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CALIFORNIA'S CEMENT INDUSTRY

FAILING THE CLIMATE CHALLENGE

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Global Efficiency Intelligence

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Acknowledgements

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Executive Summary

Cement production is one of the most energy-intensive and highest carbon dioxide (CO_2) emitting manufacturing processes in the world: On its own, the cement industry accounts for more than 5 percent of global anthropogenic CO_2 emissions.

But not all cement is made equal. The cleanest cement factories can emit as little as half the pollution as their dirtiest counterparts. New developments in the cement and concrete sector are driving additional pollution reductions through new materials, enhanced and more efficient processes, and other low-carbon innovations.

The findings of this report show that California's cement industry is not yet a part of the transition to a low-carbon cement and concrete sector. The state's cement factories are the largest consumers of coal and petroleum coke in California; in fact, California's cement factories have higher emissions per ton of cement than similar factories in China, India, and other major cement-producing regions.

California's aging and inefficient cement production facilities are substantially dirtier than new facilities in countries like China and India. The opportunity to clean up California's cement industry is significant.

California's cement factories are the largest consumers of coal in the state.

California is the second-largest cement producing state in the United States after Texas. California's nine cement plants together produced about 10 million metric tonnes (Mt) of cement and emitted 7.9 Mt of CO_2 pollution in 2015.

More than 70 percent of the energy used in California's cement industry is coal and petroleum coke, which are two of the most air polluting fossil fuels. California's cement industry used around 34.28 petajoules (PJ– 1015 joules) of fuel, which includes over 900 kilotonnes (kt) of coal and petroleum coke, and 1,340 gigawatt hours (GWh) of electricity in 2015. The 900 kt of coal and petroleum coke is the equivalent of 7,500 railcars full of these fossil fuels. The 1,340 GWh of electricity use is equal to the average monthly electricity consumption of around 2.3 million California households.

Around 60 percent of the total CO_2 emissions from California's cement industry are process-related emissions from the conversion of limestone to clinker the remaining 40 percent are energy-related emissions from fuel and electricity consumption (Figure ES 1).

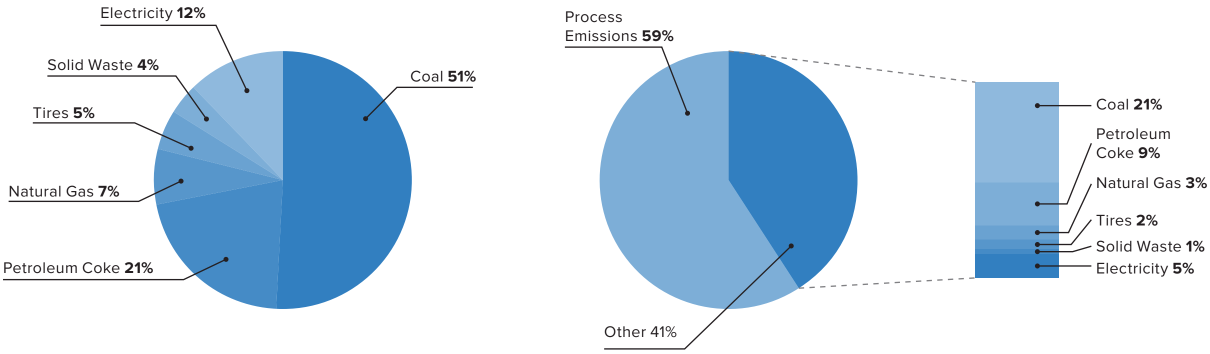

Figure ES1. Final energy use mix in California's cement industry in 2015 (left); Sources of CO_2 emissions in California's cement industry in 2015 (right)

This study analyzes the current status of cement and concrete production in California, and benchmarks the energy use and CO_2 emissions of the state's cement industry in comparison to other key cement-producing countries.

California Cement: Among the Most Polluting Per Ton

The result of our benchmarking analysis shows that California's cement industry has the second highest electricity intensity (kWh/t cement) and fuel intensity (GJ/t clinker) among 14 countries/regions studied. The electricity and fuel intensity of California's cement industry in 2015 was 66 percent and 25 percent higher, respectively, than those intensities in India, which had the lowest intensities for its cement industry among fourteen countries/regions studied.

In addition, the CO_2 emissions intensity (tCO_2/t cement) of California's cement industry was the second highest among countries/regions studied, and 57 percent higher than that of China's cement industry. One of the key reasons for significantly higher CO_2 emissions intensity of the cement industry in California, and in the U.S. in general, is a higher clinker-to-cement ratio and/or lower use of supplementary cementitious materials (SCMs) in California and the U.S. compared to China and India.

California has many options to help its cement industry reduce energy use and GHG emissions. These include: investments in more energy efficiency processes; fuel switching; clinker substitution; use of alternative materials (e.g. engineered wood and high-performance polymers); and carbon capture, utilization, and storage (CCUS).

Policy tools available to California legislators and air regulators can help accelerate this transition, and create incentives to clean up cement not just in California, but in other states and regions that supply the California market.

Table of Contents

1 Introduction

Cement is used as the binder in concrete, which is the most common manufactured product worldwide. Cement production is one of the most energy-intensive and highest carbon dioxide (CO_2) emitting manufacturing processes. In fact, the cement industry alone accounts for more than 5% of total anthropogenic CO_2 emissions in the world (UNFCCC 2017). In addition, the cement industry in some countries with weaker air pollution control regulations is a large source of air pollutants such as particulate matter (PM), sulfur dioxide (SO_2), and Nitrogen Oxide (NOx).

China is the largest producer of cement, accounting for more than 57% of the world's cement production in 2016, followed by India (7%) and the U.S. (2%) (van Oss 2017). The demand for cement is expected to increase worldwide with most of the growth coming from developing countries in Asia and Africa.

California is the second-largest cement producing state in the United States after Texas. Cement production is also expected to increase significantly in California in the next decade (Kumar and Gandhi 2016). This could result in a significant increase in absolute CO_2 emissions from the cement industry if no substantial actions are taken by the government and industry sector.

A major difference between the cement industry and most other industries is that fuel consumption is not the dominant source of CO_2 emissions. More than 50% of the CO_2 released from the cement industry is process-related, from calcination of limestone (CARB 2018). This highlights the fact that sector-specific policies and measures that address fuel-related, process-related, and electricity-related CO_2 emissions are required to reduce the carbon footprint of cement and concrete.

The goal of this study was to analyze the current status of cement and concrete production in California and conduct a benchmarking analysis for energy use and CO_2 emissions of the cement industry in comparison with some other key cement-producing countries. This will inform Californians about the gap between GHG emissions of the cement industry in California and some other major economies.

2 Description of Cement & Concrete Production

Portland cement was invented in Britain during the early 19th century and named for its resemblance to stone from the Isle of Portland on the British coast. It is the most commonly used type of cement worldwide (PCA 2012) and is a key constituent of concrete. The original Portland cement was made by heating a combination of finely ground limestone and clay that hardened when combined with water. Cements that harden when combined with water are known as hydraulic cements (PCA 2012).

The general process by which cement is manufactured today entails quarrying and crushing or grinding of the raw materials – commonly limestone or chalk, and clay – which are then combined and passed through a kiln in the form of either a dry powder or a wet slurry. For this reason, cement production is localized around geological resources and cannot be easily relocated. Kiln temperature is more than 1,500°C. The heat fuses the raw materials into small pellets known as clinker. The cooled clinker is combined with gypsum and ground into the fine powder known as Portland cement.

The American Society for Testing and Materials (ASTM) defines several types of Portland cement with different properties as well as several blended hydraulic cements that are made by combining materials such as Portland cement, fly ash, natural pozzolana (a siliceous volcanic ash), and ground granulated blast furnace slag (PCA 2012). These standards and definitions related to the performance of the building materials and play a key role in the procurement of cement and concrete. The subsections below describe the process by which cement is produced in more detail, with a focus on the energy and CO_2 emissions impacts of cement production processes.

2.1. Cement Production Processes

Mining and Quarrying

The most common raw material used for cement production is limestone. In most cases, these raw materials are mined from a quarry near the cement plant. The limestone provides calcium oxide, and clay, shale, and other materials provide the silicon, aluminum, and iron oxides needed to produce cement. About 5 percent of the total CO_2 emissions from cement production are associated with quarry mining and transportation (WWF 2008). Mining and quarrying are not included in the scope of the decarbonization roadmap presented in this study.

Raw Material Grinding and Preparation

Raw materials are ground based on whether clinker production uses dry or wet processing. In dry processing, the raw materials are ground into a powder in horizontal ball mills, vertical roller mills, or roller presses. The ground materials are then dried using waste heat or auxiliary heat. The moisture content in the dry feed is typically around 0.5 percent. In some countries and regions, raw materials are very moist, and so wet processing may be preferable. In wet processing, raw materials are ground in a ball or tube mill with water to produce a slurry. The moisture content is typically around 35-40 percent (Worrell and Galitsky 2013). Grinding raw materials for cement is an electricity-intensive step, generally requiring about 25 to 35 kilowatt-hours (kWh)/tonne raw material.

Clinker Production

Clinker production is the most energy-intensive stage in cement production due to the need for high-temperature heating. Kiln systems first evaporate the water in the raw meal, then calcine the carbonate constituents (calcination),[1] and finally form cement minerals (clinkerization). The main type of kiln used today is the dry rotary kiln, which uses feed material from dry processing. The first large dry rotary kiln process was developed in the U.S. and directly moved the raw meal to heating and calcination. Later developments added preheaters to warm up the raw meal before entering the kiln. More recently, precalciner technology has been developed, which adds a second combustion chamber between the preheater and the kiln that allows for more energy-efficient production.

After clinker production in the kiln, clinker is cooled rapidly using a grate cooler or, in older plants, a less-efficient tube/planetary cooler to minimize impurities and maximize the hardening properties of cement. The grate cooler transports clinker over a reciprocating grate through which air flows perpendicular to the clinker flow (Worrell and Galitsky 2013). The typical fuel consumption of a dry kiln with four, five, or six-stage preheating ranges from 2.9 to 3.8 GJ/t clinker. Almost all the process-related CO_2 emissions from cement production are associated with calcination during clinker production. The clinker production phase accounts for more than 90 percent of total cement industry energy use and virtually all of the fuel use.

Finish Grinding

The nodules of clinker are finely ground in ball mills, ball mills combined with roller presses, roller mills, or roller presses to produce powdered cement. At this stage, a small amount of gypsum is added to control the setting properties of the cement. Modern state-of-the-art plants use a high-pressure vertical roller mill or horizontal roller mill to save electricity. Finished cement is stored in silos before it is tested and then shipped in bulk by trucks, railcars, barges, or ships (Worrell and Galitsky 2013). The amount of electricity used for finish grinding depends strongly on the hardness of the materials (limestone, clinker, pozzolana, GGBFS, etc.) and the desired fineness of the cement as well as the amount of additive. Granulated blast furnace slag is harder to grind than clinker, and requires even finer grinding and thus requires more grinding power. Figure 1 shows the detailed steps of the cement production process using a rotary kiln.

Figure 2 shows the electricity and fuel use by process step in a typical cement plant with a dry rotary kiln. Electricity is used in motor driven systems (e.g. in grinding, conveyors, kiln drive systems, etc.) while fuel is burned in the kiln for clinker making. In some cases, a small amount of fuel might be used for raw material drying if needed.

[1] Calcination is the process of heating a substance to drive off structurally-bound volatiles.

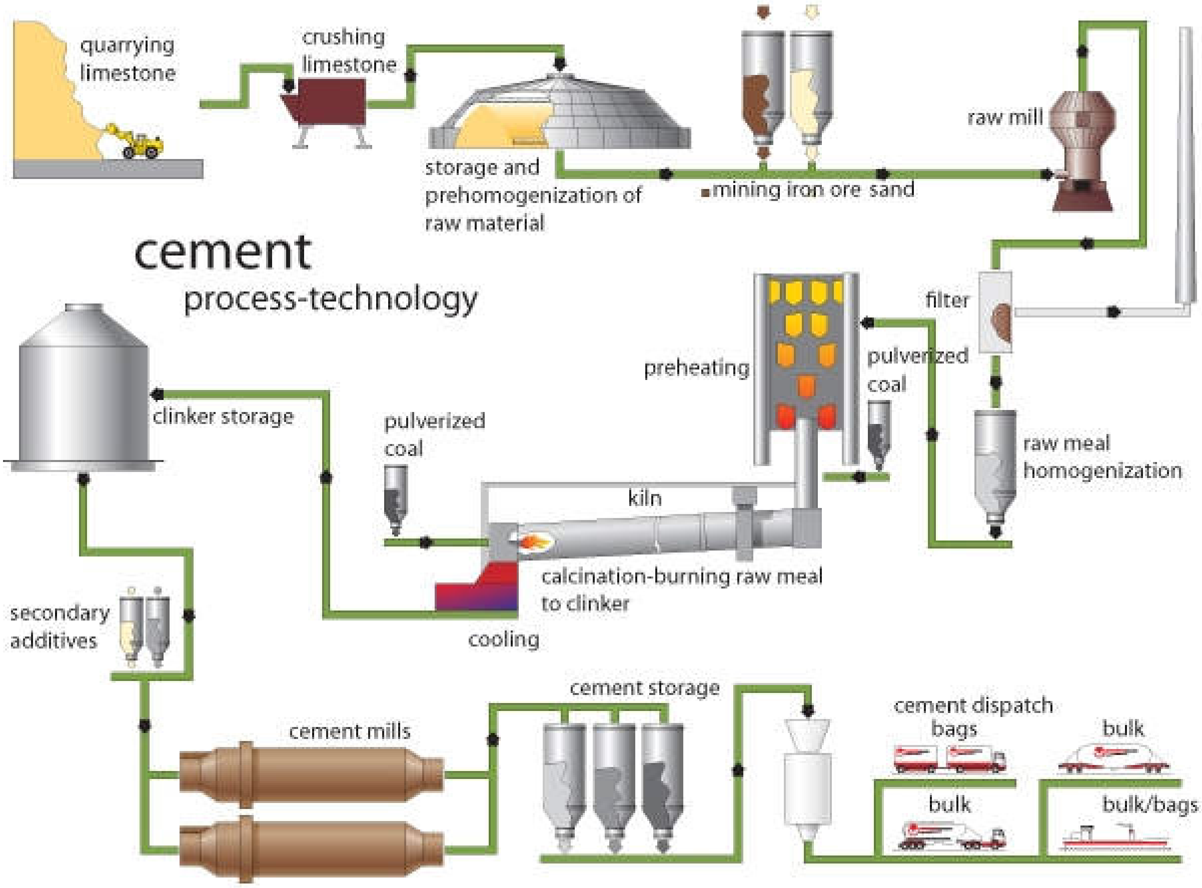

Figure 1. Steps in the cement production process using the rotary kiln (HJM 2018)

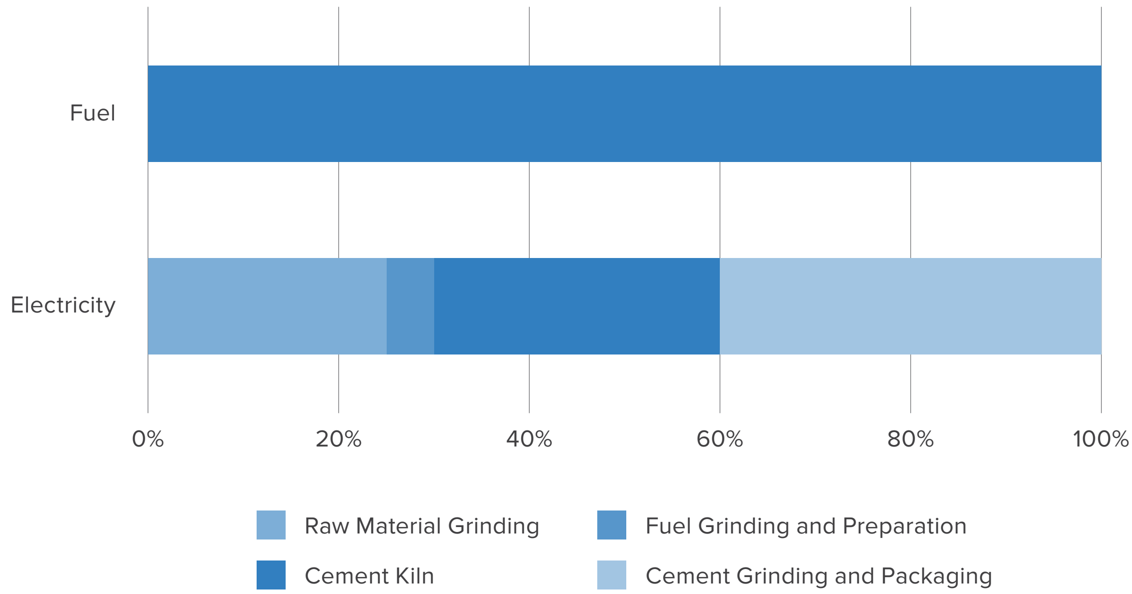

Figure 2. Share of energy use by process step in a typical cement plant with a rotary kiln (IEA/WBCSD 2018)

2.2. CO_2 Impact of Cement Production

The production of 1 metric tonne of cement releases an estimated 0.50 to 0.95 tCO_2/t cement depending on the clinker-to-cement ratio, fuel efficiency, fuel mix, and other factors. More than 50 percent of the CO_2 released during cement manufacture, or approximately 520 kg CO_2 per tonne of clinker (CARB 2018), is from calcination in which limestone ($CaCO_3$) is transformed into lime (CaO) in the following reaction:

$$CaCO_3 \longrightarrow CaO + CO_2$$

The rest of the CO_2 emitted during cement manufacture is the result of burning fuel to provide the thermal energy necessary for calcination to occur. Typically, energy accounts for 30 to 50 percent of cement production costs. Also, an average 100 to 120 kWh of electricity is consumed per tonne of cement. The share of CO_2 emissions from electricity use is, on average, 5 percent of the total CO_2 emissions in the cement industry. Depending on the energy source and the efficiency at which it is used in the local electricity mix, this figure can vary from one percent to around 10 percent. Some 5 percent of CO_2 emissions are associated with quarry mining and transportation (WWF 2008).

2.3. Concrete Production Process

Concrete is a mixture of cement paste and aggregates in a simple form. The cement paste, composed of Portland cement (and possibly supplementary cementitious materials) and water, coats the surface of the fine and coarse aggregates. Through a chemical reaction called hydration, the paste hardens and gains strength, binding the aggregate particles together to form the rock-like mass known as concrete (PCA 2012). Typically, a concrete mix is about 10 to 15 percent cement, 60 to 75 percent aggregate, and 15 to 20 percent water in volumetric basis. Entrained air in many concrete mixes may also take up another 5 to 8 percent. Figure 3 shows the typical share of each component in concrete production.

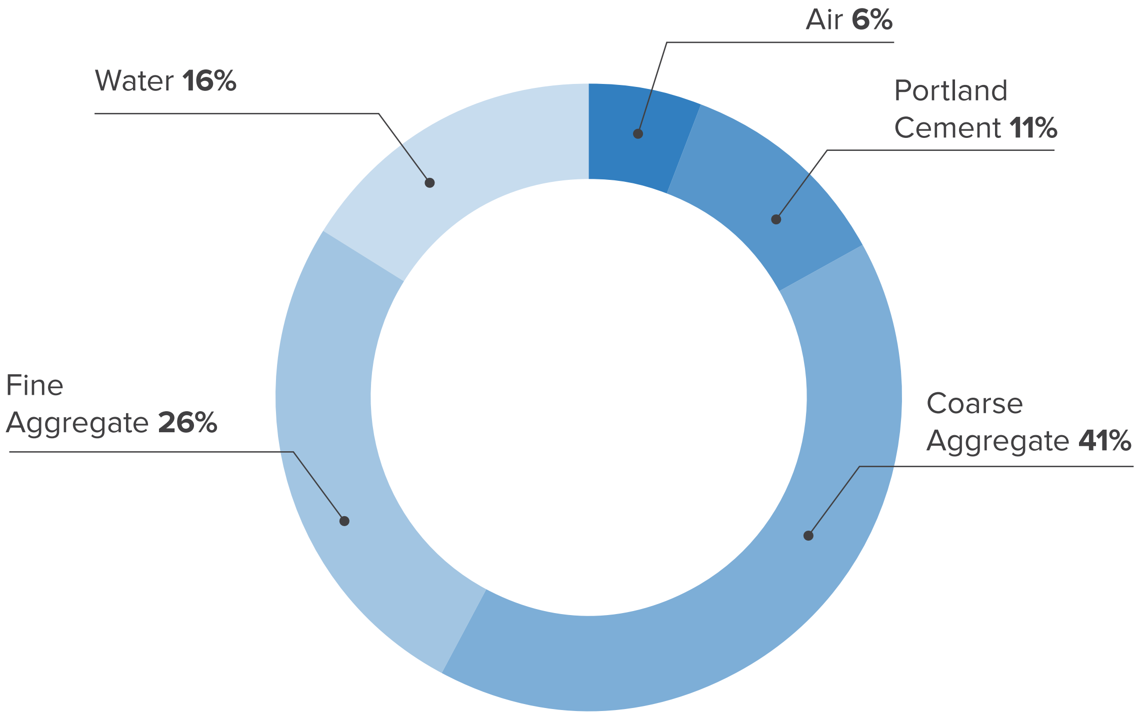

Figure 3. The typical volumetric ratio of each component in concrete production (PCA 2012)

Concrete is produced in four basic forms, which are ready-mixed concrete (more than 80%), precast concrete, concrete masonry blocks, and the cement-based applications, such as soil cement, that represent products that defy the label of "concrete," yet share many of its qualities. Each of these products has unique applications and properties. In all cases, the production of cement used for concrete accounts for the largest share of the energy and carbon dioxide footprints of the concrete produced.

3 Overview of the Cement & Concrete Industries in California

3.1. The Status of the Cement and Concrete Industries in California

California's cement industry had a total of 1,450 employees in 2016. The cement industry in California accounted for $35.6 million of state tax revenue in 2016 (PCA 2017). For reference, the California state government collected $8.5 billion in corporate taxes and $22.2 billion in sales and use taxes in the 2013-2014 fiscal year (California SCO 2018).

California had nine cement plants in 2015 (Note: the CalPortland plant in Riverside, which was a grinding-only facility, closed at the end of 2015) and more than 300 concrete manufacturing plants. The headquarters for the CalPortland and National cement companies are also located in California (PCA 2017). All of California's cement plants use the dry process with multi-stage preheater/precalciner systems (CARB 2013). Figure 4 shows the location of cement plants, offices, and cement distribution terminals in California.

Figure 4. Map of cement plants and cement terminals in California (PCA 2017)

California is the second-largest cement producing state in the U.S. after Texas. California's cement plants together produced 9.8 Mt of cement in 2016. California's cement consumption in 2016 was 9.5 Mt (van Oss 2018a). Figure 5 shows the cement and clinker production in California between 2000 and 2015. The cement production data include Portland cement, Blended cement, and Masonry cement. It should be noted that Masonry cement only accounts for 2% of the total cement production in California. Also, not all the cement used in California is produced in the state. California both imports and exports cement mostly from and to other neighboring states although the amount of these transactions is small. Since California is a large state and cement transportation is costly, in some cases it is more economical to purchase cement from a producer in neighboring state instead of transporting it from further distances within California. In some cases, import and export is done because of needs for a specific cement type.

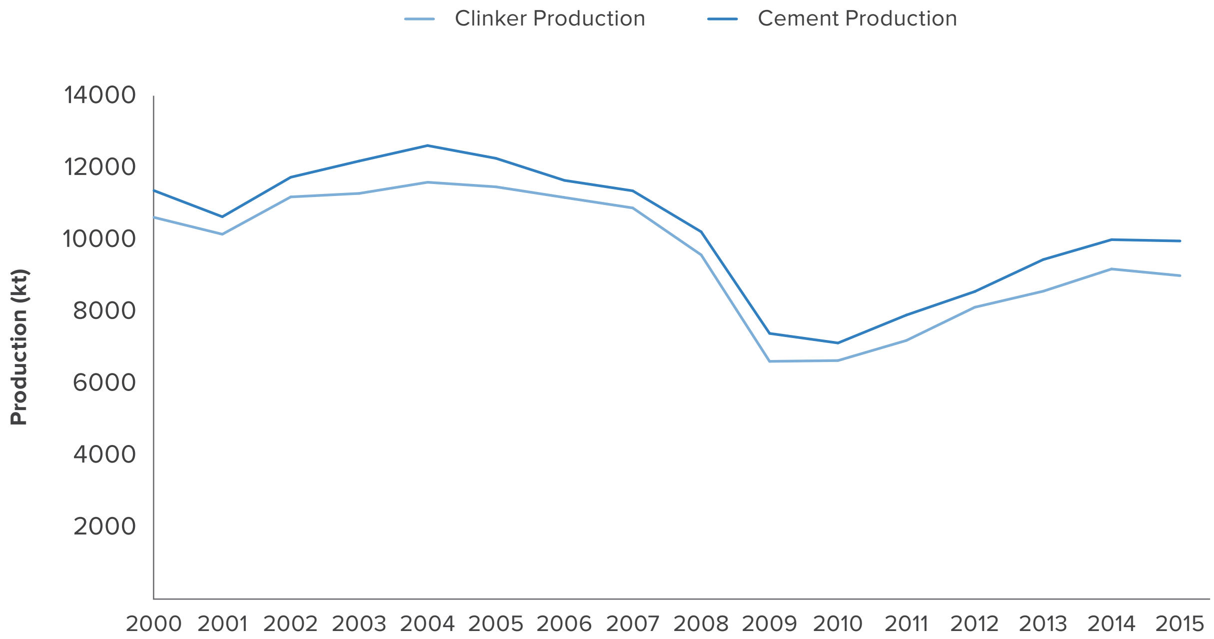

Figure 5. Cement and clinker production in California, 2000-2015 (van Oss 2017, 2018a)

Cement production in California dropped by around 45% during 2004-2010, mainly because of the financial crisis of 2008-2010. After 2010, cement production in California started to rise with the economic recovery, but it has not reached the higher production levels seen in the early 2000s.

Cement is used in a variety of construction projects such as roads, bridges, homes, hospitals, walkways, and water structures. Figure 6 shows that 75% of the cement in California is used by ready-mixed concrete manufacturers with another 13% used by other types of concrete manufacturers (van Oss 2017).

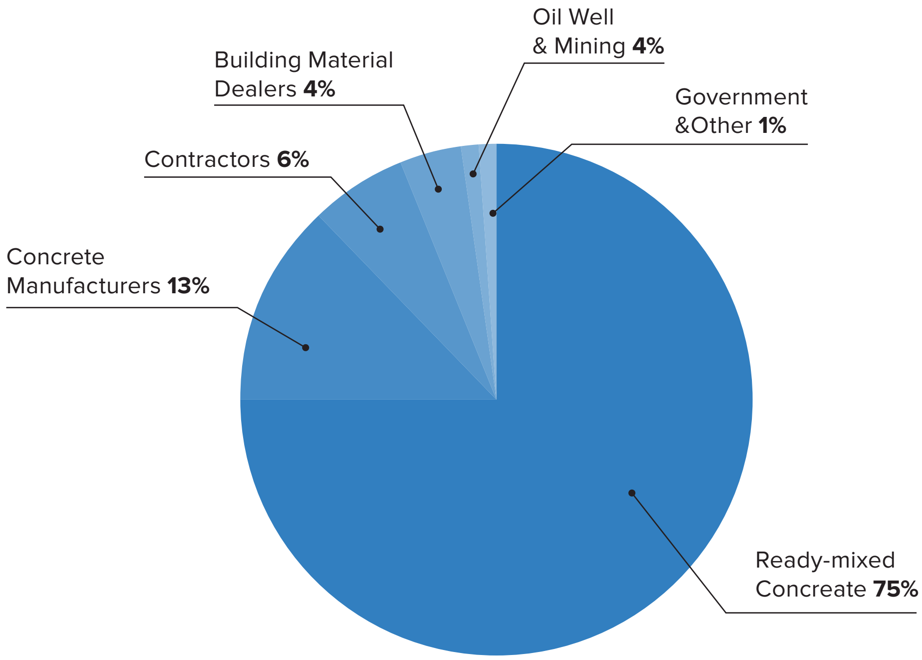

Figure 6. California's Portland Cement Shipments by Type of Customer (van Oss 2017)

Ready-mixed concrete manufacturers in California produced around 24.7 million m^3 (32.3 million yd^3) of concrete in 2015 (calculated based on IRMCA 2015 and van Oss 2018a). California has 345 ready-mixed concrete manufacturing firms as of 2017. The ready-mixed concrete plants in California together employed around 7,780 people as of the 3rd quarter of 2017 (CA EDD 2017). Major Californian ready-mix concrete producers include Granite Rock Company and National Cement Company. Top cement producers CalPortland, Lehigh Hanson, and CEMEX also quarry aggregates and make ready-mixed concrete (KEMA 2012).

3.2. Energy Use and CO_2 Emissions in the Cement Industry in California

California's cement industry used around 34.28 petajoules (PJ) of heat from fuel combustion and 1,340 gigawatt hours (GWh) of electricity in 2015. Compared with the year 2000, this was a 25% decrease in fuel consumption and a 20% drop in electricity consumption (Figure 8) (van Oss 2018a). This drop in energy use was primarily because of the reduction in the clinker and cement production in California during this period, as can be seen in Figure 5. The clinker and cement production decreased by 15% and 13% during 2000-2015, respectively. The sudden drop in energy use during 2008-2010 is also related to the 2008 financial crisis, which resulted in significant reduction in cement demand.

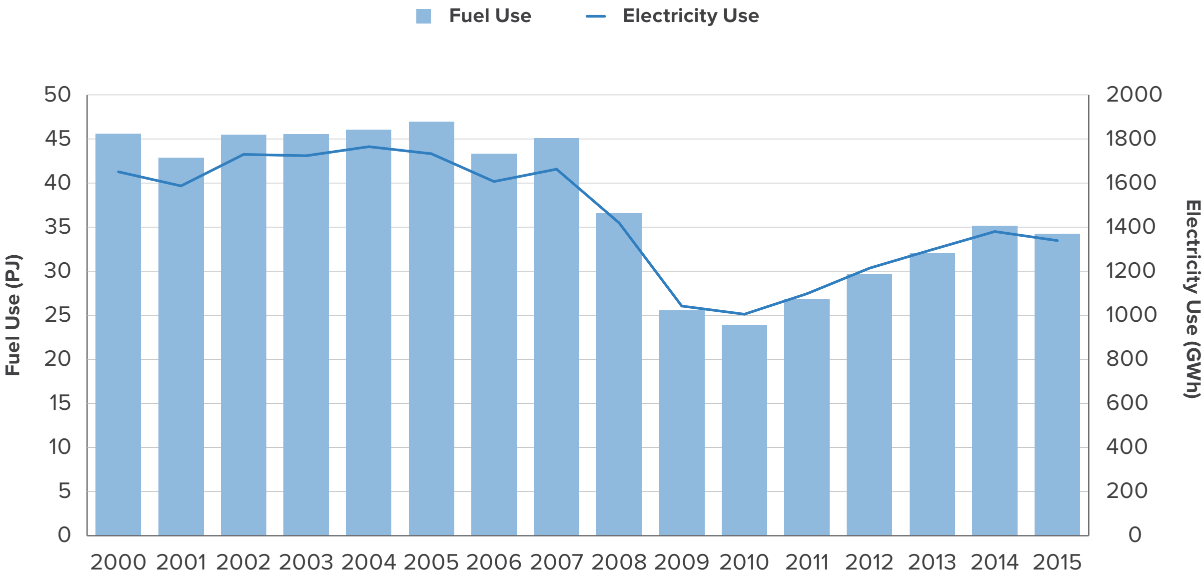

Figure 8. Fuel and electricity use in the cement industry in California, 2000-2015 (van Oss 2018a)

Figure 9 shows that despite some fluctuation, in general, the fuel intensity and electricity intensity for California's cement industry decreased during the period 2000 to 2015. The fuel intensity of California's cement industry decreased by 11% and the electricity intensity dropped by 7% between 2000 and 2015. This reduction in energy intensities can be mainly attributed to an increase in energy efficiency in California's cement industry during this period. California's cement plants all have preheater-precalciner kilns now. One plant (Oro Grande) installed a new preheater-precalciner kiln which replaced seven older long dry kilns, and several other plants have upgraded their production process in the last 10-15 years (Van Oss 2018c).

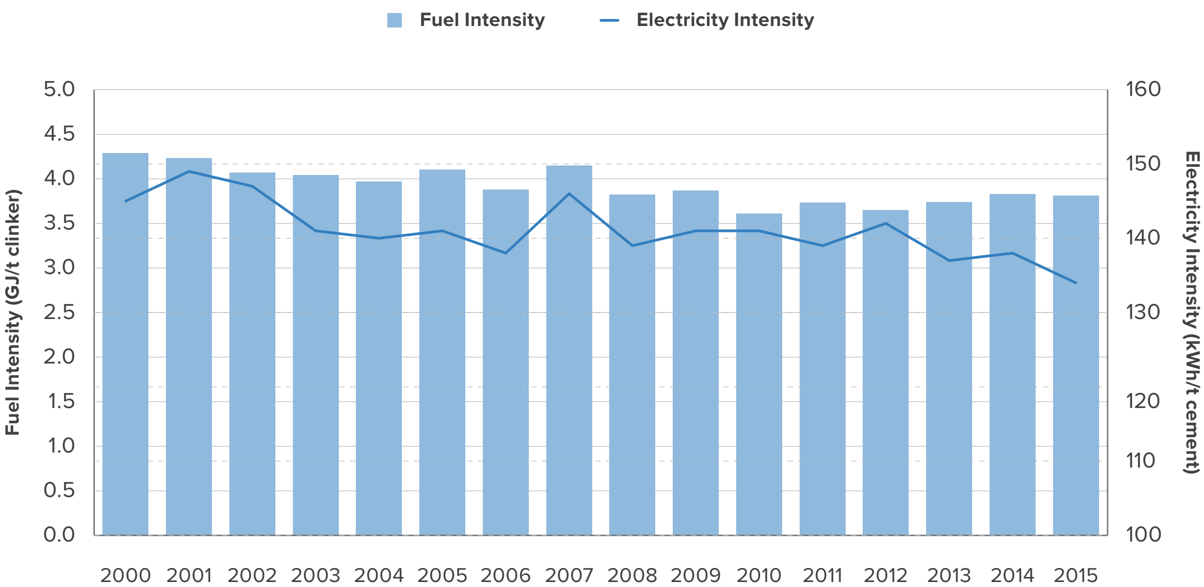

Figure 9. Fuel and electricity intensity of the cement industry in California, 2000-2015

California's cement industry is the largest consumer of coal in California. Other main fuels used include petroleum coke, natural gas, and wastes (like tires and other waste fuels). Figure 10 shows the share of different energy types used in California's cement industry. Heat from fuel combustion accounts for 88% of total final energy consumption, while electricity use accounts for the remaining 12%.

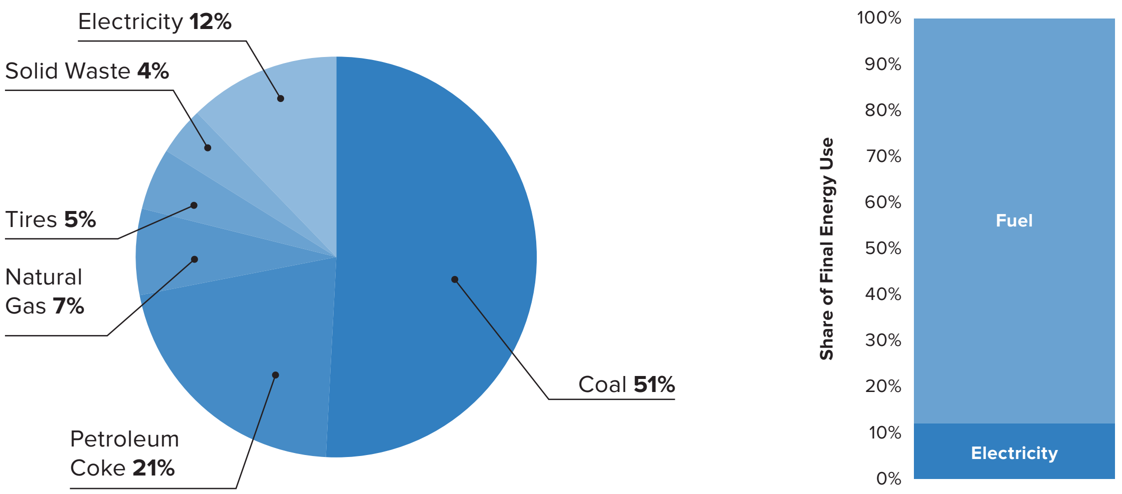

Figure 10. Energy mix in California's cement industry in 2015 (van Oss 2018a)

In California's cement industry, process-related CO_2 emissions from calcination accounted for 59% of total CO_2 emissions in 2015 while energy-related CO_2 emissions accounted for 41% of total emissions (Figure 11). In other words, 59% of the CO_2 emissions from California's cement industry are not associated with energy use. Therefore, deep decarbonization in the cement industry cannot be achieved by best available energy efficient technologies or fuel switching. Clinker substitution and CCUS are a must in order to achieve near zero emissions in cement production. Another point to note here is that electricity accounts for only 5% of California's cement industry's CO_2 emissions. Thus, strategies for decarbonizing the cement industry must include options besides just energy efficiency and fuel-switching, because the majority of emissions are inherent to the cement production process.

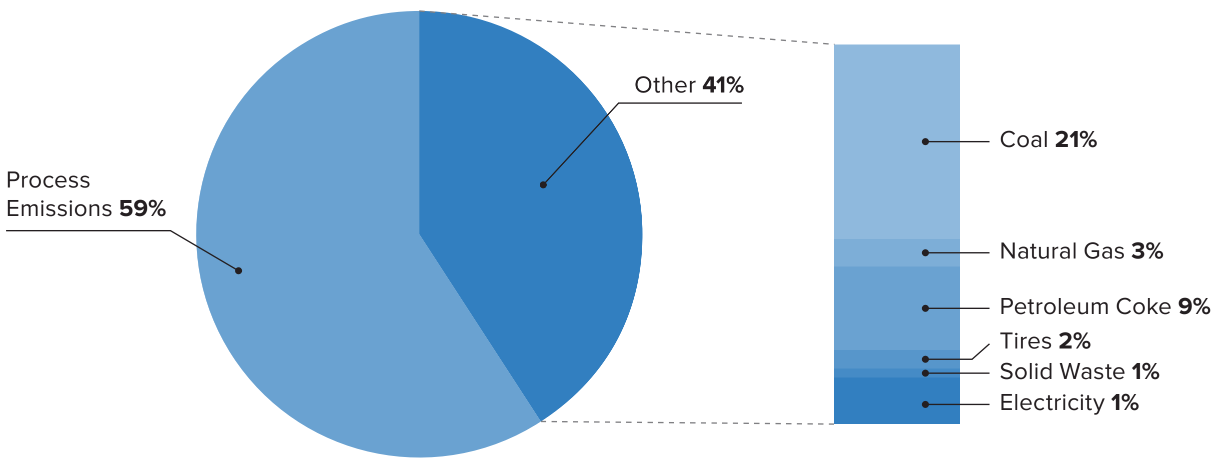

Figure 11. Sources of CO_2 emissions in California's cement industry in 2015

Figure 12 shows the time-series CO_2 emissions for California's cement industry by emissions source during 2000-2015. The total CO_2 emissions of the California cement industry decreased by 20% from 9.9 Mt in 2000 to 7.9 Mt in 2015. The main reason for this decrease is reduction in total cement production during this period, as shown in the previous section. However, the improvement in energy efficiency and changes in the fuel mix also contributed to the reduction in total CO_2 emissions during this period. The sudden drop in total CO_2 emissions during 2008-2010 is because of the 2008 financial crisis, which resulted in substantial reduction in cement demand.

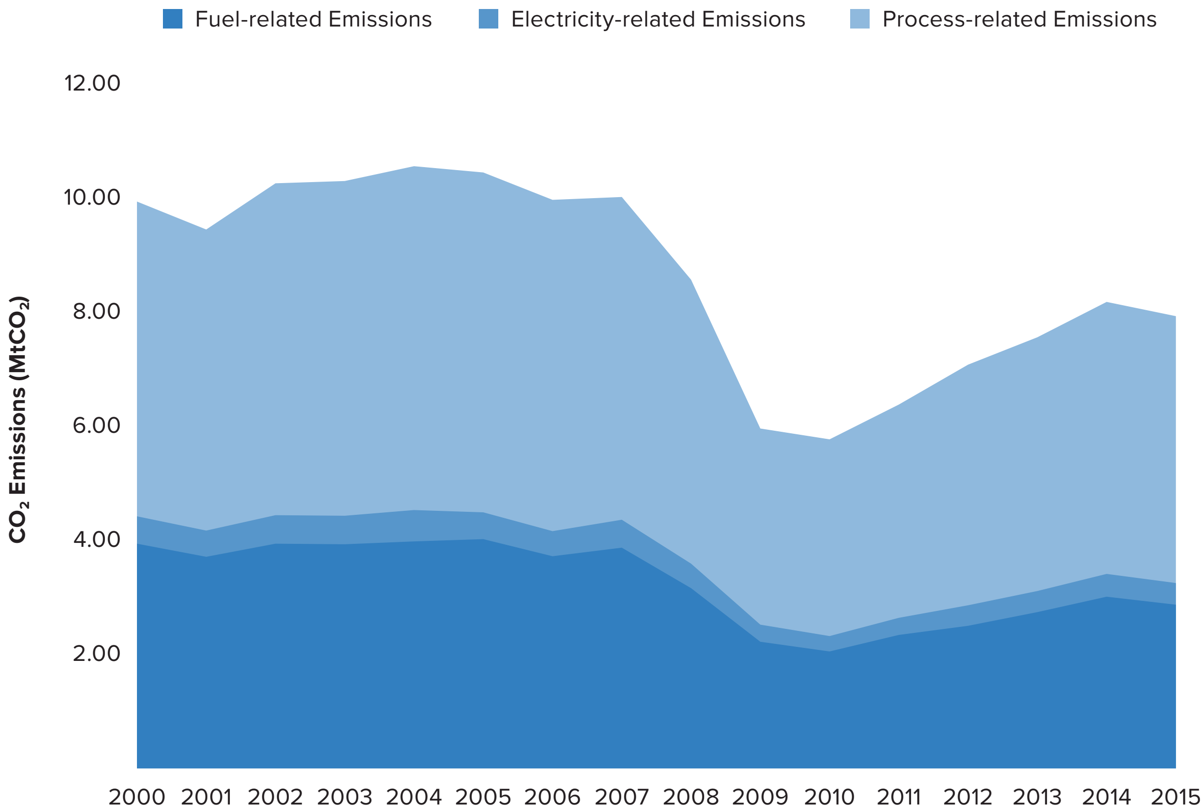

Figure 12. CO_2 emissions in the cement industry in California by emissions source, 2000-2015

Both fuel combustion- and electricity-related CO_2 emissions intensity in California's cement industry decreased during 2000-2015. The fuel-related CO_2 emissions intensity dropped by 17% mainly because of fuel efficiency improvement resulted from upgrades to more efficient preheater-precalciner kilns in several cement plants during this period. In addition, increased use of natural gas and waste fuels in the cement industry during this period helped to reduce CO_2 emissions intensity. The electricity-related CO_2 emissions intensity dropped by 10% during 2000-2015 and is mainly due to electricity efficiency improvements in cement plants and lower carbon intensity of the electricity grid in California.

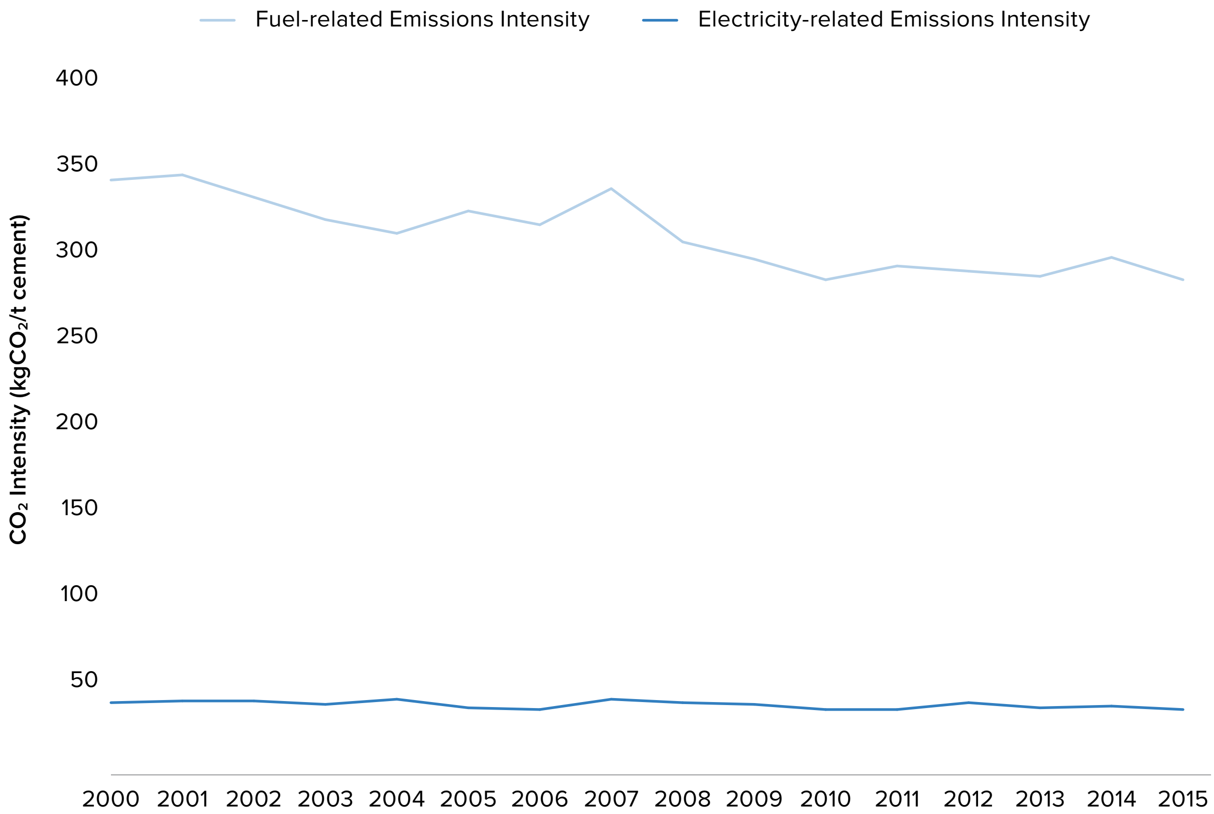

Figure 13. Fuel and electricity-related CO_2 emissions intensity in the cement industry in California, 2000-2015

The California Air and Resources Board (CARB) publishes the greenhouse gas (GHG) emissions for each of the cement plants in California under California's Regulation for the Mandatory Reporting of Greenhouse Gas Emissions. Table 1 shows the plant-level energy and process-related GHG emissions (excluding emissions from electricity) for California's cement industry in 2016, which is the latest year for which the data are reported. As can be seen, the CEMEX cement plant in Victorville had the highest total GHG emissions followed by the Mitsubishi cement plant in Lucerne Valley. It should be noted that these two plants also had higher cement production in 2016.

Table 1. Plant-level GHG emissions of cement plants in California in 2016* (CARB 2017)

Company	Plant Location	2016 GHG Emissions ($ktCO_2e$)
CalPortland	Mojave	921
CalPortland	Oro Grande	874
CEMEX	Victorville	2,157
Lehigh Hanson	Cupertino	1,017
Lehigh Hanson	Redding	199
Lehigh Hanson	Tehachapi	597
Mitsubishi	Lucerne Valley	1,319
National	Lebec	712

* The plant level GHG emissions data are direct emissions from cement plants and do not include indirect emissions from electricity used by plants. Also, CO_2 emissions account for 99.6% of total GHGs emitted by cement plants. The share of other GHGs emitted is minimal.

4 Benchmarking Energy and CO_2 Emissions Intensities of California's Cement Industry

International benchmarking of energy intensity and CO_2 emissions intensity can provide a comparison point against which a company or industry's performance can be measured to that of the same type of company or industry in other countries. Benchmarking can also be used for assessing the energy and emissions improvement potential that could be achieved by the implementation of energy efficiency or CO_2 reduction measures. Also, on a national level, policy makers can use benchmarking to prioritize energy saving and decarbonization options and to design policies to reduce energy and GHG emissions. For this study, we have conducted benchmarking of the energy intensity and CO_2 emissions intensity of California's cement industry against that of the cement industry in the U.S. and other countries/regions in 2015.

4.1. International Energy Intensity Benchmarking

We compared the electricity and fuel intensity of California's cement industry against the cement industry in the U.S. and twelve other countries/regions. Electricity intensity is commonly presented in kWh/t cement, while the fuel intensity is usually presented in GJ/t clinker. This is because almost all the fuel is used in the kiln for clinker production.

As can be seen from Figures 14-15, California's cement industry has the second highest electricity and fuel intensity compared to countries/regions listed on the graph.[2] The electricity and fuel intensity of California's cement industry was 66% and 25% higher than those intensities in India, respectively in 2015.

[2] International values are mostly from WBCSD/CSI (2018) except for Mexico and China. Intensity values for Mexico are calculated based on Buira and Tovilla (2015) and for China calculated based on Cai et al. (2016) and Yang et al. (2017). The U.S. and California values are calculated from USGS energy and production data.

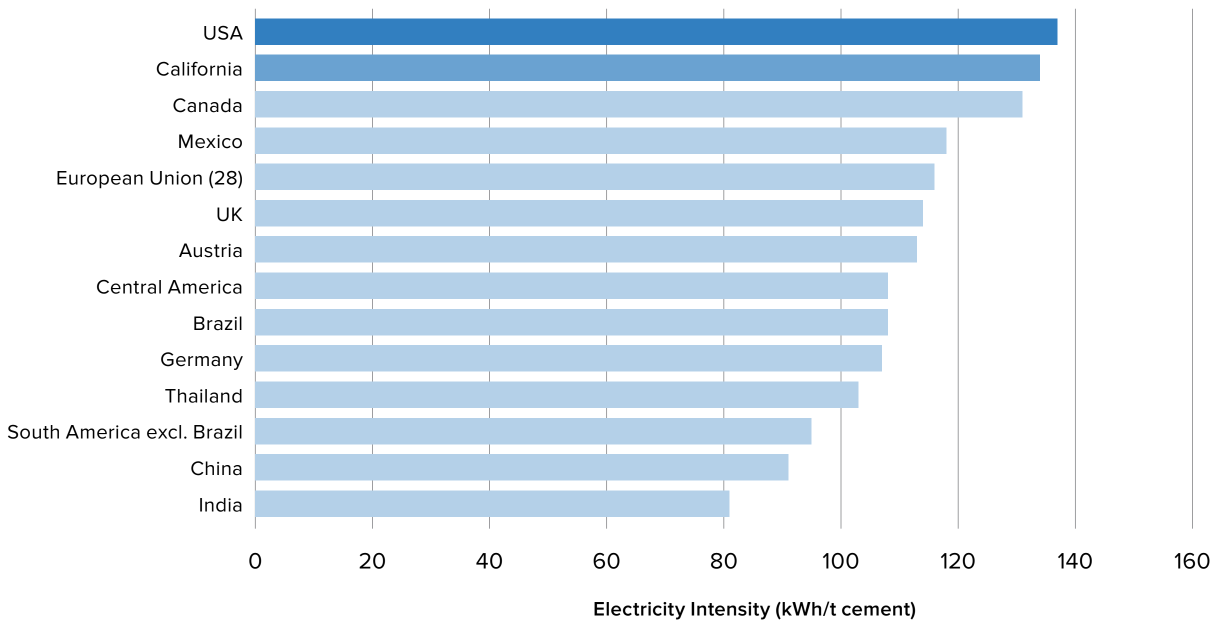

Figure 14. International comparison of electricity intensity for cement production in 2015

The cement industries in India and China both have the lowest electricity and fuel intensity of the countries compared. This is due to several factors. India and China have some of the newest cement plants, installed in the last 10 years or so, and therefore have benefited from more advanced and energy-efficient technologies. Particularly, India has some of the most efficient cement plants in the world, which were installed in recent years. All new cement plants in India and China use new suspension preheater-precalciner (NSP) kilns, which are the state-of-the-art technology with lower fuel intensity. Also, the new grinding mills are often more efficient than older ones, resulting in lower electricity intensity.

California's cement plants are now all preheater-precalciner kilns. One plant (Oro Grande) is new and several of the others have been upgraded in just the last decade or so. While these upgrades helped to reduce the energy intensity of California's cement industry over time, the upgraded kiln systems still are not as efficient as the new state-of-the-art technologies. The U.S. cement industry, however, still had (in 2015) 9 wet plants, operating a total of 14 kilns, plus many plants that operated long dry kilns, both technologies being generally much less fuel-efficient than preheater-precalciner kilns (Van Oss 2018c). This is the main reason why the energy intensity of California's cement industry is lower than that of the U.S. overall.

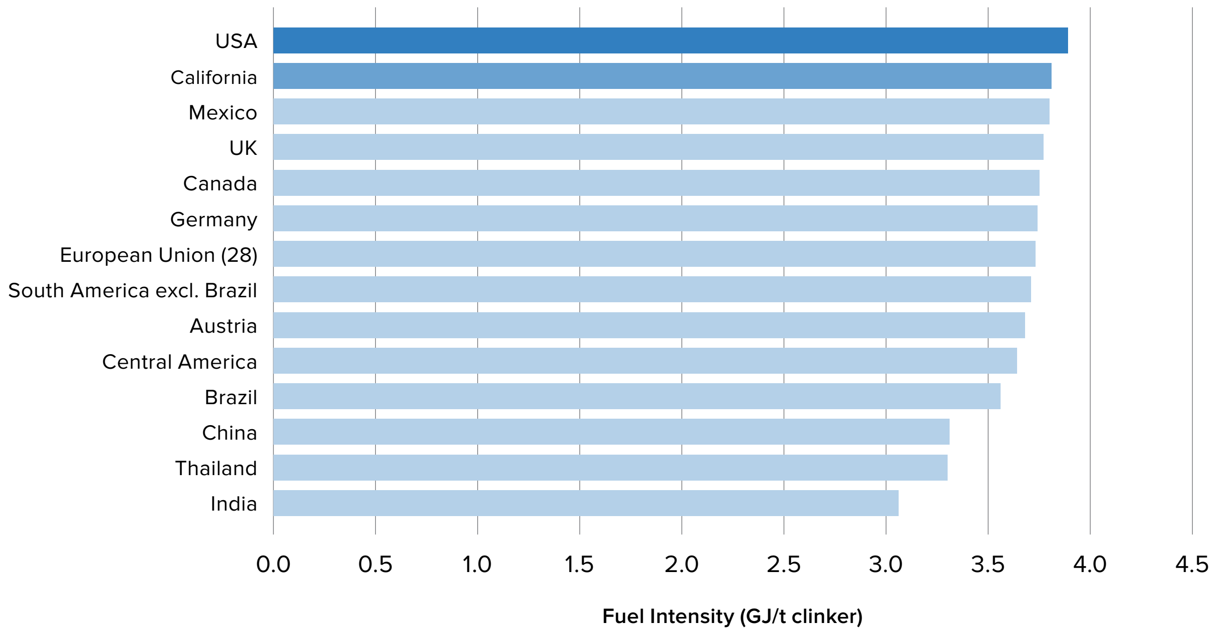

Figure 15. International comparison of fuel intensity for clinker production in 2015

Another important reason why electricity intensity (expressed in kWh/t cement) in the cement industry in California and the U.S. is so high is the higher clinker-to-cement ratio in California and the U.S. compared with other countries and regions. The clinker-to-cement ratio in California and the U.S. is around 0.9. That means 0.9 tonnes of clinker are used to produce one tonne of cement. For comparison, the clinker-to-cement ratio in China is around 0.58, which is one of the lowest in the world, and in India is around 0.72 (IEA/WBCSD 2018), which is still significantly lower than that of California and the U.S. The clinker-to-cement ratio in California and the U.S. is one of the highest in the world[3].

As shown in Figure 2, all the fuel use and around 60% of the electricity use in a cement plant are consumed for clinker production (for raw material grinding, fuel preparation, and cement kiln). A higher clinker-to-cement ratio results in higher electricity and fuel intensity per tonne of cement produced. Replacing clinker with supplementary cementitious material such as fly ash, granulated blast furnace slag, natural pozzolans, ground limestone, and calcined clay can help to significantly reduce energy intensity for cement production.

For the reasons mentioned above, we presented the fuel intensity benchmarking in GJ/t of clinker produced (Figure 15). This helps to eliminate the effect of variation in the clinker-to-cement ratio across countries and provide a better picture of energy efficiency of cement production in different countries/regions. Despite this, California and the U.S. cement industry still have the highest fuel intensities among countries/regions listed. However, if we exclude the countries with the three lowest fuel intensities (i.e. India, Thailand, and China), the difference between the fuel intensity of California's intensity and other countries is rather small (less than 7%).

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[3] In the U.S. and California, unlike many other countries, some amount of SCMs are added during concrete production at ready-mixed concrete plant and not in cement plants.

There are a few reasons why California's cement industry has a slightly higher fuel intensity per tonne of clinker produced compared with other countries/regions. First, the main types of cement made in California are Type II/V or Type V (i.e., high sulfate resistance) Portland. Because these types of cement require a clinker with lower tricalcium aluminate (C3A) content, the kilns will use more heat because the alumina in the kiln (which then forms the C3A) acts like a flux (Van Oss 2018c). Second, the fuel mix can also influence the energy intensity of cement production. California's cement industry uses a fair amount of waste fuel such as tires and other solid wastes in the kiln (12% of total fuel use in the industry). Because of moisture content and other factors, the use of some waste fuels could increase the amount of fuel used (in GJ) per tonne of clinker produced. Third, many countries grind their clinker less finely than is typical in California and the U.S. This results in lower electricity intensity per tonne of cement but does not affect the fuel intensity.

Finally, uncertainty in data should be taken into account. For this benchmarking analysis, international intensity values are mostly from WBCSD/CSI (2018) except for Mexico and China. Intensity values for Mexico are calculated based on Buira and Tovilla (2015) and for China calculated based on Cai et al. (2016) and Yang et al. (2017). The U.S. and California values are calculated from USGS energy and production data. While we took several measures to make sure the data used and the results are comparable, there are inherent uncertainties in the country-specific data, boundary of analysis, type of fuel and products for which the data are reported, etc.

4.2. International CO_2 Emissions Intensity Benchmarking

In addition to energy intensity benchmarking, we also compared the CO_2 emissions intensity of California's cement industry to the cement industry in the U.S. and twelve other countries/regions. Similar to the energy intensity benchmarking results, California's cement industry has the second highest CO_2 emissions intensity only after the U.S., which has the highest intensity (Figure 16). China and India have the lowest CO_2 emissions intensity for their cement industries. The CO_2 emissions intensity of California's cement industry was 57% higher than that of in China.

The primary reason why the cement industry in the U.S. and California have the highest and the cement industry in China and India have the lowest CO_2 emissions intensity per tonne of cement produced are the very high clinker-to-cement ratios in the U.S. and California and the significantly lower clinker-to-cement ratios in China (one of the lowest in the world) and India[4]. The cement industry in all other countries/regions listed, especially in China and India, use a significantly higher share of supplementary cementitious material (SCM) for cement production, which results in lower use of clinker per tonne of cement produced. Fuel mix can also influence the CO_2 emissions intensity of cement production. There are other reasons why the U.S. and California's cement industry have such a high CO_2 emissions intensity, such as plant ages, types of cement produced, and fineness of clinker grinding, which were discussed in previous sections.

It should be noted that in the U.S. and California, unlike many other countries, SCMs are typically added during the concrete production and not by cement plants. Even if we assume all the SCMs to be added in cement plants in the U.S. and California, this will reduce but not eliminate the gap shown in the benchmarking results.

[4] In the U.S. and California, unlike many other countries, some amount of SCMs are added during concrete production at ready-mixed concrete plant and not in cement plants.

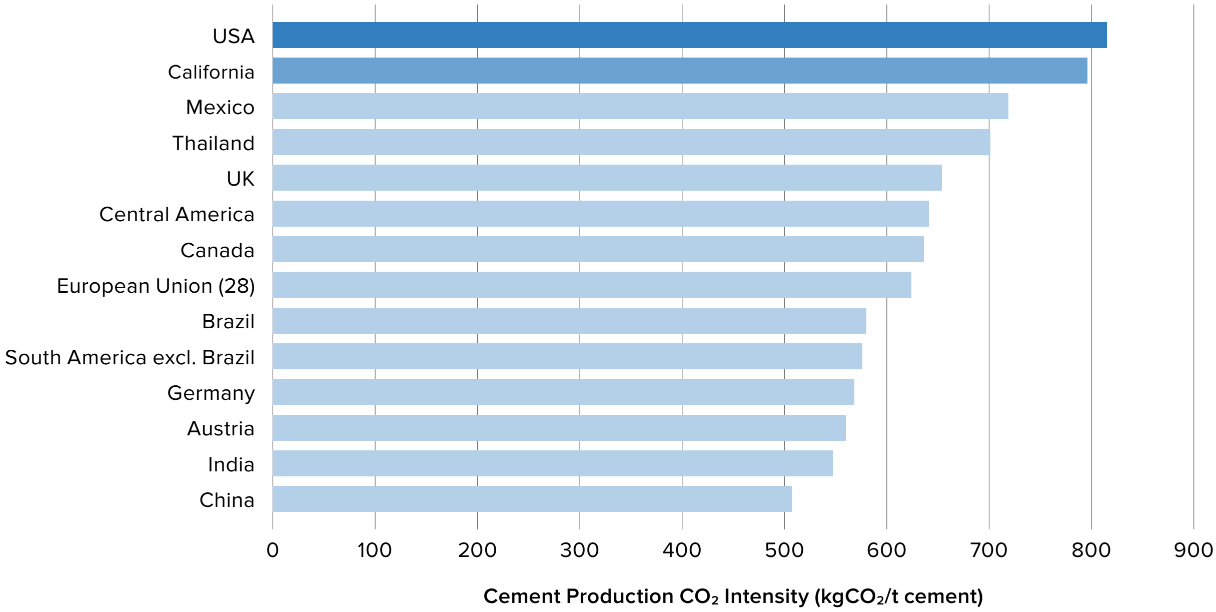

Figure 16. International comparison of cement production CO_2 intensity in 2015

It should be noted that, unlike many other countries where SCMs are added during cement production, in the U.S. (including in California), most SCMs are added during concrete production at ready-mixed concrete plants. This is mainly because ready-mixed concrete manufacturers in the U.S. prefer to buy ordinary Portland cement and add SCMs on-site to save money and to afford greater flexibility in the production of different concrete products with variety of performance levels for various end-uses.

Therefore, it is crucial to keep that aspect of the California market in mind when thinking about decarbonization of cement and concrete in California. We do not recommend trying to change the California market to be similar to other countries in the way they add SCMs. As long as a higher share of SCMs is used, from the final product carbon footprint point of view, it does not matter if they are added in cement plants or ready-mixed concrete plants. Therefore, we suggest working with the current structure and practices of the market in California and trying to encourage ready-mixed concrete producers to use more SCMs in their concrete products.

Obla et al. (2012) estimate that SCMs account for around 18% of total cementitious material used in concrete in California. From this 18%, around 5% of SCMs are added during cement production at California's cement plants, and the remaining SCMs are added during concrete production in concrete ready-mixed plants in California.

Different types of SCMs can be used in cement or concrete production. The most common SCMs are fly ash, ground-granulated blast-furnace slag (GGBFS), and ground limestone, while other SCMs such as natural pozzolans and calcined clay have substantial potential to be used in cement and concrete.

5 Conclusions

California is the second-largest cement producing state in the United States. The cement industry is the largest consumer of coal in California and is one of the top GHG emitter in the state. In this study, we analyzed the current status of cement and concrete production in California and conducted a benchmarking analysis for energy use and CO_2 emissions of the cement industry in comparison with some other key cement producing countries.

Although both electricity- and fuel-related CO_2 emissions intensity of California's cement industry decreased between 2000 and 2015, California's cement industry still has the second highest electricity intensity (kWh/t cement), fuel intensity (GJ/t clinker), and CO_2 emissions intensity (tCO_2/t cement) among 14 countries/regions studied. The CO_2 emissions intensity (tCO_2/t cement) of California's cement industry was 57 percent higher than that of China's cement industry.

One of the key reasons for significantly higher CO_2 emissions intensity of the cement industry in California and the U.S. is a higher clinker-to-cement ratio or lower use of supplementary cementitious materials (SCMs) in California and the U.S. compared to China, India and some other countries. Although it should be noted that in the U.S. and California, unlike many other countries, some amount of SCMs are added during concrete production at ready-mixed concrete plant and not in cement plants.

Several major decarbonization levers that can help California to reduce energy use and GHG emissions from its cement industry are: energy efficiency, fuel switching, clinker substitution, use of alternative materials instead of cement (e.g. engineered wood and high-performance polymers) and carbon capture, utilization, and storage (CCUS). Different policy tools can help accelerate a transition and create incentives to clean up cement not just in California, but in other states and regions that supply the California market.

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Appendices

Appendix 1. List of Acronyms

ASTM	American Society for Testing and Materials
$CaCO_3$	limestone
CaO	lime
CCUS	carbon capture, utilization, and storage
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
GJ	gigajoules
GHG	greenhouse gas
kg	kilogram
kt	kilo tonne
kWh	kilowatt-hour
MMBtu	million metric Btu
Mt	million metric tonnes
NSP	new suspension preheater
PM	particulate matter heater
R&D	research and development
SCMs	supplementary cementitious materials
SO_2	sulfur dioxide
USGS	United States Geological Survey

Appendix 2. List of Figures