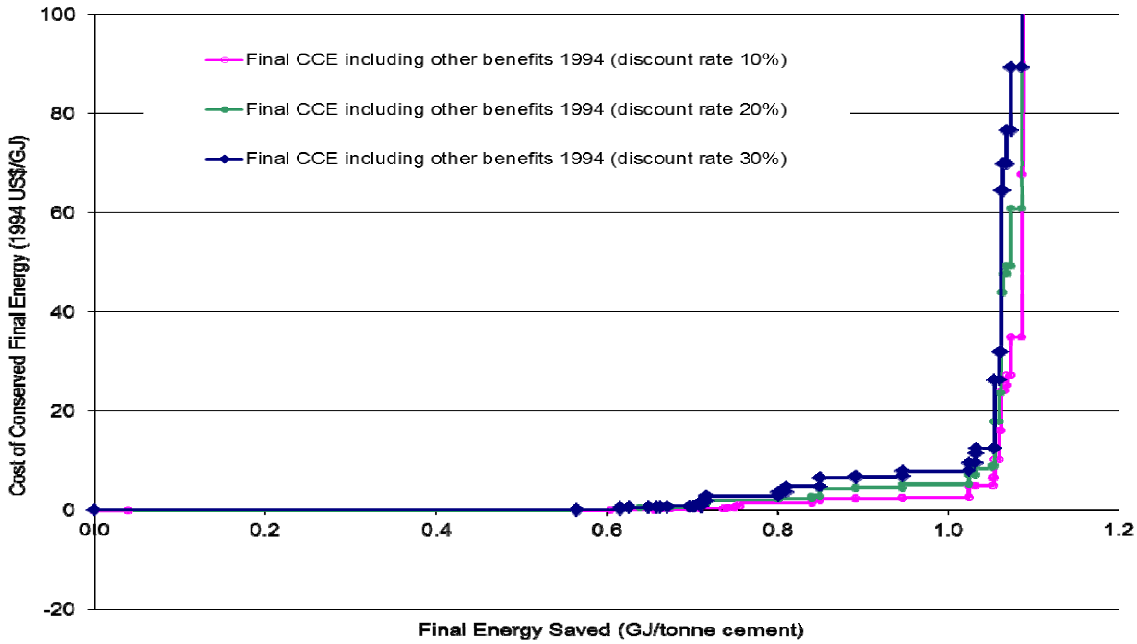

Figure 8. 1994 Cost curves of final energy savings with discounts rates of 10%, 20% and 30% (Cement).

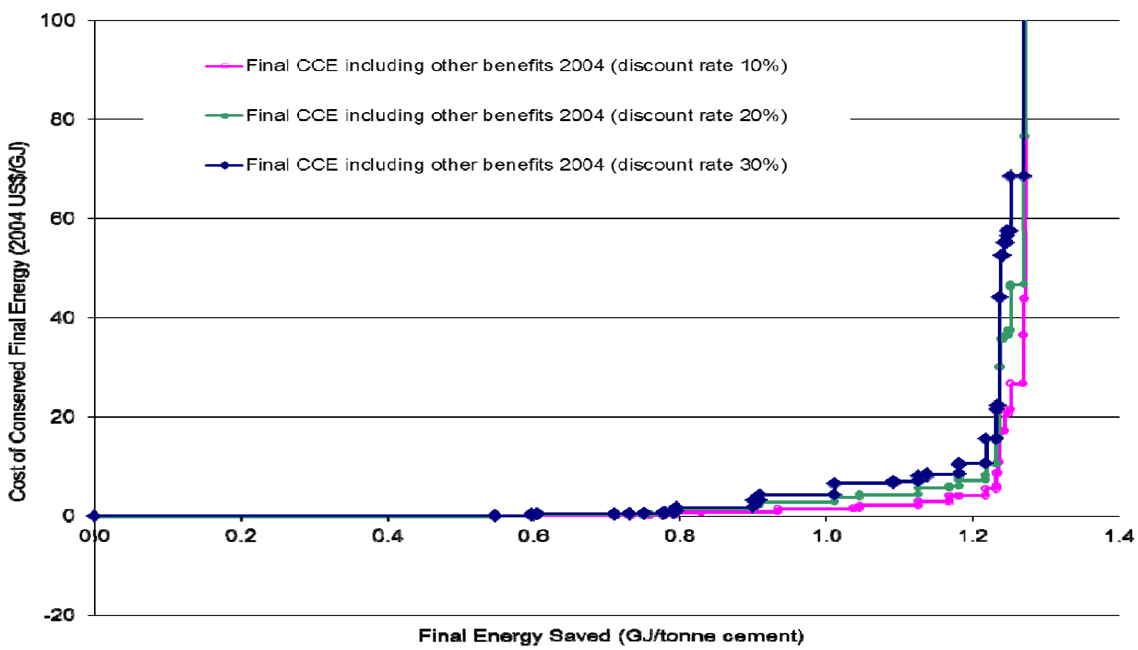

Figure 9. 2004 Cost curves of final energy savings with discounts rates of 10%, 20% and 30% (Cement).

In summary, similar to the analysis about energy saving potential, we also analyzed potential reduction in carbon emissions associated with energy use for each year (Figure 8 and Figure 9), and have found similar patterns in the cost curves. Based upon the cost curves derived from available information on mitigation measures, the rate of change in the carbon reduction potential at a given cost can be evaluated and may be used to estimate future rates of change as input for energy-climate models. For example, from the cost curves, we can quantify the rate of change in carbon reduction potential at a given cost over the studied decade (e.g., 2004 vs. 1994).

7 Conclusions

Through characterizing energy-efficiency technology costs and improvement potentials, we have developed and presented energy and carbon reduction cost curves for energy efficiency measures applicable to the U.S. cement industry for the years 1994 and 2004. The cost curves can change significantly under various scenarios: the baseline year, discount rate, energy intensity, cement production, industry structure (blended vs. non-blended cement-making, wet kiln conversion to dry cement making), efficiency measures, share of cement production to which the individual measures can be applied, and inclusion of other non-energy benefits.

We have identified a number of cost-effective mitigation measures in this study. Based upon limited data available for quantifying other benefits of individual mitigation measures, we have found that inclusion of other benefits from implementing some mitigation measures can reduce the costs of conserved energy or carbon reduction. Important findings in energy savings and carbon reductions in the U.S. cement industry are included below:

The U.S. cement industry used 366 PJ final energy in 1994 and 465 PJ final energy in 2004. The potential savings of final energy use from applying 31 measures was 42 PJ for blended cement and 39 PJ for non-blended cement in 1994; while the potential savings of final energy use resulting from applicable 36 mitigations measures was 54 PJ for blended cement and 72 PJ for non-blended cement in 2004. The technical potential of energy savings from implementing the applicable mitigation measures was approximately 22% of total annual final energy use in the U.S. cement sector in 1994 and 27% in 2004.

The potential final energy savings resulting from cost-effective mitigations measures was 53 PJ in 1994 and 89 PJ in 2004, corresponding to 15% and 19% of total annual final energy use in the U.S. cement industry in 1994 and 2004, respectively. Implementing cost effective measures can result in significant energy savings relative to the total annual energy use in the sector, and more even so when compared to the technical energy savings potential.

The total carbon emissions associated with the U.S. cement sector consist of two categories: 1) energy use for cement production (9.4 MtC in 1994, 12.1 MtC in 2004), and 2) direct emissions from cement-making processes (9.5 MtC in 1994, 12.2 MtC in 2004). We estimated that the total carbon emissions from the cement sector in the U.S. were approximately 18.9 MtC in 1994 and 24.2 MtC in 2004.

The potential reduction of carbon emissions resulting from applicable mitigations measures was 4.2 MtC (2.2 MtC blended, and 2.0 MtC non-blended) in 1994 and 6.5 MtC (2.8 MtC blended, and 3.7 MtC non-blended) in 2004, corresponding to 22% and 27% of annual total carbon emissions in 1994 and 2004, respectively. Applying cost-effective measures would reduce carbon emissions by 2.8 MtC (2.2 MtC blended, and 0.6 MtC non-blended) in 1994 and approximately 4.7 MtC (2.8 MtC blended, and 1.8 MtC non-blended) in 2004, corresponding to 15% and 19% of annual total carbon emissions in 1994 and 2004, respectively.

Implementing existing cost effective measures can result in significant reduction in carbon emissions for each year relative to the total annual carbon emissions in the sector, and more even so when compared to the technical potential reduction in carbon emissions associated with energy use.

We have developed cost curves for conserved energy and carbon reduction associated with the measures, and concluded that based upon the cost curves derived from available information on mitigation measures, the rate of change in the energy-savings or carbon-reduction potential at a given cost can be evaluated and be used to estimate future rates of change for input in energy-climate models. Such estimation of the rate change may be improved as more comprehensive information on characterizing the mitigation measures becomes available.

In addition, total costs of conserved energy increase with the increases in discount rates. The outcomes from this research provide information on initial technology database that can be accessible to integrated assessment modeling groups seeking to enhance their empirical descriptions of technologies. The report includes tabulated databases on costs (and benefits when available) of measure implementation, energy savings, carbon-emission reduction, and lifetimes. The appendix to this report also includes descriptions of the cement making processes, and the mitigation measures identified in this study.

With the available carbon-reduction cost data for various scenarios, it becomes possible to assess economics of carbon caps and efficiency potentials, which will help to understand how carbon regulation may mobilize efficiency while lowering cost of GHG-emission reduction.

8 Recommendations for Future Work

The development of concepts and information on costs of conserved energy for the U.S. cement sector provides a better understanding of costs and carbon impact of energy efficiency measures in the industrial sector. While many energy efficiency technologies have become cost-effective to mitigate long-term climate change, it is important and necessary to incorporate new information on technology characteristics, their evolution and response to energy and carbon price, which can be utilized by integrated assessment modelers who are seeking to enhance their empirical descriptions of technologies.

There appears to be a need to develop and refine sectoral algorithms and produce databases that can be used to match the needs of different integrated assessment modeling of climate policies. New algorithms should allow transformation of information on behavioral responses, technology costs, energy savings, other benefits, and policy costs into meaningful and functional data forms. Developing such algorithms may require customization and processing of database functions. Furthermore, the desired data-model linking effort will require close interfaces between modelers and the developers of the cost-curve databases on energy efficiency measures. In this study, all the cost data (U.S. dollars) are obtained and presented as the currency values for the respective reference years (i.e., 1994, 2004). A direct comparison of costs (U.S. dollars), when desired, can be made by converting the existing reference-year data (i.e., year 1994 and year 2004 in this study, respectively) to a preferred reference year (e.g., 2007). The conversions can be accomplished by multiplying the existing cost in a reference year by a GDP-based inflation index for the preferred year (BEA 2009).

In addition to the cement sector, we have completed a study on the U.S. iron and steel sector. Several other industrial sectors, such as refinery industry, petrochemicals industries, pulp and paper, food industry, fabricated metal products, transportation equipment and aluminum, are also energy intensive. It is important to develop data for the other sectors, similar to the data produced in this report on the cement sector. These too will cover information on types of mitigation options that can be readily utilized to improve energy efficiency, their economic potential, and changes that have occurred in the nature of the cost curves including the non-energy benefits.

Future work will be needed for pulp and paper sector, refineries, petrochemicals and food processing industry, and will need to include other business sectors such as commercial and residential buildings and transportation. This is particularly true if comprehensive carbon policies such as carbon offset are to be addressed, given that the building sector possesses largest potential in global carbon reduction.

9 Acknowledgement

This study is sponsored by Climate Economics Branch, Climate Change Division of U.S. Environmental Protection Agency, under Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy. This report benefits from the guidance and recommendations provided by Eric Smith and Bella Tonkonogy of Climate Economics Branch, Climate Change Division of the U.S. Environmental Protection Agency, and review comments received from Elineth Torres, Will Yelverton, and Ravi Srivastava of Air Pollution Technology Branch, National Risk Management Research Laboratory of the U.S. Environmental Protection Agency. The authors would like to thank Barbara Adams for her assistance in processing the publication of this report.

10 References

Anonymous. 1994. Cement Plant Modernization in Central Europe, World Cement (November): 35-38 (1994).

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

Bureau of Economic Analysis (BEA). 2009. National income and product accounts -NIPAs, 2009. Table C.1. GDP and Other Major NIPA Aggregates. U.S. Department of Commerce. http://www.bea.gov/.

Conroy, G.H. 1997. Industrial Application and Results of Low NOx Precalciner Systems. World Cement 7 28 pp.6369 (July 1997).

Crosilla, F. and H. Häutle. 1997. Modifying the Hot Gas Circuit in LEPOL Grate Preheaters. World Cement 3 28 pp.14-20 (March 1997).

Energy Information Administration (EIA), 1997. 1994 Manufacturing Consumption of Energy 1994. The United States Department of Energy, Washington, DC.

Energy Information Administration (EIA), 2001. 1998 Manufacturing Consumption of Energy. The United States Department of Energy, Washington, DC.

Energy Information Administration (EIA), 2005. 2002 Manufacturing Energy Consumption Survey on manufacturing and industrial energy uses and costs. The United States Department of Energy, Washington, DC. http://www.eia.doe.gov/emeu/mecs/mecs2002/data02/shelltables.html, accessed June 2009.

Grydgaard, P. 1998. Get out of the Wet, International Cement Review, April 1998.

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

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

Intergovernmental Panel on Climate Change (IPCC). 2001. Climate Change 2001 Synthesis Report. Working Group I, II, III to the third assessment report of IPCC.

International Energy Agency (IEA) 2007, Tracking Industrial Energy Efficiency and CO2 Emissions. http://www.iea.org/Textbase/npsum/tracking2007SUM.pdf

Manne, A. and L. Barreto. 2001. Learn-by-doing and Carbon Dioxide Abatement. Interim Report IR-01-057. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

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

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

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

Nakicenovic et al. (Eds) 2000. IPCC Special Report on Emission Scenarios (SRES). IPCC/UNEP/WMO, Cambridge University Press, Cambridge, United Kingdom.

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

Portland Cement Association (PCA). 1990. U.S. and Canadian 1989 Labor-Energy Input Survey, Skokie, IL: Portland Cement Association.

Portland Cement Association (PCA). 1996. U.S. and Canadian Portland Cement Industry Plant Information Summary. Skokie, IL: Portland Cement Association.

Rajbhandari, C.D. 1995. Modern Vertical Shaft Kiln Technology. World Cement 1 26 pp.65-67 (1995).

Sanstad, A.H. and Greening, L.A. 1998. Economic models for climate policy analysis: a critical discussion, Environmental Modeling and Assessment, Vol. 3, pp.3-18.

Sathaye J. and F. Wagner. 2006. Sharing the Burden of Climate Change Stabilization: An energy sector perspective. LBNL Report LBNL 52911.

Steuch, H.E. and Riley, P. 1993. Ash Grove's New 2200 tpd Seattle Plant Comes on Line. World Cement, April 1993.

Su, L.H. 1997. TPI Polene, An Operational View. International Cement Review, December 1997, pp.28-40.

United States Geological Survey (USGS), various years. Minerals Yearbook, Washington, D.C., USGS. (Located on the World Wide Web at http://minerals.er.usgs.gov/minerals/). Accessed February 2009.

US Department of State (US DOS), 2006. Asia-Pacific Partnership on Clean Development and Climate: Cement Task Force Summary of Action Plan and Projects – Summary of Cement Task Force Action Plan.

Van Oss, H. G. 2008. U.S. Geological Survey (USGS) Mineral Commodity Summaries: Cement. http://minerals.usgs.gov/minerals/pubs/commodity/cement/mcs-2008-cemen.pdf. Accessed February 2009.

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

Worrell, E. J. A Laitner, M. Ruth and H. Finman. 2003. Productivity Benefits of Industrial Energy Efficiency Measures. Energy 28: 1081-1098.

Worrell, E., N. Martin, and L. Price. 1999. Energy Efficiency and Carbon Dioxide Emissions Reduction Opportunities in the U.S. Iron and Steel Sector. Lawrence Berkeley national Laboratory: Berkeley, CA (LBNL-41724).

Xu, T., J. Sathaye, and C. Galitsky. 2010. Development of Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the Iron and Steel Sector. LBNL Formal Report-3414E.

Appendix A1: Cost Curve Data for the U.S. Cement Sector for 1994 (1994 US$)

1994 Baseline	Applied Carbon Savings kgC/tonne	Applied Final Energy Savings (GJ/tonne)	Cost of Measure (US$/tonne)	Annual Operation Cost Change (US$/tonne)	Measure Lifetime (years)	Applied Carbon Savings (kilo-ton C)	Final CRC US$/tC	Final CCE (US$/GJ)	Capital Recovery Factor
Raw Materials Preparation (Wet Cement)	-	-	-	-	-	-	-	-	
Mechanical Transport Systems (w)	0.02	0.0004	0.555	-	20	1.27	9,782.20	435.31	$0.30
Raw Materials Preparation (Dry Cement)	-	-	-	-	-	-	-	-	
Mechanical Transport Systems (d)	0.04	0.0010	0.566	-	20	3.25	3,899.33	173.52	$0.30
Raw meal blending systems (d)	0.02	0.0005	0.754	-	25	1.73	9,704.53	431.85	$0.30
Use of High Efficiency Roller Mills (d)	0.59	0.0132	3.912	-	20	43.72	2,006.08	89.27	$0.30
High Efficiency Classifiers (d)	0.22	0.0050	1.415	(0.048)	20	16.39	1,718.76	76.48	$0.30
Clinker Production (Wet Cement)	-	-	-	-	-	-	-	-	
Kiln combustion system improvements (w)	0.04	0.0009	0.004	-	20	3.27	26.50	1.23	$0.30
Kiln shell heat loss reduction (w)	0.21	0.0045	0.007	-	20	15.50	10.80	0.50	$0.30
Use of waste fuels (w)	0.42	0.0090	0.015	-	20	31.11	10.80	0.50	$0.30
conversion to grate clinker cooler (w)	0.07	0.0014	0.002	0.000	20	4.98	15.16	0.71	$0.30
conversion to semi-wet kilns (w)	0.37	0.0080	0.012	0.001	30	27.81	11.70	0.54	$0.30
Optimize heat recovery of clinker cooler (grate) (w)	0.22	0.0048	0.011	-	20	16.44	14.58	0.68	$0.30
conversion to dry multi-stage pre-heater, pre-calciner kilns (w)	3.62	0.0778	2.111	(0.025)	40	269.12	167.94	7.81	$0.30
Clinker Production (Dry Cement)	-	-	-	-	-	-	-	-	
Kiln combustion system improvements (d)	0.27	0.0048	0.027	-	20	19.74	30.98	1.72	$0.30
Kiln shell heat loss reduction (d)	0.56	0.0101	0.017	-	20	41.69	9.05	0.50	$0.30
Use of waste fuels (d)	1.26	0.0226	0.038	-	20	93.32	9.05	0.50	$0.30
conversion to grate clinker cooler (d)	0.43	0.0078	0.011	0.002	20	32.25	12.71	0.71	$0.30
Low pressure drop cyclones for suspension pre-heaters (d)	0.12	0.0021	0.450	-	20	8.70	1,160.42	64.44	$0.30
heat recovery for cogeneration (d)	0.06	0.0011	0.028	0.004	35	4.60	206.27	11.45	$0.30
conversion from dry to multi-stage pre-heater kilns (d)	3.05	0.0549	1.221	-	40	226.77	120.05	6.67	$0.30
conversion from multi-stage pre-heater to pre-calciner kiln (d)	2.19	0.0395	0.987	(0.111)	40	163.03	84.37	4.69	$0.30
conversion from dry to pre-heater, pre-calciner kilns (d)	2.35	0.0423	0.911	-	40	174.70	116.36	6.46	$0.30
Optimize heat recovery of clinker cooler (grate) (d)	1.47	0.0265	0.060	-	20	109.40	12.22	0.68	$0.30
Finish Grinding (All Cement)	-	-	-	-	-	-	-	-	
Improved Grinding Media	0.08	0.0018	0.177	-	10	5.95	716.00	31.86	$0.32
High pressure roller press-pre grinding	0.25	0.0056	0.487	-	20	18.55	588.30	26.18	$0.30
Roller press/horomill system	0.93	0.0209	0.860	-	20	69.14	278.90	12.41	$0.30
High Efficiency Classifiers	0.19	0.0043	1.000	-	20	14.29	1,568.80	69.81	$0.30
General Measures	-	-	-	-	-	-	-	-	
Variable speed drives	0.40	0.0078	0.228	-	10	29.88	183.44	9.48	$0.32
High efficiency motors	0.47	0.0090	0.100	-	10	34.59	69.52	3.59	$0.32
Energy Management and Process Control system	4.37	0.0845	0.707	-	10	324.92	52.29	2.70	$0.32
Preventative maintenance	2.65	0.0512	0.009	-	20	196.66	1.03	0.05	$0.30
Product Change	-	-	-	-	-	-	-	-	
Blended cements	29.23	0.5655	0.292	(0.083)	20	2,173.15	0.16	0.01	$0.30

Appendix A2: Cost Curve Data for the U.S. Cement Sector for 2004 (2004 US$)

2004 Baseline	Applied Carbon Savings (kgC/tonne)	Applied Final Energy Savings (GJ/tonne)	Cost of Measure (US$/tonne)	Annual Operation Cost Change (US$/tonne)	Measure Lifetime (years)	Applied Carbon Savings (kilo-ton C)	Final CRC US$/tC	Final CCE (US$/GJ)	Capital Recovery Factor
Raw Materials Preparation (Wet Cement)	-	-	-	-	-	-	-	-	-
Mechanical Transport Systems (w)	0.02	0.0004	0.60	-	20	1.82	9,864.04	438.95	0.30
Slurry Blending and Homogenizing (w)	0.00	0.0001	0.11	-	20	0.45	6,918.12	307.86	0.30
Raw Materials Preparation (Dry Cement)	-	-	-	-	-	-	-	-	-
Mechanical Transport Systems (d)	0.09	0.0019	0.72	-	20	8.55	2,526.93	112.45	0.30
Raw meal blending systems (d)	0.03	0.0007	0.75	-	25	2.99	7,450.31	331.54	0.30
Use of High Efficiency Roller Mills (d)	0.76	0.0171	3.89	-	20	75.42	1,540.10	68.53	0.30
Raw meal process control (d)	0.07	0.0016	0.24	-	20	7.12	990.03	44.06	0.30
High Efficiency Classifiers (d)	0.24	0.0053	1.17	(0.05)	20	23.53	1,291.38	57.47	0.30
Fuel Preparation (wet and dry)	-	-	-	-	-	-	-	-	-
roller mills (d)	0.02	0.0004	0.04	0.12	25	1.58	8,056.39	358.51	0.30
roller mills (w)	0.01	0.0003	0.03	0.01	25	1.26	1,270.95	56.56	0.30
Clinker Production (Wet Cement)	-	-	-	-	-	-	-	-	-
Process control & management (w)	0.15	0.0032	0.01	-	13	15.29	19.86	0.96	0.31
Kiln combustion system improvements (w)	0.00	0.0000	0.00	-	20	0.05	16.88	0.82	0.30
Kiln shell heat loss reduction (w)	0.10	0.0022	0.00	-	20	10.33	8.89	0.43	0.30
Use of waste fuels (w)	0.28	0.0059	0.01	-	20	28.09	8.89	0.43	0.30
conversion to grate clinker cooler (w)	0.14	0.0029	0.00	0.00	20	13.79	13.31	0.64	0.30
conversion to semi-dry process (w)	0.68	0.0141	0.73	-	30	67.38	322.96	15.61	0.30
conversion to semi-wet kilns (w)	0.90	0.0186	0.02	0.00	30	89.22	9.95	0.48	0.30
Optimize heat recovery of clinker cooler (grate) (w)	0.10	0.0021	0.00	-	20	10.13	10.26	0.50	0.30
conversion to dry multi-stage pre-heater, pre-calciner kilns (w)	3.84	0.0795	1.84	(0.03)	40	380.53	137.20	6.63	0.30
Clinker Production (Dry Cement)	-	-	-	-	-	-	-	-	-
Kiln shell heat loss reduction (d)	1.13	0.0208	0.03	-	20	111.47	7.94	0.43	0.30
Use of waste fuels (d)	5.66	0.1045	0.15	-	20	560.15	7.94	0.43	0.30
conversion to grate clinker cooler (d)	0.66	0.0122	0.01	0.00	20	65.21	11.90	0.64	0.30
Low pressure drop cyclones for suspension pre-heaters (d)	0.23	0.0042	0.77	-	20	22.52	1,017.58	55.08	0.30
heat recovery for cogeneration (d)	0.00	0.0001	0.00	0.00	35	0.45	191.11	10.34	0.30
conversion from dry to multi-stage pre-heater kilns (d)	2.31	0.0427	1.21	-	40	228.67	157.11	8.50	0.30
conversion from multi-stage pre-heater to pre-calciner kiln (d)	1.83	0.0338	1.07	(0.09)	40	181.39	128.48	6.95	0.30
conversion from dry to pre-heater, pre-calciner kilns (d)	5.57	0.1030	1.46	-	40	551.89	78.60	4.25	0.30
Optimize heat recovery of clinker cooler (grate) (d)	1.36	0.0251	0.04	-	20	134.71	9.16	0.50	0.30
Finish Grinding (All Cement)	-	-	-	-	-	-	-	-	-
Improved Grinding Media	0.08	0.0018	0.12	-	10	7.93	483.44	21.51	0.32
High pressure roller press-pre grinding	0.12	0.0027	0.20	-	20	11.86	502.86	22.38	0.30
Roller press/horomill system	1.65	0.0371	1.30	-	20	163.35	238.39	10.61	0.30
High Efficiency Classifiers	0.19	0.0043	0.75	-	20	19.04	1,180.05	52.51	0.30
General Measures	-	-	-	-	-	-	-	-	-
Variable speed drives	0.68	0.0131	0.33	-	10	67.50	155.52	8.11	0.32
High efficiency motors	0.47	0.0090	0.09	-	10	46.46	58.93	3.07	0.32
Energy Management and Process Control system	5.46	0.1047	0.56	-	10	540.55	33.33	1.74	0.32
Preventative maintenance	2.61	0.0500	0.01	-	20	258.26	0.87	0.05	0.30
Product Change	-	-	-	-	-	-	-	-	-
Blended cements	28.56	0.5478	0.28	(0.08)	20	2,827.47	0.16	0.01	0.30

Appendix B: Description of Measures Noted in Appendices A1 and A2[1]

1.0 Raw Materials Preparation

Efficient Transport Systems (Dry Process). Transport systems are required to convey powdered materials such as kiln feed, kiln dust, and finished cement throughout the plant. These materials are usually transported by means of either pneumatic or mechanical conveyors. Mechanical conveyors use less power than pneumatic systems. Conversion to mechanical conveyors is cost-effective when replacement of conveyor systems is needed to increase reliability and reduce downtime.

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

Most plants use compressed air to agitate the powdered meal in so-called air-fluidized homogenizing silos. Older dry process plants use mechanical systems, which simultaneously withdraw material from 6-8 different silos at variable rates (Fujimoto, 1993). Modern plants use gravity-type homogenizing silos (or continuous blending and storage silos) reducing power consumption. In these silos, material funnels down one of many discharge points, where it is mixed in an inverted cone. Gravity-type silos may not give the same blending efficiency as air-fluidized systems. Although most older plants use mechanical or air-fluidized bed systems, more and more new plants seem to have gravity-type silos, because of the significant reduction in power consumption (Holderbank, 1993). Silo retrofit options are cost-effective when the silo can be partitioned with air slides and divided into compartments which are sequentially agitated, as opposed to the construction of a whole new silo system.

Slurry Blending and Homogenizing (Wet Process). In the wet process the slurry is blended and homogenized in a batch process. The mixing is done using compressed air and rotating stirrers. The Use of compressed air may lead to relatively high energy losses because of its poor efficiency. The main energy efficiency improvement measures for slurry blending systems are found in the compressed air system.

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

---

[1] The measures described in this Appendix are a subset of a fuller set of measures that are described in Worrell and Galitsky (2008). These measures were chosen because of their significance in energy savings or availability of cost data.

Raw Meal Process Control (Dry process - Vertical Mill). The main difficulty with existing vertical roller mills are vibration trips. Operation at high throughput makes manual vibration control difficult. When the raw mill trips, it cannot be started up for one hour, until the motor windings cool. A model predictive multivariable controller maximizes total feed while maintaining a target residue and enforcing a safe range for trip-level vibration. The first application eliminated avoidable vibration trips (which were 12 per month prior to the control project).

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

Standard classifiers may have a low separation efficiency, which leads to the recycling of fine particles, and results in to extra power use in the grinding mill. Various concepts of high-efficiency classifiers have been developed (Holderbank, 1993; Süssegger, 1993). In high-efficiency classifiers, the material stays longer in the separator, leading to sharper separation, thus reducing overgrinding.

Replacing a conventional classifier by a high-efficiency classifier has led to 15% increases in the grinding mill capacity (Holderbank, 1993) and improved product quality due to a more uniform particle size (Salzborn and Chin-Fatt, 1993), both in raw meal and cement. The better size distribution of the raw meal may lead to fuel savings in the kiln and improved clinker quality.

2.0 Fuel Preparation

Coal is the most widely used fuel in the cement industry. Fuels preparation is most often performed on-site. Fuels preparation may include crushing, grinding and drying of coal. Coal is shipped “wet” to prevent dust formation and fire during transport. Passing hot gasses through the mill combines the grinding and drying. Coal is the most used fuel in the cement industry, and the main fuel for the vast majority of clinker kilns in the U.S. Most commonly a Raymond bowl mill or a roller mill is used for coal grinding. Waste heat of the kiln system (e.g. the clinker cooler) is used to dry the coal if needed.

Other advantages of a roller mill are that it is able to handle larger sizes of coal (no pre-crushing needed) and coal types with a higher humidity, and can manage larger variations in throughput. However, tube mills are preferred for more abrasive coal types. Currently, roller mills are the most common coal mills in the U.S. cement industry. Coal roller mills are available for throughputs of 5 to 200 tons/hour. Outside The U.S., coal grinding roller mills can be found in many countries around the world, e.g. Brazil, Canada, China, Denmark, Germany, Japan and Thailand. All major suppliers of cement technology offer roller mills for coal grinding. Vertical roller mills have been developed for coal grinding, and are used by over 100 plants around the world (Cembureau, 1997).

3.0 Clinker Production – All Kilns

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

One such system, called ABB LINKman, was originally developed in the United Kingdom by Blue Circle Industries and SIRA (ETSU, 1988). The LINKman system has successfully been used in both wet and dry kilns, and modern control systems now find wider application and can be found in many European plants. Other developers also market ‘fuzzy logic’ control systems, e.g., F.L. Smidth (Denmark) Krupp Polysius (Germany) and Mitsui Mining (Japan). An alternative to expert systems or fuzzy logic is model-predictive control using dynamic models of the processes in the kiln.

Additional process control systems include The Use of on-line analyzers that permit operators to instantaneously determine the chemical composition of raw materials being processed in the plant, thereby allowing for immediate changes in the blend of raw materials. A uniform feed allows for more steady kiln operation, thereby saving ultimately on fuel requirements.

Process control of the clinker cooler can help to improve heat recovery, material throughput, improved control of free lime content in the clinker and reduce NOx emissions (Martin et al., 2000).

Kiln Combustion System Improvements. Fuel combustion systems in kilns can be contributors to kiln inefficiencies with such problems as poorly adjusted firing, incomplete fuel burn-out with high CO formation, and combustion with excess air (Venkateswaran and Lowitt, 1988). Improved combustion systems aim to optimise the shape of the flame, the mixing of combustion air and fuel and reducing The Use of excess air. Various approaches have been developed. Lowes, (1990) discusses advancements from combustion technology that improve combustion through The Use of better kiln control.

Another technology that has been demonstrated in several locations is the Gyro-Therm technology that improves gas flame quality while reducing NOx emissions. Originally developed at the University of Adelaide (Australia), the Gyro-Therm technology can be applied to gas burners or gas/coal dual fuel. The Gyro-Therm burner uses a patented "precessing jet" technology. The nozzle design produces a gas jet leaving the burner in a gyroscopic-like precessing motion. This stirring action produces rapid large scale mixing in which pockets of air are engulfed within the fuel envelope without using high velocity gas or air jets. The combustion takes place in pockets within the fuel envelope under fuel rich conditions. This creates a highly luminous flame, ensuring good radiative heat transfer.

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

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

Kiln Shell Heat Loss Reduction. There can be considerable heat losses through the shell of a cement kiln, especially in the burning zone. The Use of better insulating refractories (e.g. Lytherm) can reduce heat losses (Venkateswaran and Lowitt, 1988). Refractory choice is the function of insulating qualities of the brick and the ability to develop and maintain a coating. The coating helps to reduce heat losses and to protect the burning zone refractory bricks. The Use of improved kiln-refractories may also lead to improved reliability of the kiln and reduced downtime, reducing production costs considerably, and reducing energy needs during start-ups.

Refractories. Refractories protect the steel kiln shell against heat, chemical and mechanical stress. The choice of refractory material depends on the combination of raw materials, fuels and operating conditions. Extended lifetime of the refractories will lead to longer operating periods and reduced lost production time between relining of the kiln, and, hence, offset the costs of higher quality refractories (Schmidt, 1998; van Oss, 2002). It will also lead to additional energy savings due to the relative reduction in start-up time and energy costs. The energy savings are difficult to quantify, as they will strongly depend on the current lining choice and management.

Use of Waste-Derived Fuels. Waste fuels can be substituted for traditional commercial fuels in the kiln. The U.S. cement industry is increasingly using waste fuels. In 1999 tires accounted for almost 5% of total fuel inputs in the industry, while all wastes totaled about 17% of all fuel inputs. The trend towards increased waste use will likely increase after successful tests with different wastes in Europe and North America. New waste streams include carpet and plastic wastes, filter cake, paint residue and (dewatered) sewage sludge (Hendriks et al., 1999). Cement kilns also use hazardous wastes. Since the early 1990's cement kilns burn annually almost 1 million tons of hazardous waste (CKRC, 2002). The revenues from waste intake have helped to reduce the production costs of all waste-burning cement kilns, and especially of wet process kilns. Waste-derived fuels may replace The Use of commercial fuels, and may result in net energy savings and reduced CO_2 emissions, depending on the alternative use of the wastes (e.g. incineration with or without energy recovery).

A cement kiln is an efficient way to recover energy from waste. The carbon dioxide emission reduction depends on the carbon content of the waste-derived fuel, as well as the alternative use of the waste and efficiency of use (e.g. incineration with or without heat recovery). The high temperatures and long residence times in the kiln destroy virtually all organic compounds, while efficient dust filters may reduce any potential emissions to safe levels (Cembureau, 1997). Our analysis focuses on The Use of tires or tire-derived fuel.

Conversion to Reciprocating Grate Cooler. Four main types of coolers are used in the cooling of clinker: shaft, rotary, planetary and travelling and reciprocating grate coolers. There are no longer any rotary or shaft coolers in operation in North America. However, some travelling grate coolers may still be in operation. In the U.S., planetary and grate coolers are the coolers of choice. Cembureau (1997) provides data on cooler types for U.S. cement plants. Plants that responded to the Cembureau survey (92% of plants) indicated that 6% of the industry still utilized planetary or rotary coolers.

The grate cooler is the modern variant and is used in almost all modern kilns. The advantages of the grate cooler are its large capacity (allowing large kiln capacities) and efficient heat recovery (the temperature of the clinker leaving the cooler can be as low as 83°C, instead of 120-200°C, which is expected from planetary coolers (Vleuten, 1994)). Tertiary heat recovery (needed for pre-calciners) is impossible with planetary coolers (Cembureau, 1997), limiting heat recovery efficiency. Grate coolers recover more heat than do the other types of coolers. For large capacity plants, grate coolers are the preferred equipment. For plants producing less than 500 tonnes per day the grate cooler may be too expensive (COWIconsult et al., 1993). Replacement of planetary coolers by grate coolers is not uncommon (Alsop and Post, 1995). Grate coolers are standard technology for modern large-scale kilns.

Modern reciprocating coolers have a higher degree of heat recovery than older variants, increasing heat recovery efficiency to 65% or higher, while reducing fluctuations in recuperation efficiency (i.e. increasing productivity of the kiln). Cooler conversion is generally economically attractive only when installing a precalciner, which is necessary to produce the tertiary air (see above), or when expanding production capacity.

Optimization of Heat Recovery/Upgrade Clinker Cooler. The clinker cooler drops the clinker temperature from 1200°C down to 100°C. The most common cooler designs are of the planetary (or satellite), traveling and reciprocating grate type. In the U.S. 94% of coolers in 1994 were grate coolers. All coolers heat the secondary air for the kiln combustion process and sometimes also tertiary air for the precalciner (Alsop and Post, 1995). Reciprocating grate coolers are the modern variant and are suitable for large-scale kilns (up to 10,000 tpd). Grate coolers use electric fans and excess air. The highest temperature portion of the remaining air can be used as tertiary air for the precalciner. Rotary coolers (used for approximately 5% of the world clinker capacity for plants up to 2200-5000 tpd) and planetary coolers (used for 10% of the world capacity for plants up to 3300-4400 tpd) do not need combustion air fans and use little excess air, resulting in relatively lower heat losses (Buzzi and Sassone, 1993; Vleuten, 1994).

A recent innovation in clinker coolers is the installation of a static grate section at the hot end of the clinker cooler. This has resulted in improved heat recovery and reduced maintenance of the cooler.

4.0 Clinker Production - Wet Process Kilns

Wet Process Conversion to Semi-Dry Process (Slurry Drier). In modernized wet kilns, a slurry drier can be added to dry the slurry before entering the kiln using waste heat from the kiln (Cembureau, 1997). This reduces energy consumption considerably and increases productivity. This is different from a semi-wet process as a gas drier is used instead of a slurry press filter. The drier can be combined with a hammer mill for a reliable and efficient disagglomeration and drying system (Grydgaard, 1998). Gas suspension driers could increase drying efficiency and potentially reduce fuel consumption in the kiln. The principal of preheating/drying is similar to the semi-dry process (or Lepol kiln), although in the semi-dry process dry raw meal (10-12% water) is used instead of slurry (28-48% water). The Lepol kiln uses a traveling grate preheater, and uses dry raw material grinding, followed by a pelletizer that mixes water with the dry meal to form pellets that can be carried by the traveling grate into the rotary kiln. The size of the pellets also determines the size of clinker pellets.

Wet Process Conversion to Semi-Wet Process (Filter Press System). In the wet process the slurry typically contains 36% water (range of 24-48%). A filter press can be installed in a wet process kiln in order to reduce the moisture content to about 20% of the slurry and obtain a paste ready for extrusion into pellets (COWIconsult et al., 1993; Venkateswaran and Lowitt, 1988). In the U.S. several plants have tried slurry filters, but have not been very successful.

Wet Process Conversion to Pre-heater/Pre-calciner Kiln. If economically feasible a wet process kiln can be converted to a state-of-the art dry process production facility that includes either a multi-stage preheater, or a pre-heater/pre-calciner.

5.0 Clinker Production - Dry Process Preheater Kilns

Low Pressure Drop Cyclones for Suspension Preheaters. Cyclones are a basic component of plants with pre-heating systems. The installation of newer cyclones in a plant with lower pressure losses will reduce the power consumption of the kiln exhaust gas fan system. Installation of the cyclones can be expensive, however, since it may often entail the rebuilding or the modification of the preheater tower, and the costs are very site specific. Also, new cyclone systems may increase overall dust loading and increase dust carryover from the preheater tower. However, if an inline raw mill follows it, the dust carryover problem becomes less of an issue.

Heat Recovery for Cogeneration. Waste gas discharged from the kiln exit gases, the clinker cooler system, and the kiln pre-heater system all contain useful energy that can be converted into power. Only in long-dry kilns is the temperature of the exhaust gas sufficiently high, to cost-effectively recover the heat through power generation.[2] Cogeneration systems can either be direct gas turbines that utilize the waste heat (top cycle), or the installation of a waste heat boiler system that runs a steam turbine system (bottom cycle). This report focuses on the steam turbine system since these systems have been installed in many plants worldwide and have proven to be economic (Steinbliss, 1990; Jaccard and Willis, 1996; Neto, 1990). Heat recovery has limited

[2] Technically, organic rankine cycles or Kalina cycles (using a mixture of water and ammonia) can be used to recover low-temperature waste heat for power production, but this is currently not economically attractive, except for locations with high power costs.

application for plants with in-line raw mills, as the heat in the kiln exhaust is used for raw material drying.

Dry Process Conversion to Multi-Stage Preheater Kiln. Older dry kilns may only preheat in the chain section of the long kiln, or may have single- or two-stage preheater vessels. Especially, long dry kilns may not have any preheater vessels installed at all. This leads to a low efficiency in heat transfer and higher energy consumption. Installing multi-stage suspension preheating (i.e. four- or five-stage) may reduce the heat losses and thus increase efficiency. Modern cyclone or suspension preheaters also have a reduced pressure drop, leading to increased heat recovery efficiency and reduced power use in fans (see low pressure drop cyclones above). By installing new preheaters, the productivity of the kiln will increase, due to a higher degree of pre-calcination (up to 30-40%) as the feed enters the kiln. Also, the kiln length may be shortened by 20-30% thereby reducing radiation losses (van Oss, 1999). As the capacity increases, the clinker cooler may have to be adapted to be able to cool the large amounts of clinker. The conversion of older kilns is attractive when the old kiln needs replacement and a new kiln would be too expensive, assuming that limestone reserves are adequate. Energy savings depend strongly on the specific energy consumption of the dry process kiln to be converted as well as the number of preheaters to be installed.

Installation or Upgrading of a Preheater to a Preheater/Precalciner Kiln. An existing preheater kiln may be converted to a multi-stage preheater precalciner kiln by adding a precalciner and, when possible an extra preheater. The addition of a precalciner will generally increase the capacity of the plant, while lowering the specific fuel consumption and reducing thermal NOx emissions (due to lower combustion temperatures in the pre-calciner). Using as many features of the existing plant and infrastructure as possible, special precalciners have been developed by various manufacturers to convert existing plants, e.g. Pyroclon®-RP by KHD in Germany. Generally, the kiln, foundation and towers are used in the new plant, while cooler and preheaters are replaced. Cooler replacement may be necessary in order to increase the cooling capacity for larger production volumes. Fuel savings will depend strongly on the efficiency of the existing kiln and on the new process parameters (e.g. degree of precalcination, cooler efficiency). Older calciners can also be retrofitted for energy efficiency improvement and NOx emission reduction.

Conversion of Long Dry Kilns to Preheater/Precalciner Kiln. If economically feasible a long dry kiln can be upgraded to the current state of the art multi-stage preheater/precalciner kiln. Energy savings reflect the difference between the average dry kiln specific fuel consumption and that of a modern preheater.

6.0 Finish Grinding

Process Control and Management – Grinding Mills. Control systems for grinding operations are developed using the same approaches as for kilns (see above). The systems control the flow in the mill and classifiers, attaining a stable and high quality product. Several systems are marketed by a number of manufacturers. Expert systems have been commercially available since the early 1990's. The Karlstadt plant of Schwenk KG (Germany) implemented an expert system in a finishing mill in 1992, increasing mill throughput and saving energy.

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

Air swept vertical roller mills with integral classifiers are used for finish grinding, whereas a off-shoot technology which is not air swept is now being used as a pre-grinding system in combination with a ball mill. A variation of the roller mill is the air swept ring roller mill. A new mill concept is the Horomill, first demonstrated in Italy in 1993 (Buzzi, 1997). In the Horomill a horizontal roller within a cylinder is driven. The centrifugal forces resulting from the movement of the cylinder cause a uniformly distributed layer to be carried on the inside of the cylinder. The layer passes the roller (with a pressure of 700-1000 bar (Marchal, 1997). The finished product is collected in a dust filter. The Horomill is a compact mill that can produce a finished product in one step and hence has relatively low capital costs.

Today, high-pressure roller presses are most often used to expand the capacity of existing grinding mills, and are found especially in countries with high electricity costs or with poor power supply (Seebach et al, 1996). After the first demonstration of the Horomill in Italy, this concept is now also applied in plants in Mexico (Buzzi, 1997), Germany, Czech Republic and Turkey (Duplouy and Trautwein,1997). New designs of the roller mills allow for longer operation times (> 20,000 hours).

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

Improved Grinding Media. Improved wear resistant materials can be installed for grinding media, especially in ball mills. Grinding media are usually selected according to the wear characteristics of the material. Increases in the ball charge distribution and surface hardness of grinding media and wear resistant mill linings have shown a potential for reducing wear as well as energy consumption. (Venkateswaran and Lowitt, 1988). Improved balls and liners made of high chromium steel is one such material but other materials are also possible. Other improvements include The Use of improved liner designs, such as grooved classifying liners.

7.0 General Measures

Preventative Maintenance. Preventative maintenance includes training personnel to be attentive to energy consumption and efficiency. Successful programs have been launched in a variety of industries (Caffal, 1995; Nelson, 1994). While many processes in cement production are primarily automated, there still are opportunities, requiring minimal training of employees, to increase energy savings. Also, preventative maintenance (e.g. for the kiln refractory) can also increase a plant's utilization ratio, since it has less downtime over the long term. Based on similar programs in other industries, annual and start up costs for implementing this training are estimated to be minimal and would be paid back in less than one year. For preventative maintenance of compressed air systems see below.

Motor Systems. When considering energy efficiency improvements to a facility's motor systems, it is important to take a "systems approach." A systems approach strives to optimize the energy efficiency of entire motor systems (i.e., motors, drives, driven equipment such as pumps, fans, and compressors, and controls), not just the energy efficiency of motors as individual components. A systems approach analyzes both the energy supply and energy demand sides of motor systems as well as how these sides interact to optimize total system performance, which includes not only energy use but also system uptime and productivity.

A systems approach typically involves the following steps. First, all applications of motors in a facility should be located and identified. Second, the conditions and specifications of each motor should be documented to provide a current systems inventory. Third, the needs and the actual use of the motor systems should be assessed to determine whether or not motors are properly sized and also how well each motor meets the needs of its driven equipment. Fourth, information on potential repairs and upgrades to the motor systems should be collected, including the economic costs and benefits of implementing repairs and upgrades to enable the energy efficiency improvement decision-making process. Finally, if upgrades are pursued, the performance of the upgraded motor systems should be monitored to determine the actual costs savings (SCE 2003).

The motor system energy efficiency measures below reflect important aspects of this systems approach, including matching motor speeds and loads, proper motor sizing, and upgrading system components.

Motor management plan. A motor management plan is an essential part of a plant's energy management strategy. Having a motor management plan in place can help companies realize long-term motor system energy savings and will ensure that motor failures are handled in a quick and cost effective manner. The Motor Decisions Matter^{SM} Campaign suggests the following key elements for a sound motor management plan (MDM 2007):

1. Creation of a motor survey and tracking program.
2. Development of guidelines for proactive repair/replace decisions.
3. Preparation for motor failure by creating a spares inventory.
4. Development of a purchasing specification.
5. Development of a repair specification.
6. Development and implementation of a predictive and preventive maintenance program.

The Motor Decisions Matter^{SM} Campaign's Motor Planning Kit contains further details on each of these elements (MDM 2007).

Strategic motor selection. Several factors are important when selecting a motor, including motor speed, horsepower, enclosure type, temperature rating, efficiency level, and quality of power supply. When selecting and purchasing a motor, it is also critical to consider the life-cycle costs of that motor rather than just its initial purchase and installation costs. Up to 95% of a motor's costs can be attributed to the energy it consumes over its lifetime, while only around 5%

of a motor's costs are typically attributed to its purchase, installation, and maintenance (MDM 2007). Life cycle costing (LCC) is an accounting framework that allows one to calculate the total costs of ownership for different investment options, which leads to a more sound evaluation of competing options in motor purchasing and repair or replacement decisions. A specific LCC guide has been developed for pump systems (Fenning et al. 2001), which also provides an introduction to LCC for motor systems.

The selection of energy-efficient motors can be an important strategy for reducing motor system life-cycle costs. Energy-efficient motors reduce energy losses through improved design, better materials, tighter tolerances, and improved manufacturing techniques. With proper installation, energy-efficient motors can also run cooler (which may help reduce facility heating loads) and have higher service factors, longer bearing life, longer insulation life, and less vibration.

To be considered energy efficient in the United States, a motor must meet performance criteria published by the National Electrical Manufacturers Association (NEMA). The Consortium for Energy Efficiency (CEE) has described the evolution of standards for energy-efficient motors in the United States, which is helpful for understanding "efficient" motor nomenclature (CEE 2007):

NEMA Energy Efficient (NEMA EE) was developed in the mid-1980s to define the term "energy efficient" in the marketplace for motors. NEMA Standards Publication No. MG-1 (Revision 3), Table 12-11 defines efficiency levels for a range of different motors (NEMA 2002).

The Energy Policy Act of 1992 (EPACT) required that many commonly used motors comply with NEMA "energy efficient" ratings if offered for sale in the United States.

In 1996, the CEE Premium Efficiency Criteria specification was designed to promote motors with higher efficiency levels than EPACT required, for the same classes of motors covered by EPACT. The CEE efficiency levels specified were generally two NEMA efficiency bands (Table 12-10, NEMA MG-1 Revision 3) above those required by EPACT.

In 2001, the NEMA Premium Efficiency Electric Motor specification was developed to address confusion with respect to what constituted the most efficient motors available in the market. This specification was developed by NEMA, CEE, and other stakeholders, and was adapted from the CEE 1996 criteria. It currently serves as the benchmark for premium energy efficient motors. NEMA Premium® also denotes a brand name for motors which meet this specification. Specifically, this specification covers motors with the following attributes:

- Speed: 2, 4, and 6 pole
- Size: 1-500 horsepower (hp)
- Design: NEMA A and B
- Enclosure type: open and closed
- Voltage: low and medium voltage
- Class: general, definite, and special purpose

The choice of installing a premium efficiency motor strongly depends on motor operating conditions and the life cycle costs associated with the investment. In general, premium efficiency motors are most economically attractive when replacing motors with annual operation exceeding 2,000 hours/year. However, software tools such as MotorMaster+ (see Appendix D) can help identify attractive applications of premium efficiency motors based on the specific conditions at a given plant.

Sometimes, even replacing an operating motor with a premium efficiency model may have a low payback period. According to data from the Copper Development Association, the upgrade to high-efficiency motors, as compared to motors that achieve the minimum efficiency as specified by EPACT, can have paybacks of less than 15 months for 50 hp motors (CDA 2001). Payback times will vary based on size, load factor, running time, local energy costs, and available rebates and/or incentives (see Appendix D). Given the quick payback time, it usually makes sense to by the most efficient motor available (U.S. DOE and CAC 2003).

NEMA and other organizations have created the Motor Decisions Matter^{SM} campaign to help industrial and commercial customers evaluate their motor repair and replacement options, promote cost-effective applications of NEMA Premium^{R} motors and "best practice" repair, and support the development of motor management plans before motors fail.

In some cases, it may cost-effective to rewind an existing energy efficient motor, instead of purchasing a new motor. As a rule of thumb, when rewinding costs exceed 60% of the costs of a new motor, purchasing the new motor may be a better choice (MDM 2007). When rewinding a motor, it is important to choose a motor service center that follows best practice motor rewinding standards in order to minimize potential efficiency losses. An ANSI-approved recommended best practice standard has been offered by the Electric Apparatus Service Association (EASA) for the repair and rewinding of motors (EASA 2006). When best rewinding practices are implemented, efficiency losses are typically less than 0.5% to 1% (EASA 2003). However, poor quality rewinds may result in larger efficiency losses. It is therefore important to inquire whether the motor service center follows EASA best practice standards (EASA 2006).

Maintenance. The purposes of motor maintenance are to prolong motor life and to foresee a motor failure. Motor maintenance measures can be categorized as either preventative or predictive. Preventative measures, the purpose of which is to prevent unexpected downtime of motors, include electrical consideration, voltage imbalance minimization, load consideration, and motor ventilation, alignment, and lubrication. The purpose of predictive motor maintenance is to observe ongoing motor temperature, vibration, and other operating data to identify when it becomes necessary to overhaul or replace a motor before failure occurs (Barnish et al. 1997).

Properly sized motors. Motors that are sized inappropriately result in unnecessary energy losses. Where peak loads on driven equipment can be reduced, motor size can also be reduced. Replacing oversized motors with properly sized motors saves, on average for U.S. industry, 1.2% of total motor system electricity consumption. Higher savings can often be realized for smaller motors and individual motor systems.

To determine the proper motor size, the following data are needed: load on the motor, operating efficiency of the motor at that load point, the full-load speed of the motor to be replaced, and the full-load speed of the replacement motor. The U.S. DOE's Best Practices program provides a fact sheet that can assist in decisions regarding replacement of oversized and under loaded motors. Additionally, software packages such as MotorMaster+ can aid in proper motor selection.

Adjustable speed drives (ASDs).[3] Adjustable-speed drives better match speed to load requirements for motor operations, and therefore ensure that motor energy use is optimized to a given application. Adjustable-speed drive systems are offered by many suppliers and are available worldwide. Worrell et al. (1997) provide an overview of savings achieved with ASDs in a wide array of applications; typical energy savings are shown to vary between 7% and 60%. Also, in cement plants large variations in load occur (Bösche, 1993). The savings depend on the flow pattern and loads. The savings may vary between 7 and 60%. ASD equipment is used more and more in cement plants (Bösche, 1993; Fujimoto, 1993), but the application may vary widely, depending on electricity costs. Within a plant, ASDs can mainly be applied for fans in the kiln, cooler, preheater, separator and mills, and for various drives.

Power factor correction. Inductive loads like transformers, electric motors, and HID lighting may cause a low power factor. A low power factor may result in increased power consumption, and hence increased electricity costs. The power factor can be corrected by minimizing idling of electric motors (a motor that is turned off consumes no energy), replacing motors with premium-efficient motors (see above), and installing capacitors in the AC circuit to reduce the magnitude of reactive power in the system.

Minimizing voltage unbalances. A voltage unbalance degrades the performance and shortens the life of three-phase motors. A voltage unbalance causes a current unbalance, which will result in torque pulsations, increased vibration and mechanical stress, increased losses, and motor overheating, which can reduce the life of a motor's winding insulation. Voltage unbalances may be caused by faulty operation of power factor correction equipment, an unbalanced transformer bank, or an open circuit. A rule of thumb is that the voltage unbalance at the motor terminals should not exceed 1%. Even a 1% unbalance will reduce motor efficiency at part load operation, while a 2.5% unbalance will reduce motor efficiency at full load operation.

By regularly monitoring the voltages at the motor terminal and through regular thermographic inspections of motors, voltage unbalances may be identified. It is also recommended to verify that single-phase loads are uniformly distributed and to install ground fault indicators as required. Another indicator that a voltage unbalance may be a problem is 120 Hz vibration, which should prompt an immediate check of voltage balance (U.S. DOE 2005). The typical payback period for voltage controller installation on lightly loaded motors in the United States is 2.6 years.

Compressed Air Systems. Compressed air systems are used in different parts of the plants, i.e. mixing of slurry (in wet process plants) and in the baghouse Pulse-Jet or Plenum Pulse dust collector filters and other parts. Total energy consumption by compressed air systems is relatively small in cement plants, however, it can amount to a considerable expense if the

---

[3] Several terms are used in practice to describe a motor system that permits a mechanical load to be driven at variable speeds, including adjustable speed drives (ASDs), variable speed drives (VSDs), adjustable frequency drives (AFDs), and variable frequency drives (VFDs). The term ASD is used throughout this Energy Guide for consistency.

systems run continuously and end-uses are offline. Still, energy efficiency improvement measures may be found in these systems. Compressed air is probably the most expensive form of energy available in a plant because of its poor efficiency. Typically overall efficiency is around 10% for compressed air (LBNL et al., 1998). Because of this inefficiency, if compressed air is used, it should be of minimum quantity for the shortest possible time, constantly monitored and weighed against alternatives.

8.0 Product Change

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

Blended cements are very common in Europe, and blast furnace and pozzolanic cements account for about 12% of total cement production with portland composite cement accounting for an additional 44% (Cembureau, 1997). Blended cement was introduced in the U.S. to reduce production costs for cement (especially energy costs), expand capacity without extensive capital costs, to reduce emissions from the kiln. In Europe a common standard has been developed for 25 types of cement (using different compositions for different applications). The European standard allows wider applications of additives. Many other countries around the world use blended cement. Blended cements demonstrate a higher long-term strength, as well as improved resistance to acids and sulfates, while using waste materials for high-value applications. Short-term strength (measured after less than 7 days) may be lower, although cement containing less than 30% additives will generally have setting times comparable to concrete based on portlandcement.

In the U.S. the consumption and production of blended cement is still limited. In the U.S., the most prevalent blending materials are fly ash and granulated blast furnace slag. Not all slag and fly ash is suitable for cement production. It is estimated that 68% of the fly ash in the U.S. conforms to ASTM C618 (PCA, 1997). Currently, only a small part of the blast furnace slag is produced as granulated slag, while the majority is air-cooled. Air-cooled slag cannot be used for cement production, and is of lesser value. However, investments in slag processing by slag processors and cement companies will increase this fraction. ASTM Standards exist for different types of blended cements, i.e. C989 (slag cement), C595 and C1157. U.S. EPA (2000) has issued procurement guidelines to support The Use of blended cement in (federal) construction projects.

9.0 Additional References for Mitigation Measures

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

Barnish, T. J., M. R. Muller, and D. J. Kasten (1997). Motor Maintenance: A Survey of Techniques and Results. Proceedings of the 1997 ACEEE Summer Study on Energy Efficiency in Industry. American Council for an Energy-Efficient Economy, Washington, D.C.

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

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

Buzzi, S., 1997. “Die Horomill® - Eine Neue Mühle für die Feinzerkleinerung,” ZKG International 3 **50** pp.127-138 (1997).

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

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

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

Consortium for Energy Efficiency (CEE) (2007). Energy-Efficiency Incentive Programs: Premium-Efficiency Motor & Adjustable Speed Drives in the U.S. and Canada. Boston, Massachusetts. May.

Copper Development Association (CDA) (2001). High-Efficiency Copper-Wound Motors Mean Energy and Dollar Savings. New York, New York. http://energy.copper.org/motorad.html.

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

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

Electric Apparatus Service Association (EASA) (2003). The Effect of Repair/Rewinding on Motor Efficiency. St. Louis, Missouri.

Electric Apparatus Service Association (EASA) (2006). ANSI/EASA Standard AR100-2006. Recommended Practice for the Repair of Rotating Electrical Apparatus. St. Louis, Missouri.

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

Fenning, L. et al. (Eds.) 2001. Pump Life Cycle Costs: A Guide to LCC Analysis for Pumping Systems. Hydraulic Institute/Europump/ United States Department of Energy. ISBN: 1-880952-58-0.

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

Grydgaard, P., 1998. “Get out of the Wet,” International Cement Review, April 1998.

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

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

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

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

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

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

Motor Decisions Matter (MDM) (2007). Motor Planning Kit. Boston, Massachusetts. http://www.motorsmatter.org/tools/mpkv21.pdf

National Electrical Manufacturers Association (NEMA) (2002). NEMA Standards Publication No. MG-1, Motors and Generators, Revision 3. Rosslyn, Virginia.

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

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

Portland Cement Association (PCA), 1997. Blended Cement Potential Study. Skokie, IL: Portland Cement Association.

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

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

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

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

Southern California Edison (SCE). 2003. Southern California Edison Educational Publication: Saving Money with Motors in Pharmaceutical Plants. Rosemead, California.

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

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

United States Department of Energy (DOE). 2003. Improving Compressed Air System Performance - A Sourcebook for Industry. Office of Industrial Technologies, Washington, D.C.

United States Department of Energy (DOE). 2005. Energy Tips: Estimate Voltage Unbalance. Information Sheet. Office of Industrial Technologies, Washington, DC. Motor Systems Tip Sheet #7.

United States Environmental Protection Agency (US EPA), 2000. "2000 Buy Recycled Products: Construction Products", Washington, DC (http://www.epa.gov/epaoswer/non-hw/procure/pdf/const-00.pdf).

Van Oss, H. G. 2002. U.S. Geological Survey (USGS) Mineral Commodity Summaries: Cement.

Van Oss, H. G. 1999. U.S. Geological Survey (USGS) Mineral Commodity Summaries: Cement.

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

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

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