U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY
ADVANCED MANUFACTURING OFFICE

Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Cement Manufacturing

September 2017

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Preface

Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Energy bandwidth studies of U.S. manufacturing sectors serve as general data references to help understand the range (or *bandwidth*) of potential energy savings opportunities.[1] The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze the processes and products that consume the most energy, and provide hypothetical, technology-based estimates of potential energy savings opportunities. The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macro-scale.

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of on-site energy consumption to manufacture specific products and to compare potential energy savings opportunities in U.S. manufacturing facilities (see figure).

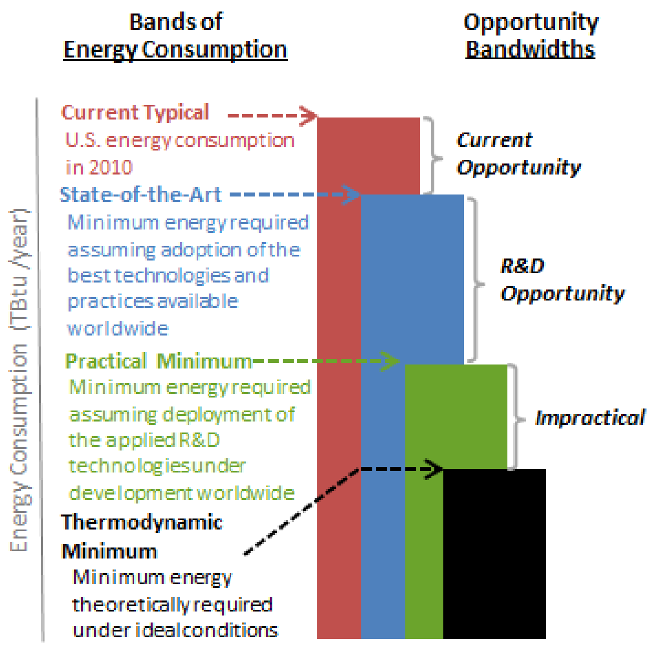

Figure P-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

Current typical (CT) is the energy consumption in 2010; **state of the art** (SOA) is the energy consumption that may be possible through the adoption of existing best technologies and practices available worldwide; **practical minimum** (PM) is the energy consumption that may be possible if applied research and development (R&D) technologies under development worldwide are deployed; and the **thermodynamic minimum** (TM) is the least amount of energy required under ideal conditions, which typically cannot be attained in commercial applications.

CT energy consumption serves as the benchmark of manufacturing energy consumption. TM energy consumption serves as the baseline (or theoretical minimum) that is used in calculating energy savings potential. Feedstock energy (the nonfuel use of fossil energy) is not included within the energy consumption estimates.

Two on-site energy savings opportunity *bandwidths* are estimated: the ***current opportunity*** spans the bandwidth from CT energy consumption to SOA energy consumption, and the ***R&D opportunity*** spans the bandwidth from SOA energy consumption to PM energy consumption. The total opportunity is the sum of the R&D and the current opportunities. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, decreasing the PM energy consumption with future R&D efforts and emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption closer to the TM energy

[1] The concept of an energy bandwidth, and its use as an analysis tool for identifying potential energy saving opportunities, originated in AMO in 2002 (when it was called the Office of Industrial Technologies). Most recently, revised and consistent versions of bandwidth studies for the *Chemicals, Petroleum Refining, Iron and Steel*, and *Pulp and Paper* sectors were published in 2015.

consumption. Significant investment in technology development and implementation would be needed to fully realize the energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future R&D technologies was not in the scope of this study.

In each sector studied in the series, the four energy bands are estimated for select individual products or processes, sub-processes, and sector-wide. The estimation method involved a detailed review and analytical synthesis of data from diverse industry, governmental, and academic sources. Where published data were unavailable, best engineering judgment was used.

Acknowledgments

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In addition, AMO wishes to acknowledge the contributions of the following for their work reviewing this study: Hongyou Lu of Lawrence Berkeley National Laboratory, Dr. Dustin McIntyre of National Energy Technology Laboratory, Dr. Edward Garboczi of National Institute of Standards and Technology, and Ellis Gartner of Imperial College London.

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List of Acronyms and Abbreviations

AMO	Advanced Manufacturing Office
Btu	British thermal unit
C_2F	Dicalcium ferrite (chemical formula $2CaO•Fe_2O_3$)
C_2S	Dicalcium silicate (chemical formula $2CaO•SiO_2$)
C_3S	Tricalcium silicate (chemical formula $3CaO•SiO_2$)
CA	Calcium aluminate (chemical formula $CaO•Al_2O_3$)
c_p	Heat capacity
CSI	Cement Sustainability Initiative
CT	Current typical energy consumption or energy intensity
DOE	U.S. Department of Energy
ECRA	European Cement Research Academy
EERE	DOE Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
G	Gibbs free energy
GJ	Gigajoule
H	Enthalpy
IFC	International Finance Corporation
IIP	Institute for Industrial Productivity
kg	Kilogram
kJ	Kilojoule
kWh	Kilowatt-hour
lb	Pound
LBNL	Lawrence Berkeley National Laboratory
MECS	Manufacturing Energy Consumption Survey
MJ	Megajoule
MMBtu	Million British thermal units
mol	Mole
NAICS	North American Industry Classification System
NREL	National Renewable Energy Laboratory
PG&E	Pacific Gas & Electric
PFD	Process flow diagram
PM	Practical minimum energy consumption or energy intensity
R&D	Research and development
SOA	State of the art energy consumption or energy intensity
T	Temperature
TBtu	Trillion British thermal units
TM	Thermodynamic minimum energy consumption or energy intensity
USCB	U.S. Census Bureau
USGS	U.S. Geological Survey
VFD	Variable frequency drive

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Executive Summary

This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. cement manufacturing (North American Industry Classification System (NAICS) code 327310). Industrial, government, and academic data are used to estimate the energy consumed in the cement manufacturing process. To give a more detailed look at energy consumption within cement manufacturing, four sub-processes are explored throughout this report—crushing/grinding, pyroprocessing with cooling, finish grinding, and storage. These sub-processes are not part of NAICS coverage of the industry and are included purely to give a more detailed reporting of cement manufacturing process. Three different energy consumption *bands* (or levels) are estimated for these select manufacturing sub-processes based on referenced energy intensities of current, state of the art, and R&D technologies. A fourth thermodynamic minimum energy consumption *band* is also estimated. The *bandwidth*—the difference between bands of energy consumption—is used to determine the potential energy savings opportunity. The costs associated with realizing these energy savings was not in the scope of this study.

The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for cement manufacturing sub-processes and sector-wide. This is a step toward understanding the processes that could most benefit from technology and efficiency improvements to realize energy savings.

Study Organization and Approach*: The present document is organized as described below. The organization reflects the study approach.*

- Chapter 1 provides an overview of the methodology and boundaries.
- Chapter 2 provides a sector overview and identifies 2010 production volumes.
- Chapter 3 estimates current typical (CT) energy consumption for four select sub-processes and sector wide.
- Chapter 4 estimates the minimum energy consumption for these sub-processes and sector wide. In developing these estimates, the study assumes the state of the art (SOA), i.e., adoption of best technologies and practices available worldwide.
- Chapter 5 estimates the practical minimum (PM) energy consumption for these sub-processes and sector wide, assuming the deployment of the applied research and development (R&D) technologies available worldwide.
- Chapter 6 estimates the thermodynamic minimum (TM), i.e., the minimum amount of energy theoretically required for these processes assuming ideal conditions. In some cases, exothermic processes result in this estimate being less than zero.
- Chapter 7 provides the estimated energy savings opportunity *bandwidths*, i.e., the differences between the energy consumption *bands* (CT, SOA, PM, TM).

The U.S. Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) provides sector-wide estimates of energy consumption for U.S. cement manufacturing; this data is referenced as sector-wide CT energy consumption. In this study, CT, SOA, PM, and TM energy consumption for *individual* sub-processes is estimated from multiple referenced sources; this data was then extrapolated based on the 97% coverage to estimate total subsector SOA, PM, and TM energy consumption. To estimate SOA, PM, and TM energy consumption for the cement sub-processes, available sources were reviewed to estimate the energy consumption data of the most energy intensive steps in each sub-process; data for the processes studied in the four sub-processes were extrapolated to estimate total sector SOA, PM, and TM energy consumption. The sub-process energy consumption values were summed to determine sector-wide SOA, PM, and TM energy consumption.

Study Results*:* Two energy savings opportunity *bandwidths*—current opportunity and R&D opportunity—are presented in Table ES-1 and Figure ES-1 for cement manufacturing [data calculated using methods and sources identified in this document].[2] The current opportunity is the difference between the 2010 CT energy

[2] The energy estimates presented in this study are for macro-scale consideration; energy intensities and energy consumption values do not represent energy use in any specific facility or any particular region in the United States. The costs associated with achieving energy savings are not considered in this study.

consumption and SOA energy consumption; the R&D opportunity is the difference between SOA energy consumption and PM energy consumption. Potential energy savings opportunities are presented for the processes studied in the four sub-processes and for the entire cement manufacturing sector based on extrapolated data. The energy savings opportunities presented reflect the estimated production of cement for selected application areas in baseline year 2010. Therefore, it is important to note that the total energy opportunities would scale with increasing or decreasing production levels.

Table ES-1. Potential Energy Savings Opportunities in the U.S. Cement Manufacturing Sector[2]

Opportunity Bandwidths	Estimated Energy Savings Opportunity for Processes Studied in Four Cement Sub-processes Studied (per year)	Estimated Energy Savings Opportunity for total Cement Manufacturing Sector Based on Extrapolated Data (per year)
Current Opportunity: on-site energy savings if the best technologies and practices available are used to upgrade production	**59.9 TBtu** [3] (34% energy savings, where TM is the baseline)[4]	**61.8 TBtu** [3] (34% energy savings, where TM is the baseline)[4]
R&D Opportunity: additional on-site energy savings if applied R&D technologies under development worldwide are successfully deployed	**6.4 TBtu** [5] (4% energy savings, where TM is the baseline)[6]	**6.6 TBtu** [5] (4% energy savings, where TM is the baseline)[6]

All estimates are for on-site energy use (i.e., energy consumed within the plant boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.

[3] Current opportunity = CT – SOA, as shown in Section 4.2.

[4] Current opportunity savings percentage = $\left(\frac{CT-SOA}{CT-TM}\right)x100$, as shown in Section 4.2.

[5] R&D opportunity = SOA – PM, as shown in Section 5.2.

[6] R&D opportunity savings percentage = $\left(\frac{SOA-PM}{CT-TM}\right)x100$, as shown in Section 5.2.

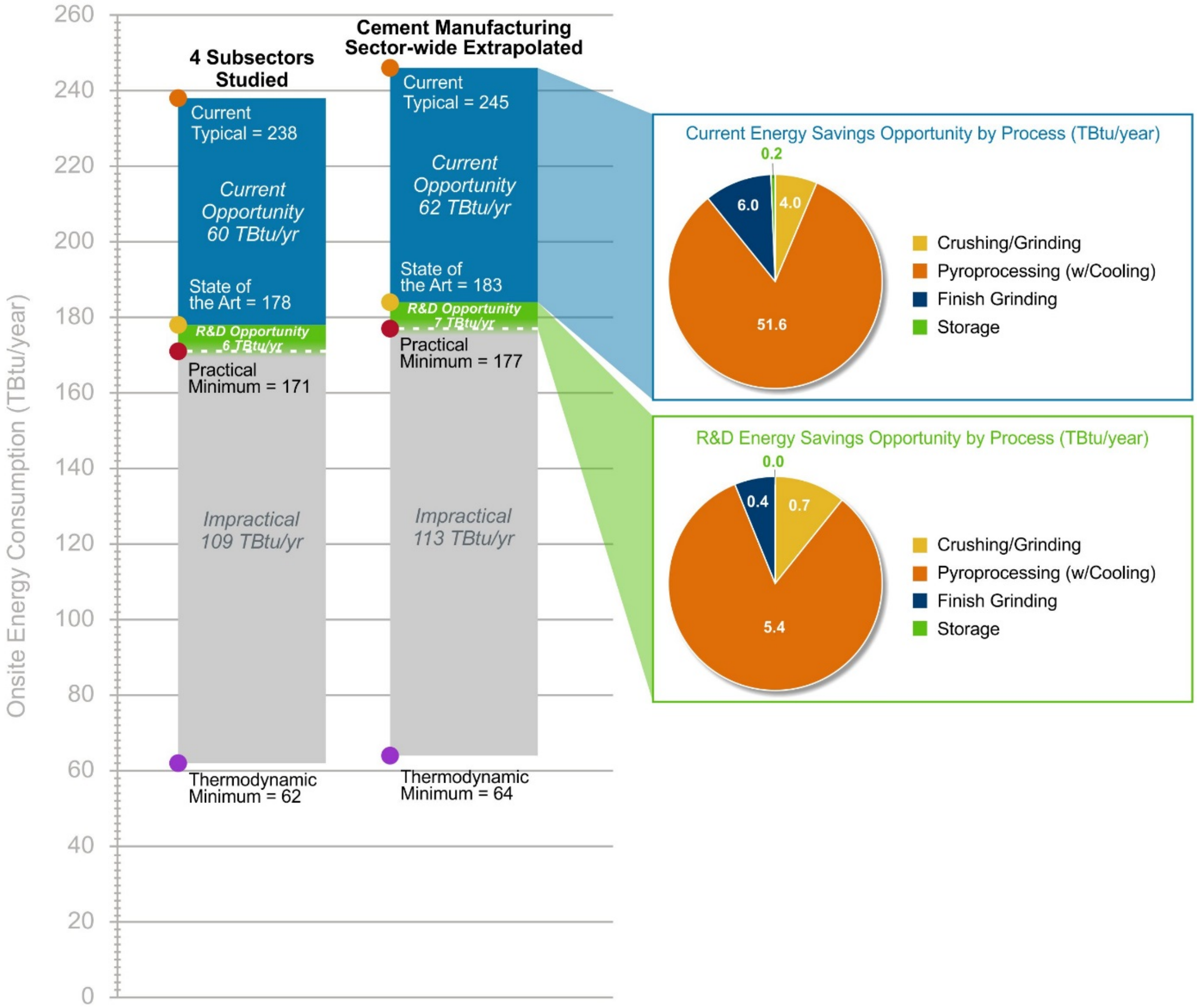

Figure ES-1. Current and R&D energy savings opportunities for the cement products manufacturing sector-wide based on extrapolated data
Source: EERE

The PM energy consumption estimates are speculative because they are based on unproven technologies. The estimates assume the successful deployment of R&D technologies that are under development; where multiple technologies were considered for a similar application, only the most energy efficient technology was considered in the energy savings estimate. The difference between PM and TM is labeled "impractical" in Figure ES-1 because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, it is shown as a dashed line with color fading because emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption.

Figure ES-1 shows 238 TBtu was consumed in 2010 to manufacture U.S. cement in the four sub-processes; total sector-wide energy consumption in 2010 was 245 TBtu to manufacture all cement in the U.S. according to EIA MECS. Based on the results of this study, an estimated 59.9 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide are used to upgrade the cement manufacturing sub-processes studied; an additional 6.4 TBtu could be saved through the adoption of applied R&D technologies under development worldwide. These values are not based on extrapolated numbers.

The current energy savings opportunities for the cement sector sub-processes are as follows:

- Pyroprocessing with Cooling – 50.0 TBtu (or 83% of the current opportunity)
- Finish Grinding – 5.8 TBtu (or 10% of the current opportunity)
- Crushing/Grinding – 3.9 TBtu (or 7% of the current opportunity)
- Storage – 0.2 TBtu (or 0% of the current opportunity).

The R&D energy savings opportunities for the cement sector sub-processes are as follows:

- Pyroprocessing with Cooling – 5.2 TBtu (or 82% of the R&D opportunity)
- Crushing/Grinding – 0.7 TBtu (or 11% of the R&D opportunity)
- Finish Grinding – 0.4 TBtu (or 7% of the R&D opportunity)
- Storage – 0.0 TBtu (or 0% of the R&D opportunity).

DOE researchers will continue to evaluate the energy consumption and opportunity bandwidths in the U.S. cement manufacturing sector, along with bandwidth study results from other manufacturing sectors.

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1. Introduction

1.1. Overview

This bandwidth study examines energy consumption and potential energy savings opportunities in the U.S. cement manufacturing sector, as defined by classification 327310 of the North American Industry Classification System (NAICS). The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for cement manufacturing sector-wide. In this study, four different energy consumption *bands* (or measures) are estimated. The *bandwidth*—the difference between bands of energy consumption—is the estimated potential energy savings opportunity.

There are many types of cement manufactured in the United States. The most prevalent type of cement, Portland cement, accounted for approximately 98% of 2010 U.S. production (146 billion pounds U.S. total). Since Portland cement is the primary product of cement manufacturing, the focus of this report is the four most energy-intensive sub-processes of Portland cement manufacture. Together, these sub-processes accounted for 97% of on-site energy consumption by the entire U.S. cement manufacturing sector in 2010.

The four bands of energy consumption estimated in this report include: the on-site energy consumption associated with manufacturing processes in four sub-processes in 2010; two energy consumption levels with progressively more advanced technologies and practices (state of the art and practical minimum); and one energy consumption level based on the minimum amount of energy needed to theoretically complete a manufacturing process (thermodynamic minimum). The bands of energy consumption are used to calculate *current* and *R&D opportunity* bandwidths for energy savings.

History of DOE Advanced Manufacturing Office Energy Bandwidth Reports

Before 2013, the U.S. Department of Energy (DOE)'s Advanced Manufacturing Office predecessor conducted industrial sector analyses to quantify savings opportunities. Here is a timeline of accomplishments.

- **2013**: Developed and refined a consistent methodology for bandwidth studies so comparisons could be made across the manufacturing sectors.
- **2015**: Published revised reports for four U.S. manufacturing sectors—chemicals, iron and steel, petroleum refining, and pulp and paper.
- **2016**: Published six additional bandwidth studies on the energy use in manufacturing lightweight structural materials (aluminum, magnesium, titanium, advanced high strength steel, carbon fiber reinforced polymer composites, and glass fiber reinforced composites) in the United States, following the same analysis methodology and presentation format.
- **2017**: Prepared bandwidth studies (including this report) for four additional U.S. manufacturing sectors: cement, food and beverage products, glass, and plastics and rubber products.

All of these reports are available on the AMO website (DOE 2017).

1.2. Comparison to Other Bandwidth Studies

This is the first DOE energy bandwidth study prepared specifically for the cement sector. Similar energy bandwidth studies (see inset) were prepared in 2015 for four other U.S. manufacturing sectors: chemicals, iron and steel, petroleum refining, and pulp and paper. Additional bandwidth studies were subsequently prepared to characterize energy use in manufacturing six lightweight structural materials in the United States: aluminum, magnesium, titanium, advanced high strength steel, carbon fiber reinforced polymer composites, and glass fiber reinforced composites. This report is one of a more recently commissioned set of bandwidth studies that also includes plastics and rubber products, food and beverage products, and glass products (DOE 2017).

The energy bandwidth studies completed in 2015 and later all follow the same analysis methodology and presentation format. Collectively, these studies explore the potential energy savings opportunities in manufacturing that are available through existing technology and investment in research and development (R&D) technologies.

1.3. Definitions of Energy Consumption Bands and Opportunity Bandwidths

The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potential within and across manufacturing sectors at the macro-scale. There are four energy consumption bands referenced throughout this report: current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM) energy consumption. These bands describe different levels of energy consumption to manufacture products.

As shown in Figure 1-1, the bands progress from higher to lower levels of energy consumption, reflecting the use of increasingly more efficient manufacturing technologies and practices. The upper bound is set by a mix of new and older technologies and practices in current use (the current typical level of energy consumption). The lower bound is defined by the theoretical minimum energy requirement assuming ideal conditions and zero energy losses (the thermodynamic minimum level of energy consumption).

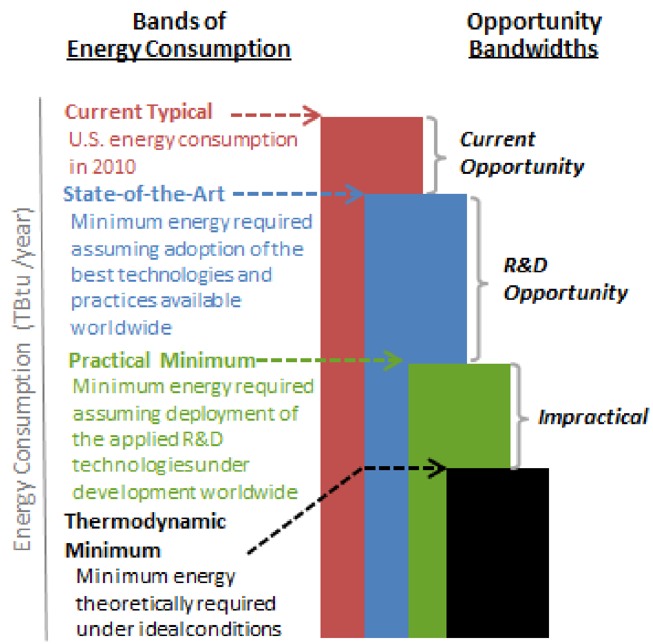

Figure 1-1. Energy consumption bands and opportunity bandwidths estimated in this study
Source: EERE

Each of these two bounds defining the extremes of energy consumption can be compared to hypothetical measures in the middle of this range. If manufacturers use the most efficient technologies and practices available in the world, energy consumption could decrease from the current typical to the level defined by the state of the art. Since these state of the art technologies already exist, the difference between the current typical and the state of the art energy consumption levels defines the *current opportunity* to decrease energy consumption. Given that this is an evaluation of technical potential, fully realizing the current opportunity would require investments in capital that may not be economically viable for any given facility. Widespread deployment of future advanced technologies and practices under investigation by researchers around the globe could help manufacturers attain the practical minimum level of energy consumption. The difference between state-of-the-art and practical minimum levels of energy consumption defines the *R&D opportunity* for energy savings.

Definitions of the four energy bands are provided in the inset (box at right). Definitions of the two opportunity bandwidths are provided below:

Definitions of Energy Bands Used in the Bandwidth Studies

The following definitions are used to describe different levels of U.S. energy consumption to manufacture a specific product industry-wide:

Current Typical (CT) energy consumption:

U.S. energy consumption in 2010.

State-of-the-Art (SOA) energy consumption:

The minimum amount of energy required assuming the adoption of the best technologies and practices available worldwide.

Practical Minimum (PM) energy consumption:

The minimum amount of energy required assuming the deployment of the best applied R&D technologies under development worldwide. This measure is expressed as a range to reflect the speculative nature of the energy impacts of the unproven technologies considered.

Thermodynamic Minimum (TM) energy consumption: The minimum amount of energy theoretically required assuming ideal conditions typically unachievable in real-world applications.

The *current opportunity* is the energy savings that is potentially attainable through capital investments in the best technologies and practices available worldwide. It is the difference between CT and SOA energy consumption.

The *R&D opportunity* is the energy savings that is potentially attainable through the applied R&D technologies under development. It is the difference between SOA and PM energy consumption. To attain this energy savings, manufacturers would need to produce cement in new ways with technologies that are not commercially available.

The difference between PM and TM energy consumption is labeled as *impractical*. The term *impractical* is used because the PM energy consumption is based on today's knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. However, decreasing the PM energy consumption with future R&D efforts and emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption closer to the TM energy consumption. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future technologies was not in the scope of this study.

1.4. Bandwidth Analysis Method

This section describes the method used in this bandwidth study to estimate the four bands of energy consumption and the two corresponding energy savings opportunity bandwidths. This section can also be used as a guide to understanding the structure and content of this report.

In this study, U.S. energy consumption is labeled as either "on-site energy" or "primary energy" and defined as follows:

- **On-site energy** (sometimes referred to as site or end use energy) is the energy consumed within the manufacturing plant boundary (i.e., within the plant gates). Non-fuel feedstock energy is not included in the on-site energy consumption values presented in this study.
- **Primary energy** (sometimes referred to as source energy) includes energy that is consumed both offsite and onsite during the manufacturing process. Off-site energy consumption includes generation and transmission losses associated with bringing electricity and steam to the plant boundary. Non-fuel feedstock energy is not included in the primary energy values. Primary energy is frequently referenced by governmental organizations when comparing energy consumption across sectors.

The four bands of energy consumption described above are quantified for processes and for the material total. To determine the total annual on-site CT, SOA, PM, and TM energy consumption (TBtu per year), energy intensity values per unit weight (Btu per pound (lb) of material manufactured) are estimated and multiplied by the production amount (lb per year of material manufactured). The year 2010 is used as a base year since it is the most recent year for which consistent energy consumption and production data are available for all materials and manufacturing sectors analyzed in this series of bandwidth studies. Unless otherwise noted, 2010 production data is used.

The estimates presented are for macro-scale consideration of energy use in cement manufacturing. The estimates reported herein are representative of average U.S. cement manufacturing; they do not represent energy use in any specific facility or any particular region in the United States or the world.

Significant investment in technology development and implementation would be needed to fully realize the potential energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future technologies was not in the scope of this study.

The calculated energy consumption values in this report are based on an examination of referenced data and extrapolation to sector-wide energy savings opportunities. The references, methodology, and assumptions employed are presented with the data in each chapter and were peer reviewed.

Chapter 2 presents the **U.S. production volumes** (million lb per year) for 2010.

Chapter 3 presents the calculated on-site **CT energy intensity** (Btu per lb) and **CT energy consumption** (TBtu per year) for the products, processes, sub-processes studied, totals, and sector-wide (along with sources).

Chapter 4 presents the estimated on-site **SOA energy intensity** (Btu per lb) and **SOA energy consumption** (TBtu per year) for the products, processes, sub-processes studied, totals, and sector-wide (along with sources). The SOA energy consumption for the process areas studied in the four sub-processes is extrapolated to estimate the entire SOA energy consumption for the cement sector (see inset). The extrapolated data for each sub-process is summed to provide an estimate of sector-wide SOA energy consumption.

Chapter 5 presents the estimated on-site **PM energy intensity** (Btu per lb) and **PM energy consumption** for the products, processes, sub-processes studied, totals, and sector-wide (along with sources). The PM energy intensity for the process areas studied in the four sub-processes is extrapolated to estimate the entire PM energy consumption for each sub-process (see inset). The extrapolated data for each sub-process is summed to provide an estimate of sector-wide PM energy consumption.

Cement Sub-process Analysis for SOA, PM, and TM Energy Consumption

To estimate SOA, PM, and TM energy consumption for the cement sub-processes, the energy consumption data for individual processes was aligned and grouped with its NAICS-defined sector.

The SOA, PM, and TM energy consumption data for each sub-process is extrapolated to match MECS 2010 data to estimate SOA, PM, and TM energy consumption for the entire sector. A consistent extrapolation method is used. The sub-process values are summed to provide sector-wide SOA, PM and TM energy consumption estimates.

Chapter 6 presents the estimated on-site **TM energy intensity** (Btu per lb) and **TM energy consumption** for the products, processes, sub-processes studied, totals, and sector-wide (along with sources).

Chapter 7 provides a summary **of current and R&D opportunity** analysis based on bandwidth summary results for the cement sub-processes and sector-wide.

1.5. Boundaries of the Study

The U.S. cement manufacturing sector is the physical boundary of this study. It is recognized that some of the major energy benefits (and costs) associated with the use of cement often occur *outside* of the manufacturing sector (e.g., improvements made in limestone quarrying). While such impacts are recognized as important, they will not be quantified as this is not a life cycle assessment study. Instead, this report focuses exclusively on the energy use directly involved in the production of cement within the manufacturing sector. This process begins when raw material enters the manufacturing plant and ends when dry cement is packaged or shipped. The focus of this bandwidth study is thus the *on-site* use of process energy (including purchased energy and on-site generated steam and electricity) that is directly applied to cement manufacturing at a production facility.

This study does not consider life cycle energy consumed during raw material extraction or quarrying, off-site treatment, transportation of materials, product use, or disposal. One of the most common misconceptions about cement is that it is the same as concrete. Concrete is a product that is composed of cement and other materials. The addition and mixing of those additional materials with cement is not included in this study. For consistency with previous bandwidth studies, feedstock energy and the energy associated with delivering feedstocks to the plant gate (e.g., producing, conditioning, and transporting feedstocks) are *excluded* from the energy consumption bands in this analysis as well.

1.5.1. Portland Cement Manufacturing

Cement manufacturing consists of several different processes but none are as pervasive as the wet and dry processes for Portland cement manufacturing. Approximately 98% of all cement produced in 2010 was Portland cement and 100% of that cement is produced by either the wet or dry process. Cement manufacturing produces a variety of products including different types of cement. Portland cement is the single most important product of cement manufacturing and is also one of the most energy intensive cement product types. Other products such as slag cement, pozzolans (including fly ash), gypsum, calcium sulfoaluminate cement, and other related materials require less energy to produce and can be effective as cement products on their own or in combination with Portland cement. However, this bandwidth does not explore different product mixes that could be implemented to lower overall cement manufacturing sector energy use. This level of analysis would require a greater understanding of cement chemistry and potential cement substitutions. Instead, the report relies on product mixes and cement types produced for 2010 to develop the CT, SOA, PM, and TM consumption values.

This report does look at the energy use of both of the main Portland cement manufacturing processes: wet and dry. While CT calculations are made using production volumes reported for each of the wet and dry processes, it is assumed for SOA, PM, and TM energy consumption calculations that all cement is produced using the more energy efficient dry process. Since cost is not considered for this report, the retrofits required to shift all U.S. Portland cement production from the wet to dry process are ignored.

2. U.S. Cement Manufacturing Sector Production

2.1. U.S. Cement Manufacturing Overview

The U.S. cement manufacturing sector consists of a large number of facilities. These facilities produce many different types of cement. In total, the industry produces a large number of diverse products that are both consumed domestically and exported to international markets. However, the main product in the cement industry is Portland cement, which accounts for approximately 98% (144 billion lbs) of all cement manufactured in the United States (146 billion lb total). Other cements like natural, masonry and pozzolanic cement make up the difference in the cement industry. Portland cement manufacture requires significant preparation and an endothermic chemical step to create the final product. Because of this, a variety of energy consuming steps are typically required throughout the manufacturing process. Overall, the main sources of energy consumption include fuel and electricity.

According to the U.S. Census Bureau, there were 256 establishments involved in cement manufacturing in 2010 (USCB 2012). These establishments employed nearly 12,992 individuals and with a total annual payroll of $815 million (USCB 2012).

2.2. U.S. Cement Manufacturing Sector Description

In 2010, the United States produced approximately 146 billion lb of cement, which accounted for 2% of world capacity. Approximately 56% of global production capacity came from the world-leading cement producer, China, in 2010 (USGS 2011).

This study focuses on production of Portland cement as reported by sources representative of the industry. The raw materials required for the Portland cement manufacturing process come from either cement quarries or waste streams from other industries like steel and rubber. These raw materials go through a series of crushers (typically jaw crushers or hammer crushers) to produce ¾-inch stone. This stone is sent through a series of grinders (such as ball mills and vertical roller mills) to produce the raw meal. Concurrently, solid fuels such as coal and petroleum coke (or “petcoke”) are prepared to be fed to a kiln. This raw meal is then sent through the kiln for the very fuel-intensive pyroprocessing step to produce clinker. The clinker is cooled, mixed with other minerals such as gypsum, and sent through a series of ball mills or vertical roller mills during the finish grinding step to form a uniform cement product. The cement is then stored in a silo and eventually packaged for future consumption. Figure 2-1 shows the process flow diagram (PFD) for cement manufacturing. Table 2-1 shows the specific processes considered under the four sub-processes studied based on available recent data. The only NAICS codes applicable to this report is 327310.

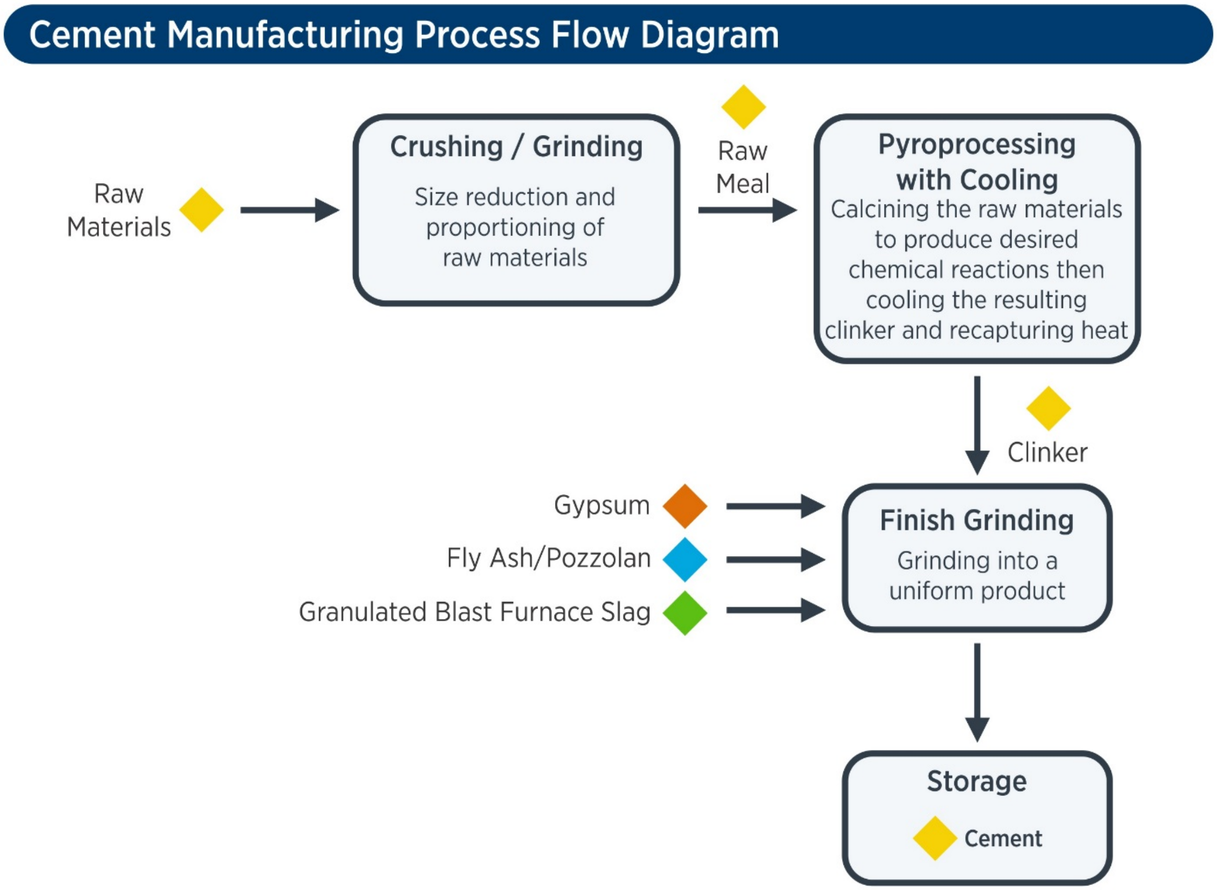

Figure 2-1. Process flow diagram (PFD) of the overall boundaries in the cement manufacturing process considered for this report
Source: EERE

Table 2-1. Cement Manufacturing Process Areas Considered in Bandwidth Analysis Based on Available Data

Sub-process	Stage	End-Use Technologies
Dry Process		
Crushing/Grinding	Initial Size Reduction	Two-stage primary size reduction (compression type crushers)
		Two-stage secondary size reduction (impact type crushers)
		Single stage-size reduction (impact type crusher)
	Preblending	Prehomogenization
		Proportioning
	Grinding	Ball mills
		Vertical roller mills
	Blending	Air-fluidized homogenizing silo
		Mechanical system
	Storage	Gravity (multi-outlet silo) dry system
	Fuel grinding	Ball mills
		Vertical roller mills
Pyroprocessing with Cooling	Kiln burning	Long dry kiln
		Kiln with preheater
		Kiln with precalciner
		Kiln with preheater and precalciner
		Kiln with multiple preheaters and precalciner
	Cooling	Reciprocating grate cooler
		Planetary cooler
		Rotary cooler
Finish Grinding	Finish grinding	Ball Mills
		Ball Mills w/ Roller Presses
		Roller Presses
		Vertical Roller Mills
		Horizontal Roller Mill
		High Pressure Roller Mill
		Advanced Horizontal Roller Mill
		OK Mill
Storage	Packaging	Silo
	Transporting	Belt conveyor
Wet Process		
Crushing/Grinding	Initial Size Reduction	Two-stage primary size reduction (compression type crushers)
		Two-stage secondary size reduction (impact type crushers)

Table 2-1. Cement Manufacturing Process Areas Considered in Bandwidth Analysis Based on Available Data

Sub-process	Stage	End-Use Technologies
		Single stage-size reduction (impact type crusher)
	Grinding	Wash mills
		Ball mills
	Storage	Gravity (multi-outlet silo) dry system
	Fuel grinding	Ball mills
		Vertical roller mills
Pyroprocessing with Cooling	Kiln burning	Long wet kiln
		Semi-wet/semi-dry kiln
	Cooling	Grate cooler
Finish Grinding	Finish grinding	Ball Mills
		Ball Mills w/ Roller Presses
		Roller Presses
		Vertical Roller Mills
		Horizontal Roller Mill
		High Pressure Roller Mill
		Advanced Horizontal Roller Mill
		OK Mill
Storage		
Storage	Packaging	Silo
	Conveying	Belt conveyor

* NAICS = North American Industry Classification System (2012 codes were used)

2.3. U.S. Cement Manufacturing Energy Consumption

On-site energy and primary energy for the U.S. cement manufacturing sector are provided in Table 2-1. DOE's Manufacturing Energy Consumption Survey (MECS) provides on-site energy consumption data by end use, including on-site fuel and electricity consumption. Primary energy includes assumptions for off-site losses (DOE 2014).

Cement manufacturing accounted for 307 TBtu (1.6%) of the 19,237 TBtu of total primary manufacturing energy consumption in 2010 (DOE 2014). Off-site electricity and steam generation and transmission losses in cement manufacturing totaled 62 TBtu in 2010; on-site energy consumed within the boundaries of U.S. cement manufacturing plants totaled 245 TBtu. Additional detail on these CT energy consumption estimates can be found in Chapter 3.

Table 2-2. U.S. Cement Manufacturing Energy Consumption Sector-Wide, 2010

On-site Energy Consumption (includes electricity, steam, and fuel energy used on site at the facility)	245 TBtu
Primary Energy Consumption* (includes on-site energy consumption, and off-site energy losses associated with generating electricity and steam off site and delivering to the facility)	307 TBtu

Source: DOE 2014

* Primary energy accounts for off-site electricity generation and transmission losses. Off-site electrical losses are based on published grid efficiency. The Energy Information Administration (EIA) Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from off-site sources including generation and transmission losses is determined to be 10,553 Btu/kWh.

2.4. U.S. Cement Manufacturing Production Values

In this report, production data refers to the amount of cement produced in the United States. Energy intensity values represent the energy that the end-use process requires to create a pound (lb) of the cement product. Energy intensity values are multiplied by the production values in the Table 2-2 in order to estimate total energy consumption by process.

The leading source for data on cement production (crushing/grinding, pyroprocessing with cooling, finish grinding, and storage) is the U.S. Geological Survey (USGS). Table 2-2 provides the production values for domestic cement manufacturing by product type. The domestic production for cement involves raw meal, fuel, and clinker production. The raw meal encompasses the major types of raw materials used for cement manufacturing, particularly calcareous materials like limestone, cement rock and cement kiln dust (USGS 2011). However, the raw meal also includes other aluminous, ferrous, and siliceous materials such as clay, iron ore, and fly ash respectively (USGS 2011). The fuel consumed in the kiln must be prepared for burning, which is particularly important for solid fuels with respect to moisture and size (USGS 2011). The value for clinker production includes only domestically produced clinker that is manufactured by the wet or dry process. Imported clinker as well as clinker produced by two U.S. plants that use both the wet and dry process are not included in the total production value (USGS 2011). The value for cement production does not include any cement produced by grinding plants or plants that produce Portland cement by regrinding other types of cement (exclusions) as well. (USGS 2011). These restrictions on cement and clinker production values lower the total volume considered in this report below the 144 billion pounds of Portland cement mentioned earlier. The final production value of Portland cement considered in this report is 141 billion pounds or 96% of the total cement manufacture in the United States.

The volumes shown in Table 2-2 are separated by wet and dry process only when calculating CT energy consumption. SOA, PM, and TM energy consumption values assume that all wet process production values are shifted to the dry process. Therefore, the sub-process 2010 production values can be added to get the production considered for SOA, PM, and TM calculations.

The production values given in Table 2-2 are used to calculate total energy consumption for each stage. Within each sub-process, these production values remain the same. There is a decrease in volume from crushing/grinding to pyroprocessing due to raw material losses and combinations. Increases are seen from pyroprocessing to finish grinding and from finish grinding to storage due to additions of other minerals.

Table 2-3. U.S. Cement 2010 Production for Each Sub-process Studied

Sub-process (product)	Stage	2010 Total Production (million lb)
Dry Process		
Crushing/Grinding (raw meal)	Initial Size Reduction	210,175

	Grinding	210,175
	Blending	210,175
	Storage	210,175
	Fuel grinding[1]	14,176
Pyroprocessing with Cooling (clinker)	Kiln burning	120,371
	Cooling	120,371
Finish Grinding (cement)	Finish grinding	131,513
Wet Process		
Crushing/Grinding (raw meal)	Initial Size Reduction	15,069
	Grinding	15,069
	Storage	15,069
	Fuel grinding[1]	1,424
Pyroprocessing with Cooling (clinker)	Kiln burning	8,638
	Cooling	8,638
Finish Grinding (cement)	Finish grinding	9,429
Storage (Both Wet and Dry Processes)		
Storage (cement)[2]	Storage	140,942
	Packaging	140,942

[1] Fuel grinding production assumed to be primarily for coal and petcoke fuels, although oil, natural gas, and waste fuels (e.g., tires, solid waste, etc.) can also be used.

[2] Cement storage assumes the annual storage requirements for the final cement product from both the wet and dry process.

3. Current Typical Energy Intensity and Energy Consumption for U.S. Cement Manufacturing

This chapter presents energy intensities and energy consumption data for cement manufacturing sub-processes and sector-wide. Energy intensities were identified for each cement sub-process and applied to the relevant wet and dry process production values reported in the previous chapter to determine U.S. energy consumption. The energy intensities were identified using a top down approach that matches researched intensities to entire sub-processes. The estimates reported are representative of U.S. consumption. In some cases, non-U.S. energy intensity values are used to fill in data gaps, if it was determined that the data would be representative of U.S. manufacturing, and high-quality U.S. data were unavailable.

3.1. Sources for Current Typical Energy Intensity

Appendix A1 presents the CT energy intensities and energy consumption for the sub-processes studied. Table 3-1 presents a summary of the main references consulted to identify CT energy intensity by sub-process. Appendix A2 provides the references used for each sub-process.

The cement sector can vary significantly in energy consumption depending on the specifics of the product and process used. The energy intensity values selected are determined to be the best approximation of the on-site energy consumption. The best criteria for selection include data that specify the process, cement type, and are based on U.S. facilities. In cases where this level of detail is not available, data gaps are filled in using the next best available source, with a priority on sources that accurately represent typical energy intensities for the type of process (e.g., crushing/grinding, pyroprocessing with cooling, finish grinding).

Table 3-1. Main Sources Referenced in Identifying Current Typical Energy Intensity by Sub-process and Material Total

Source Abbreviation	Description
Crushing/Grinding	
Worrell et al. 2013	This source provided the CT energy values for cement grinding for both wet and dry cement processes. The CT energy technology considered in this report was ball mills, as these are the most commonly used grinding mills in cement manufacturing.
Zhu 2011	This reference provided the CT energy intensity for raw meal blending. Raw meal blending is used in the dry process to assist in the homogenization of the raw meal.
Pyroprocessing with Cooling	
LBNL 2012	This reference provided the CT energy value for dry pyroprocessing. The typical technology used in cement pyroprocessing is a preheater, precalciner and rotary kiln.
ECRA 2009	This reference provided the CT cooling energy value for both wet and dry processes. The typical technology used for cooling the clinker after leaving the kiln is the reciprocating grate cooler.
Worrell et al. 2013	This source provided the CT energy intensity value for the wet kiln. A long wet kiln is the most commonly used pyroprocessing technique for the wet process.
Finish Grinding	
Worrell et al. 2013	This source provided the CT energy values for cement finish grinding for both wet and dry cement processes. The CT energy technology considered in this report was ball mills, as these are the most commonly used grinding mills in cement manufacturing.

Table 3-1. Main Sources Referenced in Identifying Current Typical Energy Intensity by Sub-process and Material Total

Source Abbreviation	Description
Storage	
Madlool et al. 2011	The CT energy intensity for packaging silos in final cement product storage was provided by this reference.
Worrell et al. 2008	The CT energy intensity for belt conveyors in final cement product storage was provided by this reference. Belt conveyors transport the final cement product to the storage silos.

3.2. Current Typical Energy Consumption by Sub-process and Sector-wide

Table 3-2 presents the energy intensities and calculated on-site and primary CT energy consumption for the cement manufacturing sub-processes studied and sector-wide. Energy consumption values were calculated by multiplying energy intensity (Btu/lb of sub-process product) by 2010 production (million lb/year). Feedstock energy is excluded from the energy values.

While multiple process types may be included at a cement manufacturing facility, the energy intensity data collected is selected based on common equipment and processes within manufacturing plants. For calculating the off-site losses when converting from primary to on-site energy, an energy mix of electricity and fuel was used based on the Manufacturing Energy Consumption Survey's (MECS) Cement Manufacturing Energy and Carbon Footprint (DOE 2014). Percent coverage is calculated by dividing the on-site CT energy consumption for the processes studied by sector-wide on-site CT energy consumption.

Cement manufacturing accounted for 307 TBtu (1.6%) of the 19,237 TBtu of total primary manufacturing energy consumption in 2010 (DOE 2014). Off-site electricity and steam generation and transmission losses in Cement manufacturing totaled 62 TBtu in 2010; on-site energy consumed within the boundaries of U.S. Cement manufacturing plants totaled 245 TBtu. In 2010, data available for the four sub-processes studied covered about 97% (238 TBtu) of the cement sector's total on-site energy consumption (245 TBtu).

Table 3-2. On-site Current Typical Energy Intensity and Consumption and Primary Energy Consumption for U.S. Cement Manufacturing Processes Studied and Sector-wide in 2010, with Percent of Sector Coverage

Sub-process	On-site CT Energy Intensity for Sub-processes Studied (Btu/lb)	Production (million lb/year)	On-site CT Energy Consumption[1] (TBtu/year)	Off-site Losses (TBtu/year)	Primary CT Energy Consumption[2] (TBtu/year)	Percent Coverage (On-site CT as a % of Sector-wide total)
Dry Process						
Crushing/Grinding						
Kiln Feed Preparation	55	210,175	11.5	23.1	34.6	
Fuel Preparation	54	14,176	0.8	1.5	2.3	
Pyroprocessing with Cooling	1,554	120,371	187.1	12.1	199.2	
Finish Grinding	92	131,513	12.0	24.2	36.3	
SUBTOTAL – Dry Process[3]			***211.4***	***60.9***	***272.3***	***86%***
Wet Process						
Crushing/Grinding						
Kiln Feed Preparation	48	15,069	0.7	1.5	2.2	
Fuel Preparation	54	1,424	0.1	0.1	0.2	
Pyroprocessing with Cooling	2,750	8,638	23.8	0.8	24.6	
Finish Grinding	105	9,429	1.0	2.0	3.0	
SUBTOTAL – Wet Process[3]			***25.6***	***4.4***	***30.0***	***11%***
Storage						
Storage[3]	5	140,942	*0.8*	*1.5*	2.3	
Total for Processes in Sub-processes Studied[3]			**237.7**	**66.9**	**304.6**	**97%**
Total for Cement Sector-wide[3]			**245.0**	**62.0**	**307.0**	**100%**

Current Typical (CT)
[1] On-site CT energy consumption for the processes studied is calculated from energy intensity and production data for individual processes and summed in the sub-process.
[2] DOE 2014 is the source for MECS/Energy Footprints data and approaches. Primary energy is calculated from on-site energy consumption data, with scaling to include offsite electricity and steam generation and transmission loss.
[3] Totals may not sum due to independent rounding.

4. State-of-the-Art Energy Intensity and Energy Consumption for U.S. Cement Manufacturing

This chapter estimates energy savings possible in cement manufacturing plants to achieve state of the art (SOA) energy consumption levels. SOA consumption represents savings possible when applying best practices and technologies that are currently commercially available globally. Plants can vary widely in size, age, efficiency, energy consumption, and production. To develop an estimate representative of U.S. industries, this analysis uses typical energy savings found from measures applicable to major sub-processes including crushing/grinding, pyroprocessing with cooling, and finish grinding, as well as measures more widely applicable to cement processing facilities. Similar to CT estimates, energy intensities were identified using a top down approach that matches researched intensities to entire sub-processes.

4.1. Sources for State of the Art Energy Intensity

Appendix A1 presents the on-site SOA energy intensity and consumption for the processes considered in this bandwidth study. The on-site SOA energy consumption values are the net energy consumed in the sub-process using the single most efficient process and production pathway. No weighting is given to processes that minimize waste, feedstock streams, and byproducts, or maximize yield, even though these types of process improvements can help minimize the energy used to produce a lb of cement. The on-site SOA energy consumption estimates exclude feedstock energy.

Table 4-1 presents the main published sources referenced to identify the SOA energy intensities.

Table 4-1. Main Sources Referenced in Identifying State of the Art Intensity by Sub-process and Material Total

Source Abbreviation	Description*
Crushing/Grinding	
Worrell et al. 2013	This source provided the SOA energy values for cement grinding for both wet and dry cement processes. The SOA energy technology considered in this report was the vertical roller mill, as it is a commonly used replacement or pre-grinder for the ball mill.
Zhu 2011	This reference provided the SOA energy intensity for raw meal blending.
Pyroprocessing with Cooling	
Worrell et al. 2013	The SOA energy intensity for the dry kiln was used from this reference for pyroprocessing. The dry kiln technology considered in this report is the dry kiln with preheaters and precalciners.
Finish Grinding	
PG&E 2006	The SOA energy intensity for finish grinding in the dry process was used from this source. The finish grinding baseline used in this report was set for energy-efficient ball mills.
Storage	
Madlool et al. 2011	It is assumed that the CT=SOA for packing silos in cement manufacturing.
Worrell et al. 2008	The low value for energy consumption in cement belt conveyors was determined as the SOA from this source.

* Some descriptions mention improvements for the wet process. Improvements to the wet process are not used in this report since all cement is assumed to be produced by the dry process for SOA, PM, and TM as mentioned in Section 1.5.1.

4.2. State-of-the-Art Energy Intensity and Consumption

SOA energy intensities were based on a literature review of existing technologies used in cements manufacturing. Table 4-2 presents the on-site SOA energy intensity and consumption for the cement manufacturing for the sub-processes studied. Full details on sub-process energy intensities used can be found in Appendix A1.

Table 4-3 presents a comparison of the on-site CT energy consumption and SOA energy consumption for each sub-process and as a total. The on-site SOA energy saving, which is the difference between CT energy consumption and SOA energy consumption, is also called the *current opportunity* bandwidth for the sub-processes studied.

Savings opportunity is presented as both SOA energy savings (or current opportunity) and SOA energy savings percent. It is useful to consider both energy savings and energy savings percentage when comparing the energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same. Among the sub-processes studied, the greatest *current opportunity* in terms of percent energy savings is finish grinding at 45% energy savings; the greatest *current opportunity* in terms of TBtu savings is pyroprocessing with cooling at 50.0 TBtu per year savings[7].

Table 4-2. On-site State of the Art Energy Intensities and Calculated Energy Consumption for Cement Manufacturing Processes in Four Sub-processes Studied

Sub-process	On-site SOA Energy Intensity (Btu/lb)	Production (million lb/year)	On-site SOA Energy Consumption, Calculated (TBtu/year)
Dry Process			
Crushing/Grinding			
Kiln Feed Preparation	39	225,244	8.7
Fuel Preparation	31	15,600	0.5
Pyroprocessing with Cooling	1,247	129,009	160.8
Finish Grinding	51	140,942	7.2
Storage	4	140,942	0.6
Total for Sub-processes Studied*	**1,371**	**n/a**	**177.8**

Current Typical (CT), State of the Art (SOA)
* Totals may not sum due to independent rounding.

[7] Some of the TBtu savings in pyroprocessing and cooling are the direct result of the assumption that all cement made through the wet process is produced by the dry process for SOA calculations. This assumption alone accounts for 3.5 TBtu per year savings.

Table 4-3. On-site State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for Cement Manufacturing in Sub-processes Studied and Sector-Wide

Sub-process	On-site CT Energy Consumption, Calculated (TBtu/year)	On-site SOA Energy Consumption, Calculated (TBtu/year)	SOA Energy Savings (CT-SOA) (TBtu/year)	SOA Energy Savings Percent** (CT-SOA)/ (CT-TM)
Dry and Wet Process				
Crushing/Grinding				
Kiln Feed Preparation	12.2	8.7	3.5	30%
Fuel Preparation	0.8	0.5	0.4	43%
Pyroprocessing with Cooling	210.9	160.8	50.0	34%
Finish Grinding	13.0	7.2	5.8	45%
Storage***	0.8	0.6	0.2	29%
Total for Sub-processes Studied* **	**237.7**	**177.8**	**59.9**	**34%**
Total for Cement Manufacturing Sector-Wide*	**245.0**	**183.2**	**61.8**	**34%**

Current Typical (CT), State of the art (SOA), Thermodynamic Minimum (TM)

* Estimates for energy savings and consumption were extrapolated by dividing the total on-site energy consumption for all the processes studied within the sub-process by the sub-process % coverage, found in Chapter 3 (97%).

** Energy savings percent is calculated using TM energy consumption shown in Chapter 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (CT-SOA)/(CT-TM). CT is comprised of the total from both the wet and dry processes.

*** Totals may not sum due to independent rounding.

To calculate the extrapolated data presented in Table 4-3, the SOA energy consumption of each individual sub-process studied is summed, and the sum is divided by the CT percent coverage for the entire sector. The extrapolated number is the estimated SOA energy consumption for the entire sector. The SOA energy savings percent across all the sub-processes studied is 34%.

If U.S cement manufacturing were able to attain on-site SOA energy intensities, it is estimated that 59.9 TBtu per year of energy could be saved from the sub-processes studied, corresponding to a 34% energy savings overall (see equation below). This energy savings estimate is based on adopting available SOA technologies and practices without accounting for future gains in energy efficiency from R&D. This is a simple estimate for potential savings; it should not be inferred that all existing plants could achieve these SOA values or that the improvements would prove to be cost effective in all cases.

The SOA energy savings percent is the percent of energy saved with SOA energy consumption compared to CT energy consumption, while referencing the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed further in Chapter 6, is considered to be equal to zero in an ideal case with perfect efficiency (i.e., energy input to a system is considered fully recoverable with no friction losses or change in surface energy). For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., chemical reaction or permanent crystalline change due to deformation), TM is not usually equal to zero; in some cases (e.g., cement manufacture) the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating energy savings percent provides the most accurate measure of absolute savings potential. The equation for calculating on-site SOA energy savings percent is:

$$SOA\ Savings\ \% = Current\ Opportunity\ \% = \frac{CT - SOA}{CT - TM}$$

5. Practical Minimum Energy Intensity and Energy Consumption for U.S. Cement Product Manufacturing

For the cement industry, the majority of the practical energy savings potential comes from state-of-the-art technologies that are already commercially available. The remaining energy savings potential comes in the form of R&D technologies. Innovation in these technologies can further improve efficiency and drive U.S. economic growth. This chapter determines the R&D opportunity for the cement industry as defined by the practical minimum (PM): the minimum amount of energy required assuming the deployment of applied R&D technologies currently under development worldwide. Unlike the CT and SOA energy intensities, PM intensities were calculated by looking at efficiency improvements to individual processes or equipment. The corresponding energy savings were applied to a SOA baseline for the particular process or equipment and the calculated savings were integrated with the particular sub-process category. The collection of energy efficiency improvements to major processes or pieces of equipment collectively shifted SOA energy intensity to PM energy intensity. These steps were repeated for each PM technology identified and deemed relevant.

5.1. Sources for Practical Minimum Energy Intensity

In this study, PM energy intensity is the estimated minimum amount of energy consumed in a specific cement manufacturing sub-process assuming that the most advanced technologies under research or development around the globe are deployed.

R&D progress is difficult to predict and potential gains in energy efficiency can depend on financial investments and market priorities. To estimate PM energy consumption for this bandwidth analysis, a search of R&D activities in the cement industry was conducted. The focus of this study's search was applied research and emerging technologies, defined as the investigation and development of new technologies with the intent of accomplishing a particular commercial objective. Basic research, involving experimentation and modeling to expand understanding of fundamental mechanisms and principles without a direct link to commercial objectives, was not considered. Many of the technologies identified were disqualified from consideration due a lack of data from which to draw energy savings conclusions. Further, applied R&D technologies without a clear connection to manufacturing energy consumption were not considered in this study. Appendix A3 provides an example of the range of technologies considered for evaluation.

Table 5-1 presents some key sources consulted to identify PM energy intensities in cement manufacturing.

Table 5-1. Sources Referenced in Identifying Practical Minimum Energy Intensity by Sub-process and Material Total

Source Abbreviation	Description*
Crushing/Grinding	
Zhu 2011	The PM energy intensities for dry process blending were determined from this reference. The PM technology chosen for this report was the gravity type silo.
Worrell et al. 2013	This source provided the PM energy intensity for dry process crushing/grinding. The advanced horizontal roller mill was used as the PM energy baseline for cement crushing/grinding.
LBNL 2009	This source provided the PM energy savings for crushing/grinding for fuel preparation. The technologies in this reference that were considered in the PM energy intensity were the new efficient coal separators, efficient roller mills for coal grinding, as well as installation of variable frequency drives (VFDs) & replacement coal mill bag dust collector's fans.
APP 2009	This source provided the PM energy savings for crushing/grinding for fuel preparation. The technology in this reference considered in the PM energy intensity was the vertical coal mill.
Pyroprocessing with Cooling	
ECRA 2009	This reference provided the PM energy for grate coolers in the dry and wet process.
IFC 2013	Electrical and thermal efficiency improvements in the kiln are applicable for both wet and dry kilns. This source provided a fuel energy savings of 0.09 MJ/kg (or 40 Btu/lb) cement for PM kiln conversions.
Finish Grinding	
APP 2009	This source provided the PM energy savings for finish grinding steps in cement manufacturing. The energy savings were determined from this reference using pre-grinding of the roll press system, pre-grinding of roller mill system, and automatic run control of tube mill.
Storage	
Madlool et al. 2011	It is assumed that SOA=PM for cement storage processes.
Worrell et al. 2008	It is assumed that SOA=PM for cement storage processes.

* Some descriptions mention improvements for the wet process. Improvements to the wet process are not used in this report since all cement is assumed to be produced by the dry process for SOA, PM, and TM as mentioned in Section 1.5.1.

5.2. Practical Minimum Energy Consumption by Sub-process and Sector-wide

Table 5-2 presents the on-site PM energy consumption for the cement manufacturing sub-processes studied. Full details on sub-process energy intensities used can be found in Appendix A1. Table 5-3 presents the on-site PM energy savings, which is the difference between CT energy consumption and PM energy consumption. The on-site energy consumptions and energy savings are presented as TBtu per year.

In Table 5-3, data from Table 5-2 is extrapolated to estimate the total PM sub-process consumption and the sector-wide energy savings. Table 5-3 presents the PM sub-process energy savings, which is the sum of *current* and *R&D opportunity*. Table 5-4 calculates the R&D opportunity for the processes studied and sector-wide opportunity.

To calculate the extrapolated data presented in Table 5-3, the PM energy consumption of each individual sub-process is summed, and the sum is divided by the CT percent coverage for the entire sector. The extrapolated number is the estimated PM energy consumption for the entire sector. The PM energy savings percent is assumed to be the average taken across all the sub-processes studied (38%).

Table 5-2. On-site Practical Minimum Energy Consumption for Cement Manufacturing Processes in Four Sub-processes Studied

Sub-process	On-site PM Energy Intensity (Btu/lb)	Production (million lb/year)	On-site PM Energy Consumption, Calculated (TBtu/year)
Dry Process			
Crushing/Grinding			
Kiln Feed Preparation	36	225,244	8.1
Fuel Preparation	28	15,600	0.4
Pyroprocessing with Cooling	1,206	129,009	155.6
Finish Grinding	48	140,942	6.8
Storage	4	140,942	0.5
Total for Sub-processes Studied*	**1,322**	**n/a**	**171.4**

Current Typical (CT), Practical Minimum (PM)
* Totals may not sum due to independent rounding.

Table 5-3. On-site Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for Cement Manufacturing in Sub-processes Studied and Sector-Wide

Sub-process	On-site CT Energy Consumption, Calculated (TBtu/year)	On-site PM Energy Consumption, Calculated (TBtu/year)	PM Energy Savings* (CT-PM) (TBtu/year)	PM Energy Savings Percent** (CT-PM)/ (CT-TM)
Dry Process				
Crushing/Grinding				
Kiln Feed Preparation	12.2	8.1	4.2	34%
Fuel Preparation	0.8	0.4	0.4	48%
Pyroprocessing with Cooling	210.9	155.6	55.3	37%
Finish Grinding	13.0	6.8	6.2	48%
Storage	0.8	0.5	0.2	29%
Total for Sub-processes Studied***	**237.7**	**171.4**	**66.3**	**38%**
Total for Cement Manufacturing Sector-Wide*****	**245.0**	**176.7**	**68.3**	**38%**

Current Typical (CT), Practical Minimum (PM), Thermodynamic Minimum (TM)
***** When generalized to the full sector, PM energy savings is the Current Opportunity plus the R&D Opportunity.
** Energy savings percent is calculated using TM energy consumption shown in Chapter 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (CT-PM)/(CT-TM). CT is comprised of the total from both the wet and dry processes.
*** Totals may not sum due to independent rounding.
**** Estimates for the entire sub-process were extrapolated by dividing the total on-site PM energy consumption for all the processes studied within the sub-process by the sub-process % coverage, found in Chapter 3.

It is useful to consider both TBtu energy savings and energy savings percent when comparing the energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same. Among the sub-processes studied the greatest combination of *current* and *R&D opportunity* in terms of percent energy savings is in finish grinding at 48% energy savings; the greatest combination of *current* and *R&D opportunity* in terms of TBtu savings is pyroprocessing with cooling at 55.3 TBtu per year savings.

If U.S cement manufacturing (for the 2010 production level) were able to attain on-site PM energy intensities, it is estimated that 66.3 TBtu per year of energy could be saved from the sub-processes studied alone, corresponding to a 38% energy savings overall. This energy savings estimate is based on adopting available PM technologies and practices. This is a simple estimate for potential savings; it is not inferred that all existing plants could achieve these PM energy intensity values or that the improvements would prove to be cost effective in all cases.

The R&D savings percent is the percent of energy saved with SOA energy consumption compared to CT energy consumption. The PM energy savings percent is the percent of energy saved with PM energy consumption compared to CT energy consumption, while referencing the thermodynamic minimum as the baseline energy consumption. Thermodynamic minimum (TM), discussed in the following section, is considered to be equal to zero in an ideal case with perfect efficiency (i.e., energy input to a system is considered fully recoverable with no friction losses or change in surface energy). For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (e.g., from a chemical reaction or permanent crystalline change), TM is not necessarily equal to zero; in some cases (e.g., cement manufacture) the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0). Referencing TM as the baseline in comparing bandwidths of energy consumption and calculating energy savings percent provides the most accurate measure of absolute savings potential. The equation for calculating on-site PM energy savings percent is:

$$R\&D\ Opportunity\ \% = \frac{SOA - PM}{CT - TM}$$

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

R&D opportunity represents the opportunities for energy savings from technologies currently an R&D stage of development (early TRL) and are not ready for deployment to manufacturing. It represents the energy savings opportunities that can be achieved if the R&D is put into those technologies to get them to a high enough TRL level that they can be deployed in the manufacturing sector. Table 5-4 shows the R&D opportunity totals and percent for the evaluated sub-processes and extrapolated sector-wide.

Table 5-4. On-site Practical Minimum Energy Consumption and R&D Opportunity Energy Savings for Cement Manufacturing Processes in Four Sub-processes Studied

Sub-process	On-site SOA Energy Consumption (TBtu/year)	On-site PM Energy Consumption (TBtu/year)	R&D Opportunity (SOA-PM) (TBtu/year)	R&D Opportunity Savings Percent* (SOA-PM)/(CT-TM)
Total for Sub-processes Studied**	177.8	171.4	6.4	3.6%
Total for Cement Sector-wide **	183.2†	176.7†	6.6	3.6%

Current Typical (CT), State of the Art (SOA), Practical Minimum (PM), Thermodynamic Minimum (TM)
† Estimates for the entire sub-process were extrapolated by dividing the total on-site PM energy consumption for all the processes studied within the sub-process by the sub-process % coverage, found in Chapter 3.
* Energy savings percent is calculated using TM energy consumption shown in Chapter 6 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (SOA-PM)/(CT-TM).
** Totals may not sum due to independent rounding.

6. Thermodynamic Minimum Energy Intensity and Energy Consumption for U.S. Cement Manufacturing

Real world cement production does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture cement can provide a more complete understanding of the realistic opportunities for energy savings. This baseline can be used to establish more realistic projections (and bounds) for the future R&D energy savings that may be achieved. This chapter presents the thermodynamic minimum (TM) energy consumption required to manufacture cement.

6.1. Thermodynamic Minimum Energy Intensity

TM energy consumption, which is based on Gibbs free energy (G) calculations, assumes ideal conditions that are unachievable in real-world applications. TM energy consumption assumes that all energy is used productively, that there are no energy losses, and that energy is ultimately perfectly conserved by the system (i.e., when cooling a material to room temperature or applying work to a process, the heat or work energy is fully recovered – perfect efficiency). It is not anticipated that any manufacturing process would ever attain this value in practice. A reasonable long-term goal for energy efficiency would be the practical minimum (see Chapter 5).

For manufacturing processes where there is an irreversible change to the material, resulting in a change to the embodied free energy content of the material (i.e., a chemical reaction or permanent crystalline change due to deformation), TM is not necessary equal to zero; in some cases the change in theoretical free energy content of the material requires energy input (TM > 0) and in other cases the change creates a theoretical free energy gain (TM < 0).

6.2. Calculated Thermodynamic Minimum Energy Intensity for Individual Cement Sub-processes

The thermodynamic minimum energy intensity was calculated for each cement sub-process by determining the Gibbs free energy (G) associated with the chemical transformations involved, under ideal conditions for a manufacturing process.[8] The change in Gibbs free energy (ΔG) is defined in terms of the change in enthalpy (ΔH), temperature (T), and the change in entropy (ΔS), as shown in the following equation:

$$\Delta G = \Delta H - T\Delta S$$

The TM energy intensity calculation is path independent (state function), but is directly related to the relative energy levels of the substrates and the products. The reported value depends only on the starting material and the end product, and would not change if the process had greater or fewer process steps. Note that for processes that involve no net chemical changes or reactions, the TM energy intensity is *zero* because all energy expended is assumed to be perfectly recovered. The TM energy intensity is *negative* when the chemical reaction is net-exergonic and *positive* when the chemical reaction is net-endergonic.[9] It is important to note that a negative TM value does not imply that the reaction will occur without being forced by a manufacturing process.

Most cement products have a zero TM energy intensity because there are no significant chemical reactions involved. There is one process of this sector that involves chemical reactions: pyroprocessing with cooling. The TMs for these sub-processes were calculated based on the net Gibbs free energy change and can be found below in Table 6-1. Complete details on the calculations can be found in Appendix A4.

[8] Unless otherwise noted, "ideal conditions" means a pressure of one atmosphere and a temperature of 77°F.
[9] Exergonic (reaction is favorable) and endergonic (reaction is not favorable) are thermodynamic terms for total change in Gibbs free energy (ΔG). This differs from exothermic (reaction is favorable) and endothermic (reaction is not favorable) terminology used in describing change in enthalpy (ΔH).

Table 6-1. Calculated Thermodynamic Minimum Energy Intensities for Cement[10]

Sub-process	On-site TM Energy Intensity for Sub-processes Studied (Btu/lb)
Dry Process	
Crushing/Grinding	
Kiln Feed Preparation	0
Fuel Preparation	0
Pyroprocessing with Cooling	481
Finish Grinding	0
Wet Process	
Crushing/Grinding	
Kiln Feed Preparation	0
Fuel Preparation	0
Pyroprocessing with Cooling	481
Finish Grinding	0
Storage	
Storage	0

Thermodynamic Minimum (TM)

In this report, TM energy consumption is referenced as the baseline (or minimum amount of energy) when calculating the absolute energy savings potential. The equations used to determine the absolute energy savings for current opportunity (SOA), R&D and PM are defined below. PM savings percent is the sum of the current opportunity percent and the R&D opportunity percent.

$$Current\ Opportunity\ \% = \frac{CT - SOA}{CT - TM}$$

$$R\&D\ Opportunity\ \% = \frac{SOA - PM}{CT - TM}$$

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

For cement processes requiring an energy intensive transformation (e.g., pyroprocessing with cooling), this percent energy savings approach results more realistic and comparable energy savings estimates. Using zero as the baseline (or minimum amount of energy) would exaggerate the total bandwidth to which SOA energy savings and PM energy savings are compared to determine the energy savings percent. When TM energy consumption is referenced as the baseline, SOA energy savings and PM energy savings are relatively more comparable, resulting in more accurate energy savings percentages.

[10] It is important to note that values close to a theoretical minimum energy value of 757 Btu/lb clinker are also reported in literature (Lea & Desch 1956) (Taylor 1997). This value is calculated based on the standard enthalpy of formation for each of the reactants and products in clinker production. The Gibbs free energy change of that same process was determined as 481 Btu/lb clinker from values reported in the literature, and is the value used for this study to maintain consistency with previous bandwidth studies.

6.3. Thermodynamic Minimum Energy Consumption by Sub-process and Sector-wide

The minimum baseline of energy consumption for a cement manufacturing process is its TM energy consumption. If all the 2010 level of cement manufacturing occurred at TM energy intensity, there would be 100% savings. The percentage of energy savings is determined by calculating the decrease in energy consumption and dividing it by the total possible savings (CT energy consumption-TM energy consumption).

Table 6-2 provides the TM energy consumption for the sub-processes studied and sector-wide. It is important to keep in mind that ideal conditions are unrealistic goals in practice and these values serve only as a guide to estimating energy savings opportunities. As mentioned, the TM energy consumption was used to calculate the *current* and *R&D* energy savings percentages (not zero). The total TM energy consumption sector-wide for the processes studied is positive due to energy required for the pyroprocessing with cooling step.

Table 6-2. On-site Thermodynamic Minimum Energy Consumption for Cement Manufacturing in Sub-processes Studied and Sector-Wide

Sub-process	On-site TM Energy Intensity (Btu/lb)	Production (million lb/year)	On-site TM Energy Consumption, Calculated (TBtu/year)
Dry Process			
Crushing/Grinding			
Kiln Feed Preparation	0	225,244	0.0
Fuel Preparation	0	15,600	0.0
Pyroprocessing with Cooling	481	129,009	62.1
Finish Grinding	0	140,942	0.0
Storage	0	140,942	0.0
Total for Sub-processes Studied*	**481**	**n/a**	**62.1**

Thermodynamic Minimum (TM)
* Totals may not sum due to independent rounding.

7. U.S. Cement Manufacturing Current and R&D Opportunity Analysis/Bandwith Summary

This chapter presents the energy savings bandwidths for the cement manufacturing sub-processes studied and sector-wide based on the analysis and data presented in the previous Chapters and the following Appendices. Data is presented for the four sub-processes studied and extrapolated to estimate the energy savings potential for all of U.S. cement manufacturing.

Table 7-1 presents the *current opportunity* and *R&D opportunity* energy savings for the sub-processes studied for cement manufacturing as well as the total sector. Each row in Table 7-1 shows the opportunity bandwidth for a specific cement sub-process and as a sector-wide total. As previously noted, the energy savings opportunities presented reflect the estimated production of cement products for selected sub-processes and sector-wide in baseline year 2010.

Table 7-1. Current and R&D Opportunity for Cement Manufacturing

Sub-process	**Current Opportunity for Sub-processes Studied***** (CT-SOA) (TBtu/year)	**R&D Opportunity for Sub-processes Studied***** (SOA-PM) (TBtu/year)
Crushing/Grinding*	3.9	0.7
Pyroprocessing with Cooling**	50.0	5.2
Finish Grinding**	5.8	0.4
Storage	0.2	0.0
Total for Processes Studied***	**59.9**	**6.4**
Total for Cement Manufacturing Sector-wide (extrapolated)	**61.8**	**6.6**

Current typical (CT), state of the art (SOA), practical minimum (PM)
* Includes both the wet and dry process for kiln feed preparation and fuel grinding sub-processes
** Includes both the wet and dry process
*** Totals may not sum due to independent rounding.

As shown in Figure 7-1, four hypothetical opportunity bandwidths for energy savings are estimated (as defined in Chapter 1). For the four sub-processes studied, the analysis shows the following:

- *Current Opportunity* – 59.9 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 6.4 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

For sector-wide U.S. cement manufacturing (based on extrapolated data), the analysis shows the following:

- *Current Opportunity* – 61.8 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 6.6 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

Figure 7-1 also shows the estimated *current* and *R&D* energy savings opportunities for individual cement manufacturing sub-processes as well as sector-wide. The area between *R&D opportunity* and *impractical* is shown as a dashed line with color fading because the PM energy savings impacts are based on today's knowledge of research tested between laboratory and demonstration scale; emerging technologies being investigated through modeling and theoretical calculations may eventually bring the PM energy consumption further into the faded region and closer to the TM energy consumption.

From the sub-processes studied, the greatest *current* and *R&D* percent energy savings opportunity for cement manufacturing comes from upgrading finish grinding. In addition, the greatest total *current and R&D* energy savings opportunity for cement manufacturing comes from upgrading pyroprocessing with cooling—this is largely due to the fact that a significant amount of energy consumed in the sector occurs in these sub-processes.

The *impractical* bandwidth, or the difference between PM energy consumption and TM energy consumption, represents the area that would require fundamental changes in cement manufacturing. The term *impractical* is used because the PM energy consumption is based on current knowledge of R&D technologies tested between laboratory and demonstration scale; further decreases in energy intensity have not been displayed at any physical scale. The TM energy consumption is based on ideal conditions that are typically unattainable in commercial applications. It was used as the baseline for calculating the energy savings potentials (not zero) to provide more accurate targets of energy savings opportunities.

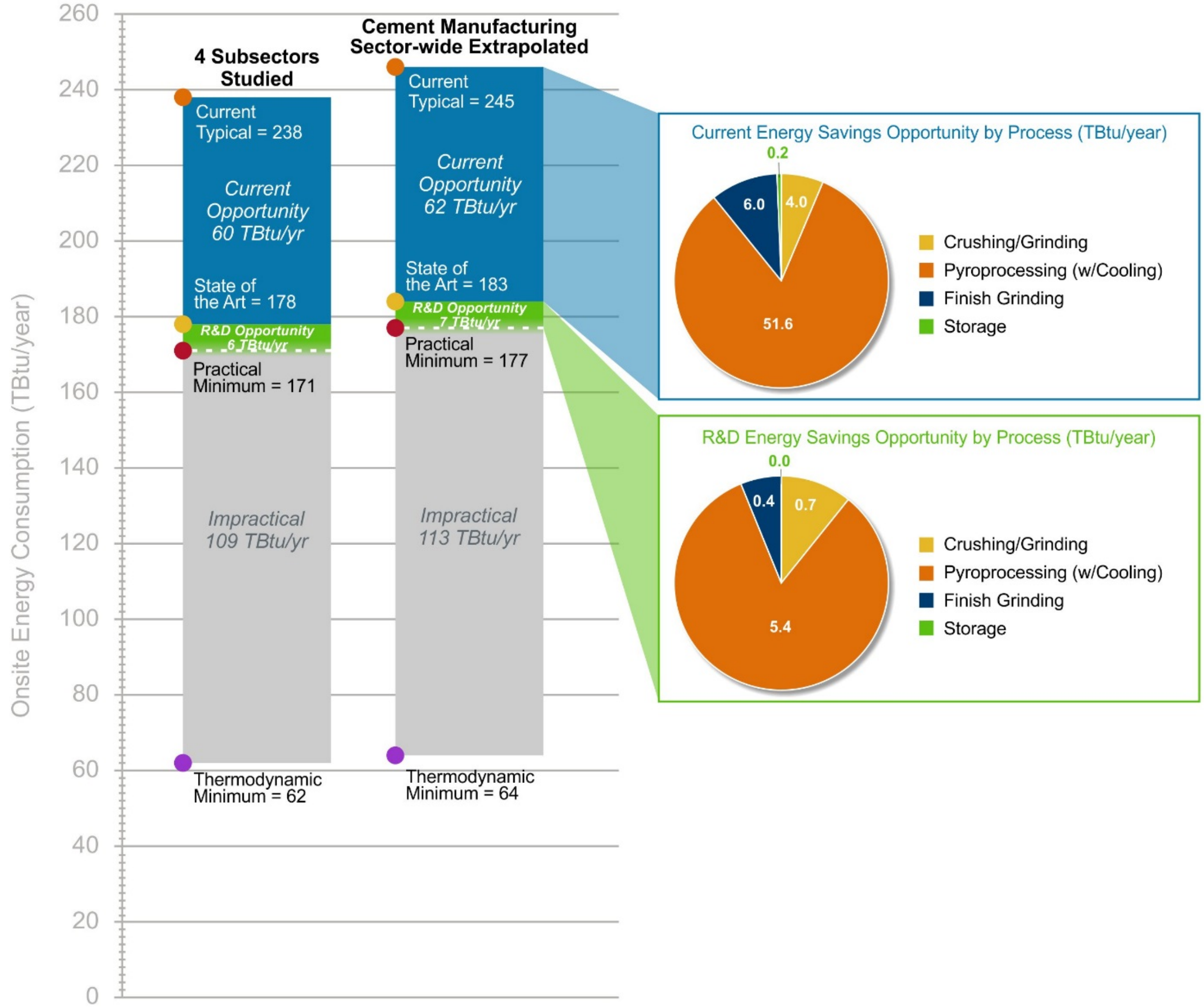

Figure 7-1. Current and R&D energy savings opportunities in U.S. cement products manufacturing sector-wide based on extrapolated data
Source: EERE

The Current Energy Savings Opportunities for the cement sector sub-processes are as follows (not based on extrapolated values):

- Pyroprocessing with Cooling – 50.0 TBtu (or 83% of the current opportunity)
- Finish Grinding – 5.8 TBtu (or 10% of the current opportunity)
- Crushing/Grinding – 3.9 TBtu (or 7% of the current opportunity)
- Storage – 0.2 TBtu (or 0% of the current opportunity).

The R&D Energy Saving Opportunities for the cement sector sub-processes are as follows:

- Pyroprocessing with Cooling – 5.2 TBtu (or 82% of the R&D opportunity)
- Crushing/Grinding – 0.7 TBtu (or 11% of the R&D opportunity)
- Finish Grinding – 0.4 TBtu (or 7% of the R&D opportunity)
- Storage – 0.0 TBtu (or 0% of the R&D opportunity)

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Appendix A1: Master Cement Manufacturing Summary Table

Table A1. U.S. Production Volume of Cement Manufacturing Processes in 2010 with Energy Intensity Estimates and Calculated On-site Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Sub-process (Product)	2010 Production (million lb)	On-site Energy Intensity (Btu/lb)				Calculated On-site Energy Consumption* (TBtu/year)			
		CT	SOA	PM	TM	CT	SOA	PM	TM
Dry Process									
Crushing/Grinding (raw meal, fuel)									
Kiln Feed Preparation (raw meal)	210,175 (CT); 225,244 (SOA, PM, TM)	55	39	36	0	11.5	8.7	8.1	0.0
Fuel Preparation (fuel)	14,176 (CT); 15,600 (SOA, PM, TM)	54	31	28	0	0.8	0.5	0.4	0.0
Pyroprocessing with Cooling (clinker)	120,371 (CT); 129,009 (SOA, PM, TM)	1,554	1,247	1,206	481	187.1	160.8	155.6	62.1
Finish Grinding (cement)	131,513 (CT); 140,942 (SOA, PM, TM)	92	51	48	0	12.0	7.2	6.8	0.0
Wet Process									
Crushing/Grinding (raw meal, fuel)									
Kiln Feed Preparation (raw meal)	15,069 (CT); 0 (SOA, PM, TM)	48	39	39	0	0.7	0.0	0.0	0.0
Fuel Preparation (fuel)	1,424 (CT); 0 (SOA, PM, TM)	54	31	28	0	0.1	0.0	0.0	0.0
Pyroprocessing with Cooling (clinker)	8,638 (CT); 0 (SOA, PM, TM)	2,750	1,653	1,612	481	23.8	0.0	0.0	0.0
Finish Grinding (cement)	9,429 (CT); 0 (SOA, PM, TM)	105	30	27	0	1.0	0.0	0.0	0.0
Storage									
Storage (cement)	140,942	5	4	4	0	0.8	0.5	0.5	0.0
*Dry Process SUBTOTAL, Processes Studied**						*211.4*	*177.2*	*170.9*	*62.1*
*Wet Process SUBTOTAL, Processes Studied**						*25.6*	*0.0*	*0.0*	*0.0*
*Storage SUBTOTAL, Processes Studied**						*0.8*	*0.5*	*0.5*	*0.0*
Total for all Processes Studied*						**237.7**	**177.8**	**171.4**	**62.1**
Total for Sector-Wide, CT from MECS, Extrapolated for SOA, PM, TM*						**245.0**	**183.2**	**176.7**	**64.0**

Table A1. U.S. Production Volume of Cement Manufacturing Processes in 2010 with Energy Intensity Estimates and Calculated On-site Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Sub-process (Product)	2010 Production (million lb)	On-site Energy Intensity (Btu/lb)				Calculated On-site Energy Consumption* (TBtu/year)			
		CT	SOA	PM	TM	CT	SOA	PM	TM

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).
* Totals may not sum due to independent rounding.

Appendix A2: References for Production, CT, SOA, PM, and TM

Table A2. U.S. Production Volume of Cement Manufacturing Processes in 2010 with Energy Intensity Estimates and Calculated On-site Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Sub-process	Production Reference(s)	CT Energy Intensity Reference(s)	SOA Energy Intensity Reference(s)	PM Energy Intensity Reference(s)	TM Energy Intensity Reference(s)
Dry Process					
Crushing/Grinding					
Kiln Feed Preparation	USGS 2011	Zhu 2011, Worrell et al. 2013	Zhu 2011, Worrell et al. 2013	Zhu 2011, Worrell et al. 2013	Set to zero due to minimal chemical conversions
Fuel Preparation	USGS 2011	IIP 2017	IIP 2017	IIP 2017, LBNL 2009, APP 2009	Set to zero due to minimal chemical conversions
Pyroprocessing with Cooling	USGS 2011	LBNL 2012, ECRA 2009	Worrell et al. 2013, ECRA 2009	IFC 2013, ECRA 2009	Internal calculations
Finish Grinding*	USGS 2011	Worrell et al. 2013	PG&E 2006	APP 2009	Set to zero due to minimal chemical conversions
Wet Process					
Crushing/Grinding					
Kiln Feed Preparation	USGS 2011	Zhu 2011, Worrell et al. 2013	Zhu 2011, Worrell et al. 2013	Zhu 2011, Worrell et al. 2013	Set to zero due to minimal chemical conversions
Fuel Preparation	USGS 2011	IIP 2017	IIP 2017	IIP 2017, LBNL 2009, APP 2009	Set to zero due to minimal chemical conversions
Pyroprocessing with Cooling	USGS 2011	Worrell et al. 2013, ECRA 2009	Worrell et al. 2013, ECRA 2009	IFC 2013, ECRA 2009	Internal calculations
Finish Grinding*	USGS 2011	Worrell et al. 2013	Worrell et al. 2008	APP 2009	Set to zero due to minimal chemical conversions
Storage					
Storage	USGS 2011	Madlool et al. 2011, Worrell et al. 2008	Madlool et al. 2011, Worrell et al. 2008	Madlool et al. 2011, Worrell et al. 2008	Set to zero due to minimal chemical conversions

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM)
* Peer reviewer indicated that wet process finish grinding should have the same energy intensity as dry process finishing grinding for SOA and PM. References listed here used as basis for value given in Table A1.

Appendix A3: Practical Minimum Energy Intensity Calculation and Example Technologies Considered

To estimate PM energy consumption for this bandwidth analysis, a broad search of R&D activities in the cement industry was conducted. A large number and range of potential technologies were identified. If more than one technology was considered for a particular process, the technology that resulted in the lowest energy intensity was selected for the PM energy intensity. The on-site PM energy intensity and consumption values are shown in Table A3-1 below.

Table A3-1. Calculated PM Energy Consumption for Cement Manufacturing

Sub-process	On-site PM Energy Intensity (Btu/lb)	On-site PM Energy Consumption, Calculated* (TBtu/year)
Dry Process		
Crushing/Grinding		
Kiln Feed Preparation	36	8.1
Fuel Preparation	28	0.4
Pyroprocessing with Cooling	1,206	155.6
Finish Grinding	48	6.8
Wet Process		
Crushing/Grinding		
Kiln Feed Preparation	39	0.0
Fuel Preparation	28	0.0
Pyroprocessing with Cooling	1,612	0.0
Finish Grinding	27	0.0
Storage		
Storage	4	0.5
Total for Sub-processes Studied		**171.4**

Practical Minimum (PM)
* Totals may not sum due to independent rounding.

The PM energy intensity for cement manufacturing was determined based on the technologies outlined in Table A3-2. The applicability column indicates the sub-process where the technology is considered for application. The percent savings over the PM baseline is estimated, along with a brief explanation.

Some technologies in Table A3-2 were considered but not included in the final PM model (in most of the cases the savings estimates were conservative compared to SOA energy intensity).

In some cases, there was a limited amount of information available on technologies for specific stages (such as storage and finish grinding), requiring best engineering judgment to be used in determining the PM energy intensity. For storage, the PM energy intensity and consumption values are calculated to be the same as the SOA energy intensity and consumption values based on best engineering judgment.

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	**Energy Savings** Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
Upgrading to gravity-fed silo	Standalone savings for blending step. Saving over mechanical blending system.	Crushing/Grinding (dry)	Energy savings estimated as 0.00576 MJ/kg over mechanical system	71%	No	Yes	Zhu 2011
High-activation grinding	Mechanical activation or enhanced reactivity of fly ash or blast furnace slag in cement	Crushing/Grinding	Energy consumption is 30 to 50 kWh/t product. For every t of clinker replaced by additives from mechanical activation grinding, the avoided energy uses are approximately: • thermal energy: 3.0 to 6.5 GJ/t clinker • electricity: 60 to 100 kWh/t clinker (European Commission 2010)	62 Btu/lb cement	No	No	LBNL 2012
Calcareous Oil Shale as an	Calcareous oil shale can be used as an alternative feedstock	Crushing/Grinding	Energy use could be reduced by 74 MJ/t cement if oil shale is used to make	32 Btu/lb cement	No	No	LBNL 2012

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
Alternative Raw Material	and partial fuel substitute in clinker production		up 8 percent of the raw meal in cement production.				
Switch from pneumatic to mechanical raw material transport	Pneumatic and mechanical conveyor systems are used throughout cement plants to convey kiln feed, kiln dust, finished cement, and fuel. Mechanical systems typically use less energy than pneumatic systems, and switching to mechanical conveyor systems can save 2.9 kWh/ton of cement.	Crushing/Grinding	Energy savings of 2.9 kWh/ton cement	5 Btu/lb cement	No	No	EPA 2010
Use of belt conveyors and bucket elevators instead of pneumatics	Conversion from pneumatic systems to mechanical systems may be cost-effective due to increased reliability and reduced downtime, which can also reduce energy consumption.	Crushing/Grinding	Energy savings of 2.5 kWh/ton cement	4 Btu/lb cement	No	No	EPA 2010

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	**Energy Savings** Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
Convert raw meal blending silo to gravity-type homogenizing silo	Gravity-fed raw meal blending systems mixes the raw meal thoroughly to form a homogenous mixture, which optimizes clinker production.	Crushing/Grinding	Energy savings of 1.4-3.5 kWh/ton cement	4 Btu/lb cement	No	No	EPA 2010
Improvements in raw material blending	Energy efficiency measure used to increase production volumes and decrease energy consumption.	Crushing/Grinding	Energy savings of 1.0 kWh/ton cement	2 Btu/lb cement	No	No	EPA 2010
Replace ball mills with high efficiency roller mills	Ball mills combined with high pressure roller presses, or horizontal roller mills, used to increase grinding efficiency, which may reduce energy consumption by 9 – 11 kWh/ton cement	Crushing/Grinding	Energy savings of 10 kWh/ton cement	17 Btu/lb cement	No	No	EPA 2010
Replace ball mills with vertical	Replacing older ball mills with vertical roller mills or high	Crushing/Grinding	Energy savings of 11-15 kWh/ton cement	22 Btu/lb cement	No	No	EPA 2010

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
roller mills	pressure grinding rolls can reduce the electricity demand of the grinding operation from 11 – 15 kWh/ton cement.						
Advanced horizontal roller mill	High-pressure roller mill and the horizontal roller mill	Crushing/Grinding	Modern state-of-the-art concepts utilize a high-pressure roller mill and the horizontal roller mill (e.g., Horomill®) (Seebach et al., 1996) that are claimed to use 20-50% less energy than a ball mill. Zhu 2011 states an SOA value of 0.043 MJ/kg raw meal. Taking 50% of this value results in an estimated energy value of 0.022 MJ/kg raw meal. Estimated percent savings with the reported SOA is; 1-(0.022/0.025) = 13%.	13%	No	Yes	Harder 2010; Worrell et al. 2013; Zhu 2011
		Finish Grinding				No	
High Efficiency Classifiers	Classifiers that efficiently separate	Crushing/Grinding	Energy savings of 3.8-5.2 kWh/ton cement	8 Btu/lb cement	No	No	EPA 2010

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	**Energy Savings** Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
	particles by size, which minimizes grinder loading and energy consumption as a result.	Finish Grinding	Energy savings of 1.7-2.3 kWh/ton cement	3 Btu/lb cement	No	No	EPA 2010
External circulating system to vertical roller mill	The uncrushed materials jumped out from the table, fall through gas inlet box to, and collected by the mechanical transportation equipment installed below the mill such as chain conveyor and bucket elevator etc.	Crushing/Grinding	As compared with conventional internal circulating system, power consumed for fan is reduced until half and it's possible to reduce power of grinding system by about 30%	30%	No	No	APP 2009
Direct dust collection system to vertical mill grinding process	The raw materials are dried and ground by the mill simultaneously in one-pass kiln exit gas and then fine product after separation is sent to EP directly.	Crushing/Grinding	Power consumption of fan(s) reduces about 3 to 4 kWh/t.	5 Btu/lb raw meal	No	No	APP 2009
Pre-grinding equipment for	A pre-grinder, which is roller mill or roller press, as coarse grinding before the	Crushing/Grinding	Specific power consumption of tube mill only: 25% down	25%	No	No	APP 2009

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
raw material grinding process	existing tube mill, which is exclusively used for fine grinding.						
Classification of powder returned from raw material separator	The cause of this phenomenon is that grids contained in the separator returned power directly enters the second chamber. To separate grids from the returned powder and return them to the first chamber for coarse grinding, a simple grid screen (classifier). was installed at the return chute of the separator	Crushing/Grinding	The decrease of power consumption rate is not remarkable but below 1 kWh per ton of raw materials.	2 Btu/lb raw meal	No	No	APP 2009
Wash mills and classifiers	Use of wash mills instead of tube mills and circuit classifiers	Crushing/Grinding (wet)	Baseline set at efficient tube mill: 13 kWh/ton of raw meal	22 Btu/lb raw meal	No	No	PG&E 2006, Madlool et al. 2011
Slurry blending and homogenizing	Optimizing the water content in the raw meal slurry for the wet process leads to	Crushing/Grinding (wet)	0.3-0.5 kWh/tonne energy/fuel savings; 0.5-	3 Btu/lb raw meal	No	No	Madlool et al. 2011

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
	less electrical energy requirements for grinding.		0.9 kWh/tonne electricity savings				
Raw material blending	Use of gravity-type homogenizing silos instead of mechanical or air-fluidized bed systems	Crushing/Grinding (dry)	Baseline set at efficient tube mill: 2 kWh/ton of raw meal	3 Btu/lb raw meal	No	No	PG&E 2006
New efficient coal separator	An external, high efficiency fan provides airflow through the material that is falling from the distribution plate into a cage rotor with a variable speed drive.	Crushing/Grinding (fuel preparation)	Electrical energy savings of 0.26 kWh/t clinker	0.4 Btu/lb clinker	No	Yes	LBNL 2009
Efficient roller mills for coal grinding	Efficient vertical roller mills have been developed for on-site fuel preparation at cement plants. Fuel preparation may include crushing, grinding and drying of coal.	Crushing/Grinding (fuel preparation)	Electrical energy savings of 1.47 kWh/t clinker	2 Btu/lb clinker	No	Yes	LBNL 2009

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
Installation of VFD & replacement of coal mill bag dust collector's fan	Variable frequency drives can be installed on coal mill bag dust collector fans to improve energy efficiency.	Crushing/Grinding (fuel preparation)	Electrical energy savings of 0.16 kWh/t clinker	0.2 Btu/lb clinker	No	Yes	LBNL 2009
Vertical coal mill	In a vertical coal mill, drying, grinding, and separating/classifyin g of coal can be done simultaneously. Hence, production and energy efficiency is higher.	Crushing/Grinding (fuel preparation)	Capable of reducing electricity consumptions for coal grinding by 20-25%.	23%	No	No	APP 2009
High Efficiency and Low Pressure Drop Preheating Stage	Energy and thermal efficiency measures can drive down SOA energy value	Pyroprocessing with Cooling	Electrical energy savings of 3.0 kWh/tonne clinker; fuel savings of 20.0 kcal/kg clinker	40.6 Btu/lb clinker	No	Yes	Harder 2010
Fluidized bed kiln	Burns raw materials into powder with granules 1.5 to 2.5 millimeters (mm) in diameter	Pyroprocessing with Cooling	FBK energy use is expected to be 10 to 15 percent lower than that of conventional rotary kilns.	13%	No	No	LBNL 2012
Use of Steel Slag as Raw Material for the Kiln -	During the kiln pyroprocess, ¾-inch- to 1-inch-diameter	Pyroprocessing with Cooling	Using 10 percent slag would reduce energy consumption by 0.19	82 Btu/lb cement	No	No	LBNL 2012

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
CemStar® Technology	slag is added to the feed end of the kiln as a component of the raw material mix		GJ/tonne, CO_2 emissions by roughly 11 percent, and NO_x emissions by 9 to 60 percent, depending on kiln type and plant specific conditions (Worrell et al. 2008; Perkins 2000).				
Process control and management systems	Automated control systems that can be used to maintain operating conditions in the kiln at optimum levels, which leads to more efficient operation throughout the cement manufacturing process.	Pyroprocessing with Cooling	2.5-5% or 42-167 MJ/ton cement and electricity savings of 1 kWh/ton cement	4%	No	No	EPA 2010
Replacement of kiln seals	Minimizing leaks in the kiln seals (which are used at the inlet and outlet of the kiln to reduce heat loss and air penetration) can result in decreased heat loss and as a result decreased fuel use.	Pyroprocessing with Cooling	0.4% or 0.01 MMBtu/ton cement	0.4%	No	No	EPA 2010

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	**Energy Savings** Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
Kiln combustion system improvements	Optimization of the kiln burning process by minimizing incomplete combustion via incomplete fuel burning, poor fuel/air mixtures, and poorly adjusted firing.	Pyroprocessing with Cooling	2-10% reduction in fuel usage	6%	No	No	EPA 2010
Fluxes and mineralizers	The use of fluxes and mineralizers can reduce the temperature at which the clinker melt begins to form in the kiln, promote formation of clinker compounds, and reduce the lower temperature limit of the tricalcium silicate stability range. All of these factors can reduce the fuel energy demand of the kiln.	Pyroprocessing with Cooling	42–150 MJ/ton cement	91 Btu/lb cement	No	No	EPA 2010
Kiln/preheater insulation (internal)	Proper insulation for the kiln shell minimizes heat losses, which	Pyroprocessing with Cooling	0.1–0.31 MMBtu/ton cement	102 Btu/lb cement	No	No	EPA 2010

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	**Energy Savings** Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
	decreases fuel consumption.						
Kiln/preheater insulation (external)	Proper insulation for the upper preheater vessels and the cooler housing were estimated to provide energy savings of 17 Btu/ton cement.	Pyroprocessing with Cooling	17 Btu/ton cement	0.01 Btu/lb cement	No	No	EPA 2010
Refractory material selection	The refractory bricks lining the combustion zone of the kiln protect the outer shell from the high combustion temperatures, as well as chemical and mechanical stresses.	Pyroprocessing with Cooling	49,800 Btu/ton cement	25 Btu/lb cement	No	No	EPA 2010
Replacement of planetary and travelling grate cooler with reciprocating grate cooler	Grate coolers are used to cool the clinker immediately after it exits the kiln. Grate coolers that operate with higher efficiencies will lead to less wasted heat and reduce fuel	Pyroprocessing with Cooling	Reduce energy consumption by 8% or 84–251 MJ/ton cement; increase electricity use by 1–5 kWh/ton cement	8%	No	No	EPA 2010

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
	usage elsewhere in the process.						
Heat recovery for power - cogeneration	Based on the heat recovery system and the kiln technology, 7–8 kWh/ton cement can be produced from hot air from the clinker cooler, and 8–10kWh/ton cement from the kiln exhaust.	Pyroprocessing with Cooling	Energy savings of 7–20 kWh/ton cement	23 Btu/lb cement	No	No	EPA 2010
Suspension preheater low pressure drop cyclones	Exhaust gases from the kiln or clinker cooler are routed to the cyclone and provide the heat to preheat the raw meal suspended or residing in the cyclone.	Pyroprocessing with Cooling	Energy savings of 0.5–0.6 kWh/ton cement	1 Btu/lb cement	No	No	EPA 2010
Multistage preheater	Multistage preheaters allow higher energy transfer efficiency and lower fuel requirements.	Pyroprocessing with Cooling	Energy savings of 0.4 MMBtu/ton cement	200 Btu/lb cement	No	No	EPA 2010

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	**Energy Savings** Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
Conversion from long dry kiln to preheater/precalciner kiln	Converting to a preheater/precalciner kiln may increase production by 40 percent and may require more extensive upgrades in the raw grinding and clinker cooling areas to handle the increased production.	Pyroprocessing with Cooling	Energy savings of 1.1 MMBtu/ton cement	550 Btu/lb cement	No	No	EPA 2010
Kiln drive efficiency improvements	When direct current motors are used, the efficiency of the motors is maximized by using a single pinion drive with an air clutch and a synchronous motor.	Pyroprocessing with Cooling	Energy savings of 0.5 kWh/ton cement	1 Btu/lb cement	No	No	EPA 2010
Adjustable speed drive for kiln fan	Adjustable speed drives assist in replacing the damper on the kiln fan system, which can reduce energy consumption of the kiln fan.	Pyroprocessing with Cooling	Energy savings of 5 kWh/ton cement	9 Btu/lb cement	No	No	EPA 2010

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
The new suspension preheaters burning system	In a new suspension preheater (NSP) burning furnace, all materials are fully combusted at once.	Pyroprocessing with Cooling	Reduction in average unit consumption of energy (in calorific value) SP type burning furnace is 3,470~3,600kJ/kg; NSP type 2,930～3,350kJ/kg	1,350 Btu/lb clinker	No	No	APP 2009
Automatic control of bottom cyclone outlet temperature	The outlet temperature of the bottom cyclone is used as an operation index on behalf of the decomposition rate and the kiln is operated to keep its transition stable	Pyroprocessing with Cooling	The heat consumption for burning clinkers goes down by 0.8%.	1%	No	No	APP 2009
Air beam type clinker cooler	Cooling air is supplied directly to each block that is constructed by 4 to 8 pieces of grate plate	Pyroprocessing with Cooling	1) Heat consumption: Approx. 42 – 167 kJ/kg decrease 2) Power consumption: Approx. 0.5 – 1.5 kWh/t decrease 3) Maintenance cost of grate plate: decrease (Extension of life)	Average thermal savings: 45 Btu/lb Average electric savings: 2 Btu/lb	No	No	APP 2009

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	**Energy Savings** Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
Improved ball mills	The electricity savings when replacing an older ball mill with a new finish grinding mill may be 25 kWh/ton cement. The addition of a pre-grinding system to an existing ball mill can reduce electricity consumption by 6–22 kWh/ton cement.	Finish Grinding	Energy savings of 6–25 kWh/ton cement	26 Btu/lb cement	No	No	EPA 2010
Improved grinding media	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.	Finish Grinding	Energy/fuel savings of 3–5 kWh/tonne cement	6 Btu/lb cement	No	No	Madlool et al. 2011
Process control and management in grinding mills for finish grinding	Optimizing process controls can increase cement production and decrease energy consumption.	Finish Grinding	Energy/fuel savings of 2.5–10%	6%	No	No	Madlool et al. 2011

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
High pressure roller press for ball mill pre-grinding	Adding a high pressure roller press as pre-grinding to the ball mill for younger cement plants can potentially increase the energy efficiency.	Finish Grinding	Electrical energy savings of 0.26 kWh/t clinker	0.4 Btu/lb clinker	No	No	LBNL 2009
High efficiency cement mill vent fan	Replacement of a cement mill fan with a higher efficiency fan has the potential to reduce energy requirements by 0.13 kWh/ton clinker.	Finish Grinding	Electrical energy savings of 0.13 kWh/t clinker	2.3 Btu/lb clinker	No	No	LBNL 2009
Classification liner for the second chamber of tube mill	This liner improves the coarse grinding capacity at the inlet of the second chamber; the grinding performance of the entire mill may improve of the first chamber is made short and the second chamber long.	Finish Grinding	The power consumption rate is down 1 to 2 kWh/t.	2 Btu/lb cement	No	No	APP 2009

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
Clinker flow rate regulator for tube mill	For clinker flow rate adjustment, the angle of scooping ground materials that flowed into the partition is adjusted or an on-off valve attached to the ground material discharge port is operated from outside the mill.	Finish Grinding	The power consumption rate is down 2 to 3 kWh/t.	4 Btu/lb cement	No	No	APP 2009
Improvement of separator	The separators are divided into three types according to their structures. The first generation is the built-in fan type, the second is the cyclone air type, and the third is the rotor type.	Finish Grinding	1) Grinding capacity 15% to 25% (Increase) 2) Specific power consumption 10% to 20% (Reduction)	20%	No	No	APP 2009
Pre-grinding of roll press system	This system increases the output of finish tube mill by installing the pre-grinding roll crusher in upstream of the tube mill.	Finish Grinding	1) Grinding capacity of finish mill increases about 30%. 2) Specific power consumption in finishing process decreases about 10%.	10%	No	No	APP 2009

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
Pre-grinding of roller mill system	This system installs a vertical roller mill (of high grinding efficiency) for a pre-grinding in the upstream of the tube mill.	Finish Grinding	1) Grinding capacity of finish mill increases about 30~60%. 2) Specific power consumption in finishing process decreases 10~20%.	15%	No	No	APP 2009
Automatic run control of tube mill	For this control, the power of the bucket elevator at the mill outlet used to be kept constant.	Finish Grinding	1) The power consumption rate is down about 2 to 10%. 2) The labor for running operation can be reduced. 3) The quality becomes stable because of stable run.	6%	No	No	APP 2009
Vertical roller mill for cement grinding	Ground cement materials are sent to separator installed in mill upper position by air and classified to coarse particles and fine product. Coarse particles are returned on the grinding table to be re-ground and the fine product is sent to dust collectors such as	Finish Grinding	Electrical power consumption can be reduced by 30% (compared with the tube mills).	30%	Yes	No	APP 2009

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	Energy Savings Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
	cyclone and/or bag filter.						
External materials circulating system to cement grinding vertical mill	The external circulating system is adopted to vertical roller mill grinding process in order to reduce power consumption of mill fan.	Finish Grinding	Specific power consumption is down about 10%.	10%	No	Yes	APP 2009
Automatic control of cement grain size	Adjusts the separator automatically; the grain size of refined powder (product) changes with the passage of time under the influence of various factors even when the running conditions are fixed.	Finish Grinding	1) The cement quality (grain size) is stable. 2) The power consumption rate is down 3 to 5%.	4%	No	Yes	APP 2009
High efficiency grinding of blast furnace slag	Improvements in the grinding process to produce fine granulated blast furnace slag suitable for use in the production of blast furnace cement was	Finish Grinding	Reduction in unit electricity consumption (Blended value 4,000 cm^2/g) * Tube mill 70 kWh/t (approx., excluding drying) * Vertical mill <40 kWh/t (including separator, wind-	31 Btu/lb cement	No	No	APP 2009

Table A3-2. Details of Cement Practical Minimum Technologies Considered

Technology Name	Description	Applicability	Explanation of Energy Savings Assumptions	**Energy Savings** Estimate (percentage or energy intensity)	Included in SOA Calculations	Included in PM Calculations	References
	achieved with pre-grinding and vertical mill technologies used in cement manufacturing.		chamber/fan, conveyor systems, etc.)				

In cases where more than one technology was considered for a given subarea/sub-process, the following calculation was used:

$$PM = PMBaseline * [(1 - P_1) * (1 - P_2) * \ldots * (1 - P_n)]$$

where *PM* is the practical minimum energy intensity, *PMBaseline* is the baseline energy intensity (i.e., the SOA energy intensity), and P_1, P_2, … P_n are the percent savings for each of the *n* PM technologies included in the model. Energy savings from different technologies were not considered additive; rather, this formula considers technologies as compounding when more than one is applicable to a certain subarea. Energy savings from cross-cutting technologies were applied across all subareas and sub-processes as part of the compounded savings estimate.

Appendix A4: Thermodynamic Minimum Calculation Details

This Appendix provides details on how the thermodynamic minimum energy intensities for pyroprocessing with cooling stages were calculated for cement manufacturing processes, as well as any assumptions and reference values used.

The thermodynamic minimum energy intensity of pyroprocessing with cooling for a cement kiln depends upon the moisture content fraction of the input materials. The main inputs for the raw meal for dry kiln feed consists primarily of calcium carbonate ($CaCO_3$), magnesium carbonate ($MgCO_3$), silica (SiO_2), alumina (Al_2O_3), and iron(III) oxide (Fe_2O_3). The pyroprocessing reaction sequence begins with the formation calcium oxide (CaO), and magnesium oxide (MgO), as well as kaolinite ($Al_2O_3 \bullet 2SiO_2 \bullet 2H_2O$) decomposition, as shown in the following equations (Farag 2012):

$$Al_2O_3 \bullet 2SiO_2 \bullet 2H_2O \rightarrow Al_2O_3 + 2SiO_2 + 2H_2O \text{ [1]}$$

$$MgCO_3 \rightarrow MgO + CO_2 \text{ [2]}$$

$$CaCO_3 \rightarrow CaO + CO_2 \text{ [3]}$$

From these oxide materials, intermediate cement materials are formed. According to Farag 2012, the main intermediates in cement pyroprocessing are calcium aluminate ($CaO \bullet Al_2O_3$, or CA), dicalcium ferrite ($2CaO \bullet Fe_2O_3$, or C_2F), and dicalcium silicate ($2CaO \bullet SiO_2$, or β-C_2S). The formation of these intermediates are shown in the following reactions (Farag 2012):

$$Al_2O_3 + CaO \rightarrow CaO \bullet Al_2O_3 \text{ (CA) [4]}$$

$$Fe_2O_3 + 2CaO \rightarrow 2CaO \bullet Fe_2O_3 \text{ (}C_2F\text{) [5]}$$

$$2CaO + SiO_2 \rightarrow 2CaO \bullet SiO_2 \text{ (}\beta\text{-}C_2S\text{) [6]}$$

The reaction intermediates then undergo further reactions to form clinker. The clinker is primarily composed of tetracalcium aluminoferrite ($4CaO \bullet Al_2O_3 \bullet Fe_2O_3$, or C_4AF), tricalcium aluminate ($3CaO \bullet Al_2O_3$, or C_3A), and tricalcium silicate ($3CaO \bullet SiO_2$, or C_3S). The clinkering reactions are then summarized in the following chemical equations:

$$CA + C_2F + CaO \rightarrow 4CaO \bullet Al_2O_3 \bullet Fe_2O_3 \text{ (}C_4AF\text{) [7]}$$

$$CA + 2CaO \rightarrow 3CaO \bullet Al_2O_3 \text{ (}C_3A\text{) [8]}$$

$$CaO + \beta\text{-}C_2S \rightarrow 3CaO \bullet SiO_2 \text{ (}C_3S\text{) [9]}$$

The mineral composition of the clinker as it leaves the rotary kiln consists of approximately 8% C_4AF, 20% β-C_2S, 10% C_3A, 56% C_3S. The remaining 6% of the final product is comprised of various other minerals and impurities (Farag 2012).

To determine the TM energy intensity, the enthalpy and Gibbs free energy changes were determined for each of the nine reactions. Robie and Hemingway 1995 provided most of the thermodynamic data for each of the reactants and products considered in Table A4-1 except for CA, C_4AF, and C_3A. The thermodynamic data for CA were determined from Fumo et al. 1996 and C_4AF and C_3A from Matschei 2007.

Table A4-1. Calculated Enthalpy and Gibbs Free Energy Changes for Clinker Production Reactions

Reaction	Molecular weight (g/g-mol)	Mass (kg)	ΔH (kJ/kg clinker) [Btu/lb clinker]*	ΔG (kJ/kg clinker) [Btu/lb clinker]*
Kaolinite decomposition [1]	258.16	0.15	80.4 [35]	26.4 [11]
$MgCO_3$ dissociation [2]	84.31	0.04	56.1 [24]	31.2 [13]
$CaCO_3$ dissociation [3]	100.09	1.29	2,295.6 [987]	1,681.9 [723]
CA formation [4]	158.04	0.09	-9.1 [-4]	-13.7 [-6]
C_2F formation [5]	271.85	0.05	-7.9 [-3]	-9.2 [-4]
β-C_2S formation [6]	172.24	0.69**	-502.5 [-216]	-514.1 [-221]
C_4AF formation [7]	485.96	0.09	3.7 [2]	4.7 [2]
C_3A formation [8]	270.19	0.11	14.1 [6]	12.9 [6]
C_3S formation [9]	228.32	0.62	23.6 [10]	21.2 [9]
Clinker formation***	N/A	1.11	1,953.9 [840]	1,241.2 [534]
	N/A	1.00	1,761.9 [757]	1,119.2 [481]

*Each of the reactions enthalpies and Gibbs free energies were calculated in Farag 2012 based on 1.109 kg clinker. Values are adjusted to the formation of 1.00 kg clinker in the final row of the table.
** 0.22 kg β-C_2S was left in the final clinker composition.
***Totals may not sum due to independent rounding.

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