

DEEP DECARBONIZATION ROADMAP FOR THE CEMENT AND CONCRETE INDUSTRIES IN CALIFORNIA



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Executive Summary

Cement production is one of the most energy-intensive and highest carbon dioxide (CO₂) emitting manufacturing processes. In fact, the cement industry alone accounts for more than 6% of total anthropogenic CO₂ emissions in the world. California is the second-largest cement producing state in the United States after Texas. California's eight cement plants together produced 10 million metric tonnes (Mt) of cement and emitted 8.2 MtCO₂ in 2017 (This also includes indirect emissions from electricity consumption).

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.

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

Around 60% of the total CO₂ emissions from California's cement industry are process-related emissions from calcination of limestone in the kiln, while the remaining 40% are energy-related emissions from fuel combustion and electricity consumption (Figure ES1).

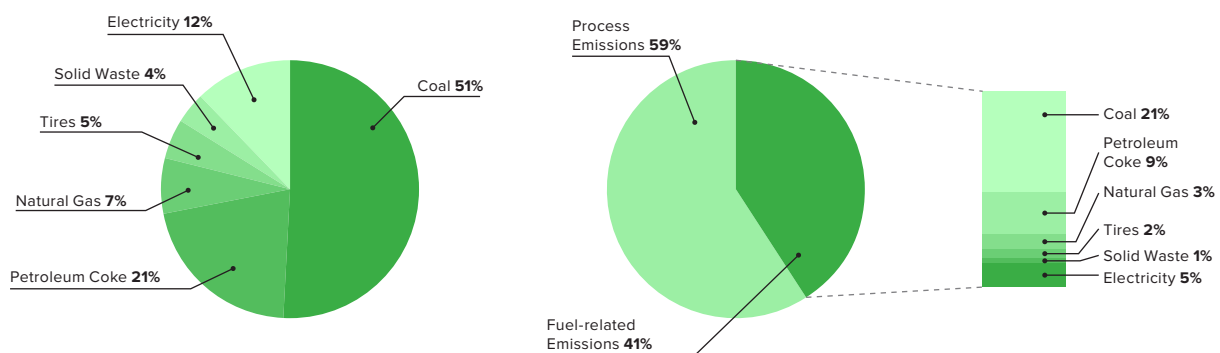


Figure ES1. Final energy use mix in California's cement industry in 2015 (left); Sources of CO₂ emissions in California's cement industry in 2015 (right)

In early 2019, we published a report titled "California's Cement Industry: Failing the Climate Challenge" (Hasanbeigi and Springer, 2019). In that report we analyzed the current status of cement and concrete production in California, and benchmarked the energy use and CO₂ emissions intensity of the state's cement industry in comparison to other key cement-producing countries. The study presented in this report is a follow up to that study.

The goal of this study is to develop a roadmap for decarbonization of California's cement and concrete production. In this study, we look at the current status of cement and concrete production in California and develop scenarios up to 2040 to analyze different decarbonization levers that can help to reduce CO₂ emissions of cement and concrete production in California.

We included four key major decarbonization levers in our analysis, which are: energy efficiency, fuel switching, clinker substitution, and carbon capture, utilization, and storage (CCUS).

Under our Advanced scenario, the total CO₂ emissions from California’s cement industry will decrease by 68% in 2040 compared to 2015 level, while the cement production increases by 42% in the same period.

Our scenario analysis up to 2040 shows that under the business-as-usual (BAU) scenario, which assumes no significant changes in current policies and market practices, the total CO₂ emissions from California’s cement industry will increase from 7.9 MtCO₂ per year in 2015 to 10.7 MtCO₂ per year in 2040, a 36% increase. Under our Advanced Technology and Policy (Advanced) scenario, however, the total CO₂ emissions from California’s cement industry will decrease to about 2.5 MtCO₂ per year in 2040, a 68% reduction compared to the 2015 level (Figure ES 2). This is while the cement production in California is assumed to increase by 42% from 9.9 Mt in 2015 to 14.1 Mt in 2040.

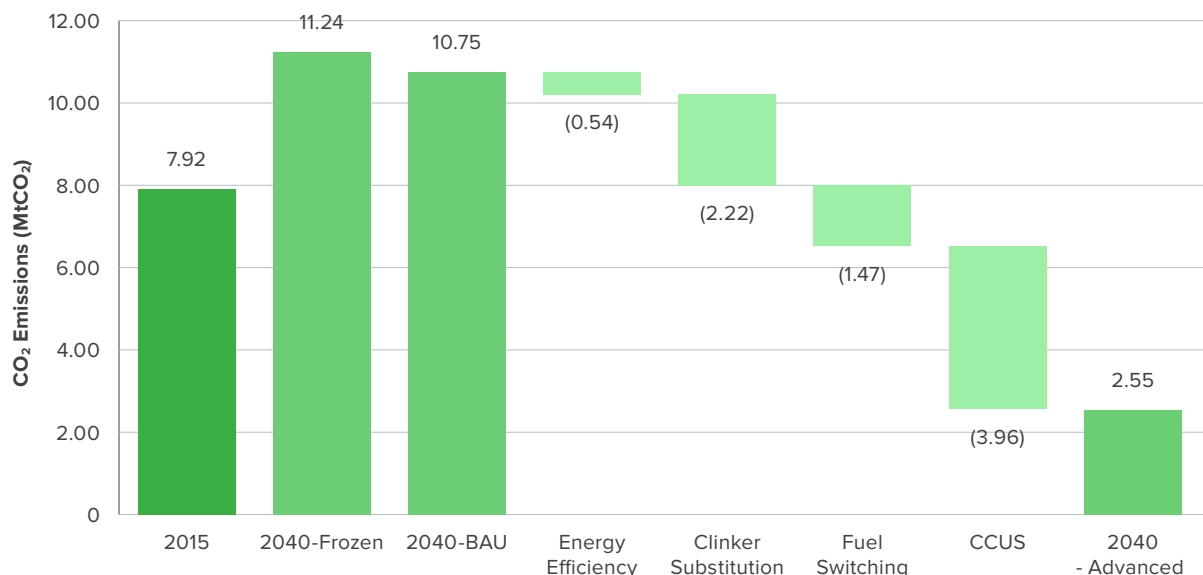


Figure ES 2. The impact of CO₂ emissions reduction levers on emissions from California’s cement industry up to 2040

The difference between the CO₂ emissions of California’s cement industry in the BAU and Advanced scenarios in 2040 is equal to emissions from around 1.8 million passenger cars per year or annual electricity-related CO₂ emissions of around 4.9 million households in California.

Carbon capture utilization and storage (CCUS) could make the largest contribution to CO₂ emissions reduction in California’s cement industry through 2040, followed by clinker substitution (i.e. replacing clinker with SCMs in cement or in concrete) and fuel switching. Energy efficiency (EE) technologies provide additional CO₂ emissions reductions potential.

Our Advanced Technology and Policy decarbonization scenario is completely achievable with commercially available and cost-effective technologies and measures except for CCUS technologies which are emerging technologies with some technologies requiring more demonstration and financial support. Policy tools such as the California cap-and-trade program, the Buy Clean California Act, and the 45Q tax credit for CCS should be leveraged to incentivize both cement and concrete producers to move towards low-carbon cement and concrete production.

In addition to decarbonization levers included in our analysis and discussed above, there are other options for reduce the CO₂ emissions footprint of cement and concrete production. For example, alternative raw materials and products for cement and concrete production (not based on Portland cement) can help to reduce CO₂ emissions from the cement industry. Also, the use of alternative materials in construction can help to reduce the demand for cement and concrete products.

We believe with the right set of policies and partnership between industry and regulators, California's cement and concrete industry not only can become one of the cleanest in the world, but it could go beyond that and show the world how the cement and concrete industry can move towards deep decarbonization in order to meet Paris Climate Agreement's goal to keep the increase in global average temperature to well below 2 °C above pre-industrial levels.

Table of Contents

Executive Summary	2
1. Introduction	6
2. Overview of the Cement and Concrete Industries in California	8
2.1. The status of the cement and concrete industries in California	8
2.2. Energy use and CO ₂ emissions in the cement industry in California	10
3. Decarbonization Roadmap for California’s Cement and Concrete Industry	16
3.1. 2040 pathways	16
3.2. Decarbonization roadmap	19
3.3. Energy efficiency impact	21
3.4. Clinker substitution impact	22
3.5. Fuel switching impact	27
3.6. Carbon capture, utilization, and storage (CCUS) impact	32
4. Policy, Regulatory, and Market Recommendations	36
References	38
Appendices	41
Appendix 1. Description of Cement and Concrete Production	41
A.2.1. Cement production processes	41
A.2.2. CO ₂ impact of cement production	44
A.2.3. Concrete production process	44
Appendix 2. List of acronyms	45
Appendix 3. List of figures and tables	46

The cement industry is the largest consumer of coal in California. 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 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 CO₂ emissions from the cement industry if no substantial actions are taken by the government and industry sector.

Cement is used as the binder in concrete, which is by mass the most common manufactured product worldwide. Cement production is one of the most energy-intensive and highest carbon dioxide (CO₂) emitting manufacturing processes. In fact, the cement industry alone accounts for more than 6% of total anthropogenic CO₂ 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 (SO₂), and nitrogen oxide (NO_x).

A major difference between the cement industry and most other industries is that fuel consumption is not the dominant source of CO₂ emissions. Around 60% of the CO₂ 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 CO₂ emissions are required to reduce the carbon footprint of cement and concrete.

In early 2019, we published a report titled "California's Cement Industry: Failing the Climate Challenge" (Hasanbeigi and Springer, 2019). In that report we analyzed the current status of cement and concrete production in California and benchmarked the energy use and CO₂ emissions intensity of the state's cement industry in comparison to other key cement-producing countries. The study presented in this report is a follow up to that study.

The goal of this study is to develop a roadmap for decarbonization of California's cement and concrete production. In this study, we developed scenarios up to 2040 to analyze different decarbonization levers that can help to reduce CO₂ emissions of cement and concrete production in California. We included four key major decarbonization levers in our analysis, which are: energy efficiency, fuel switching, clinker substitution, and carbon capture, utilization, and storage (CCUS).



Overview of the Cement and Concrete Industries in California

2.1. 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 eight cement plants in 2017 (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 1 shows the location of cement plants, offices, and cement distribution terminals in California.



Figure 1. The 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 10 Mt of cement in 2017. California's cement consumption in 2017 was about 9.5 Mt (van Oss 2018a). Figure 2 shows the cement and clinker production in California between 2000 and 2017. 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.

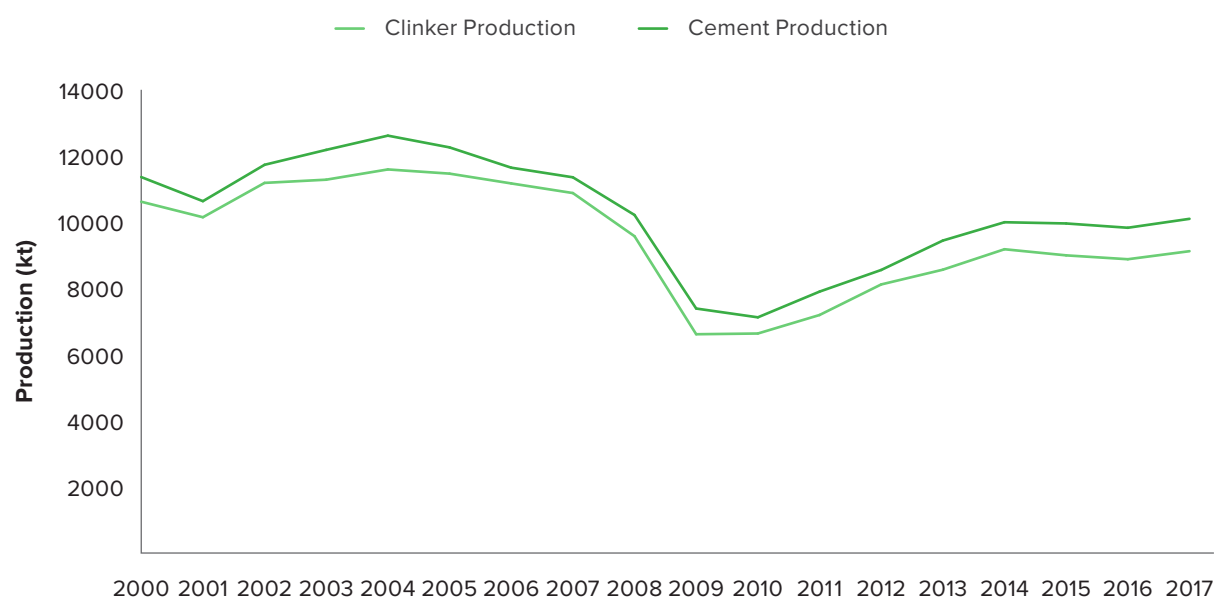


Figure 2. Cement and clinker production in California, 2000-2017 (van Oss 2017, 2018a)

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. Around 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).

Ready-mixed concrete manufacturers in California produced around 24.7 million m³ (32.3 million yd³) 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).

2.2. Energy Use and CO₂ 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 (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. 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.

Although the production and emissions data are available up to 2017, detailed energy use by fuel type was only available up to 2015. That is why 2015 is chosen as the base year for our analysis in this study.

Figure 3 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). The drop in electricity intensity can mainly be attributed to upgrade to more efficiency grinding mills in some plants.

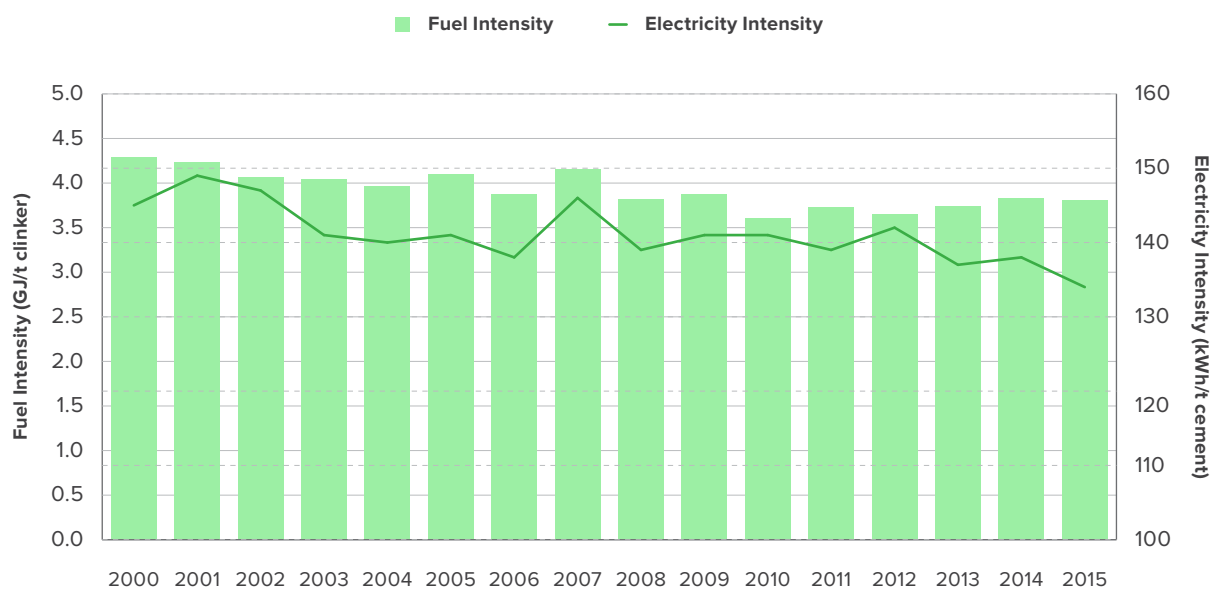


Figure 3. Fuel and electricity intensity of the cement industry in California, 2000-2015

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 4 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%.

The main reason CA cement plants use large of dirty and polluting petroleum coke is that CA has a large refining industry and petroleum coke is a refinery byproduct, so it's locally available in large amount. That is one of the forces of inertia holding back a switch away from petroleum coke in CA cement plants.

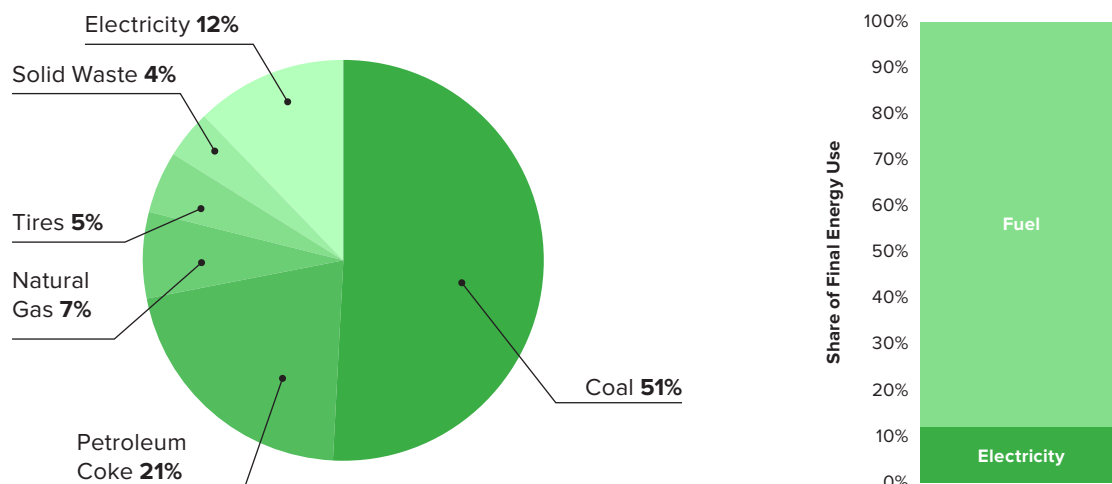


Figure 4. Energy mix in California's cement industry in 2015 (van Oss 2018a)

In California's cement industry, process-related CO₂ emissions from calcination accounted for 59% of total CO₂ emissions in 2015 while energy-related CO₂ emissions account for 41% of total emissions (Figure 5). In other words, 59% of the CO₂ emissions from California's cement industry are not associated with energy use (calculated using USGS and CARB data). Therefore, deep decarbonization in the cement industry cannot be achieved by best available energy efficient technologies or fuel switching alone. Clinker substitution and CCUS are imperative among commercialized technologies in order to achieve near zero emissions in the cement production. Another point to note here is that electricity accounts for only 5% of total California's cement industry's CO₂ emissions.

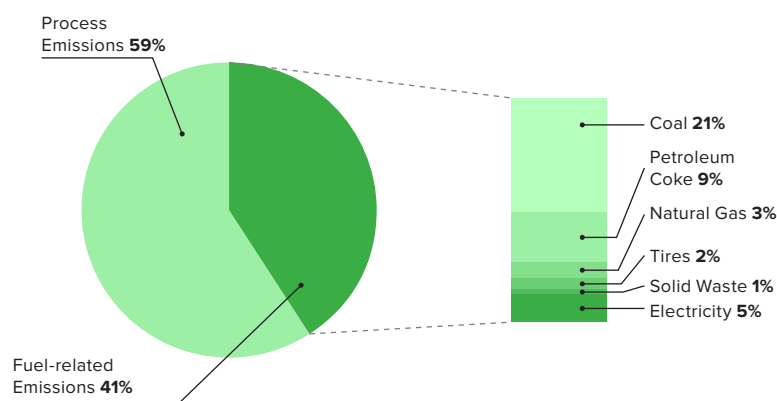


Figure 5. Sources of CO₂ emissions in California's cement industry in 2015

Figure 6 shows the time-series CO₂ emissions for California’s cement industry by emissions source during 2000-2015. The total CO₂ 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 CO₂ emissions during this period. The sudden drop in total CO₂ emissions during 2008-2010 is because of 2008 financial crisis, which resulted in substantial reduction in cement demand.

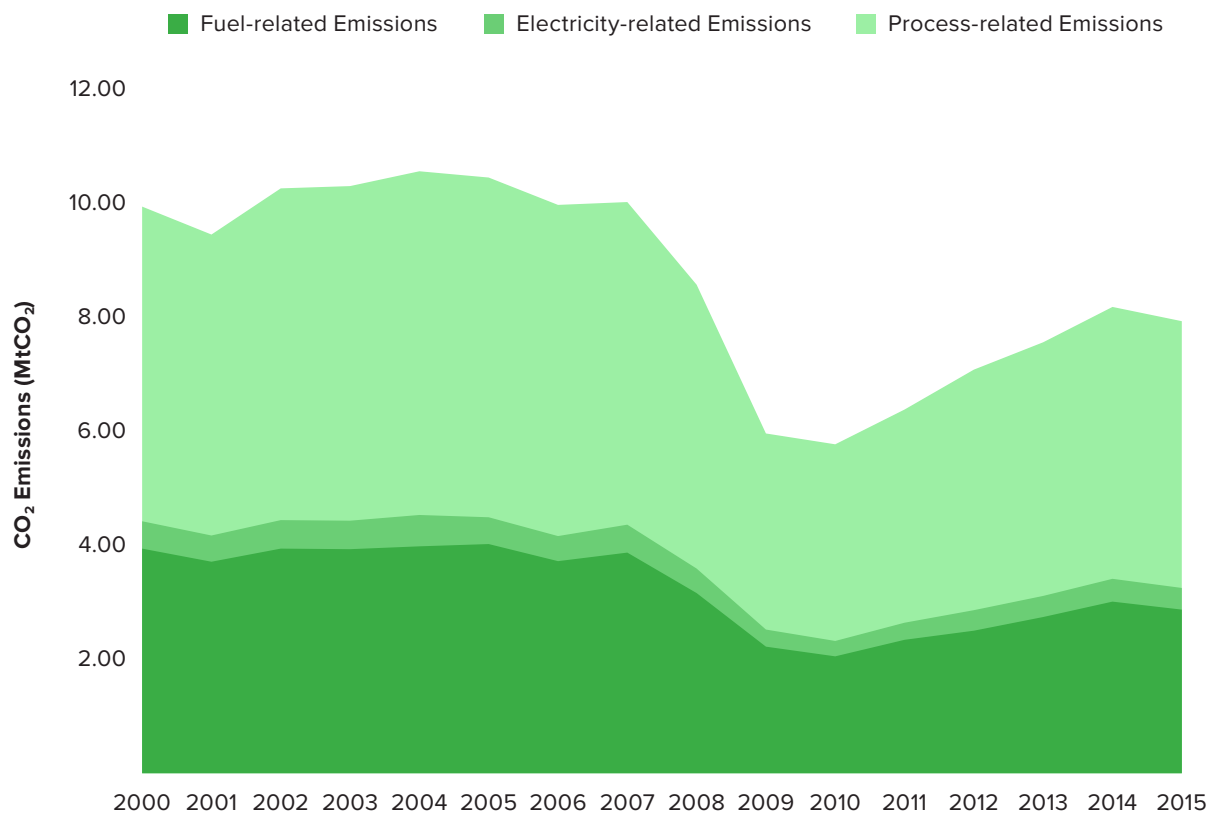


Figure 6. CO₂ emissions in the cement industry in California by emissions source, 2000-2015

Both fuel combustion- and electricity-related CO₂ emissions intensity in California’s cement industry decreased during 2000-2015. The fuel-related CO₂ emissions intensity dropped by 17% mainly because of fuel efficiency improvement resulted from upgrades to more efficient preheater-precaciner kilns in several cement plants during this period. In addition, increased use of natural gas in the cement industry during this period helped to reduce CO₂ emissions intensity. The electricity-related CO₂ emissions intensity dropped by 10% during 2000-2015 and is mainly due to electricity efficiency improvements in cement plants (e.g. use of more efficient grinding mills) and lower carbon intensity of the electricity grid in California.

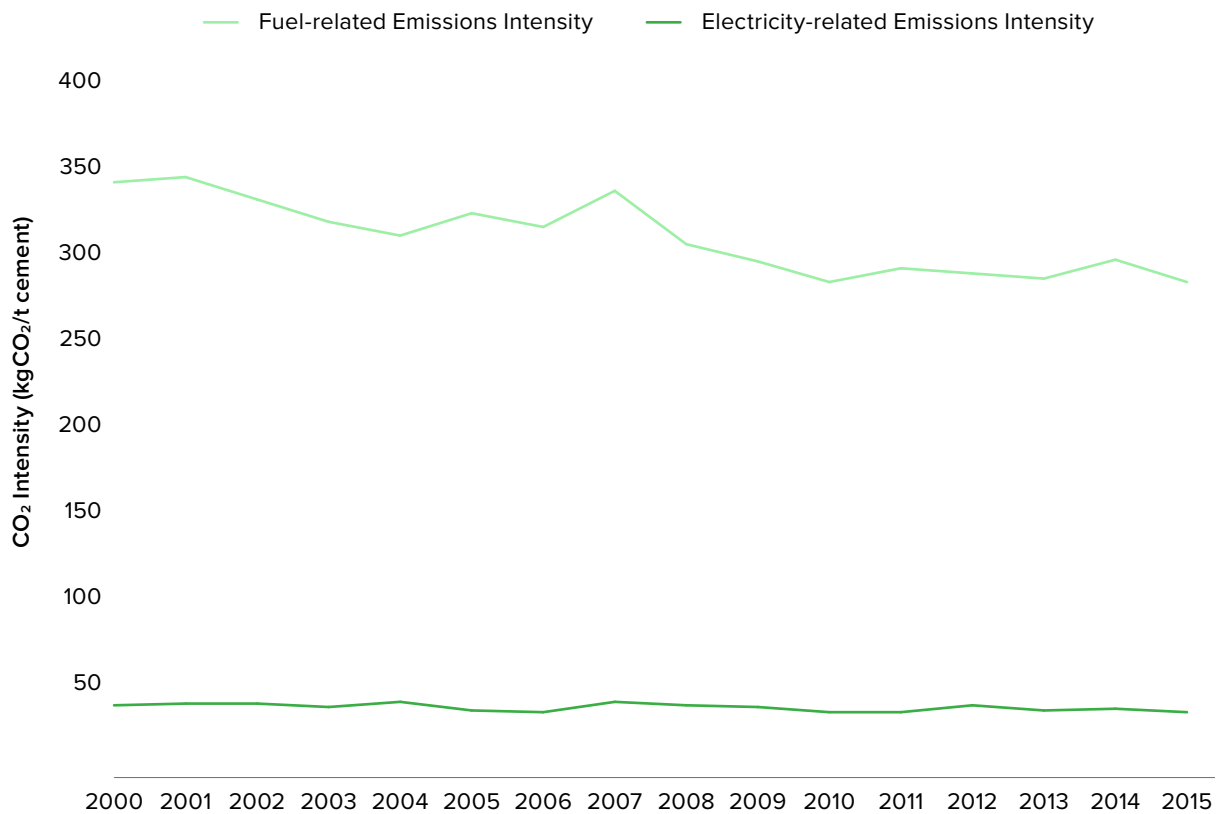


Figure 7. Fuel and electricity-related CO₂ emissions intensity in the cement industry in California, 2000-2015

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 2017, 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 a higher cement production in 2017.

Table 1. Plant-level GHG emissions of cement plants in California in 2017* (CARB 2018)

Company	Plant Location	2017 GHG Emissions (ktCO ₂ e)
CalPortland	Mojave	1,103,128
CalPortland	Oro Grande	1,025,122
CEMEX	Victorville	2,057,688
Lehigh Hanson	Cupertino	831,772
Lehigh Hanson	Redding	270,980
Lehigh Hanson	Tehachapi	599,316
Mitsubishi	Lucerne Valley	1,258,740
National	Lebec	722,466

* The plant level GHG emissions data are direct emissions from cement plants and do not include indirect emissions from electricity used by plants. If we add the electricity-related emissions estimated based on recent years electricity use adjust for variation in cement production in each year, the cement industry in California emitted 8.2 MtCO₂ in 2017. Also, CO₂ emissions accounts for 99.6% of total GHGs emitted by cement plants. The share of other GHGs emitted is minimal.

In early 2019, we published a report titled “California’s Cement Industry: Failing the Climate Challenge” (Hasanbeigi and Springer, 2019). In that report we analyzed the current status of cement and concrete production in California, and benchmarked the energy use and CO₂ emissions intensity of the state’s cement industry in comparison to other key cement-producing countries. Our results show that California’s cement industry has the highest energy intensity and CO₂ emissions intensity compared to the other 12 countries studied. In the next sections we will shows and discuss a roadmap for deep decarbonization of California’s cement and concrete industry.

We believe California’s cement and concrete industry not only should strive to become one of the cleanest in the world, but it could go beyond that and show the world how the cement and concrete industry can move towards deep decarbonization in order to meet Paris Climate Agreement’s goal to keep the increase in global average temperature to well below 2 °C above pre-industrial levels.



3.1. 2040 Pathways

After analyzing the current status of California's cement and concrete industry and its energy and CO₂ intensity, and comparing them with other countries/regions, we developed a decarbonization roadmap for California's cement and concrete industry. In this subsection, we present some of the key assumptions and indicators used in our roadmap development. We developed two main scenarios:

1. **Frozen scenario:** The Frozen scenario assumes that energy intensity, fuel mix, clinker-to-cement ratio, and carbon capture or utilization¹ stay at the 2015 level during the study period (2015-2040). Cement production in the Frozen scenario is similar to that in the BAU scenario.
2. **Business as Usual (BAU) scenario:** The BAU scenario assumes slow improvement in energy efficiency and slow adoption of commercially available CCUS technologies, which is likely to happen with current business practices and current policies and regulations.
3. **Moderate Technology and Policy (Moderate) scenario:** This scenario assumes higher energy efficiency improvement, more fuel switching to lower carbon fuels, and a higher rate of clinker substitution compared to BAU. It also assumes low adoption of commercially available CCUS technologies.
4. **Advanced Technology and Policy (Advanced) scenario:** This scenario assumes significantly higher energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower carbon fuels, and a higher rate of clinker substitution similar to today's world best practice. It also assumes higher adoption of commercially available CCUS technologies. It should be noted that all suggested improvements in the Advanced scenario can be achieved by implementing existing commercially available and mostly cost-effective technologies. For carbon capture and storage technologies, however, while the technologies are commercially available, the implementation require substantial investment that demand financial incentives or higher carbon price.

The first step in developing the pathways was to make a projection for cement and clinker production in California during the period 2015 to 2040 (Figure 8). We revised a previous projection made by Kumar and Gandhi (2016) based on the historical cement per capita in the past 25 years and California population projections up to 2040. We project that the annual cement production in California increases by 42% between 2015 and 2040. The difference in clinker production between the BAU and Advanced scenarios is because of different clinker-to-cement ratio assumptions in this scenario with a lower ratio in the Advanced scenario².

¹ It should be noted that there was zero carbon capture in CA cement plants in 2015.

² It should be noted that materials efficiency (e.g. optimized concrete elements, reduced mass elements, element reuse, etc.) is out of scope of this study, since materials efficiency could change the demand outlook. In this study, the cement demand outlook is fixed between all scenarios.

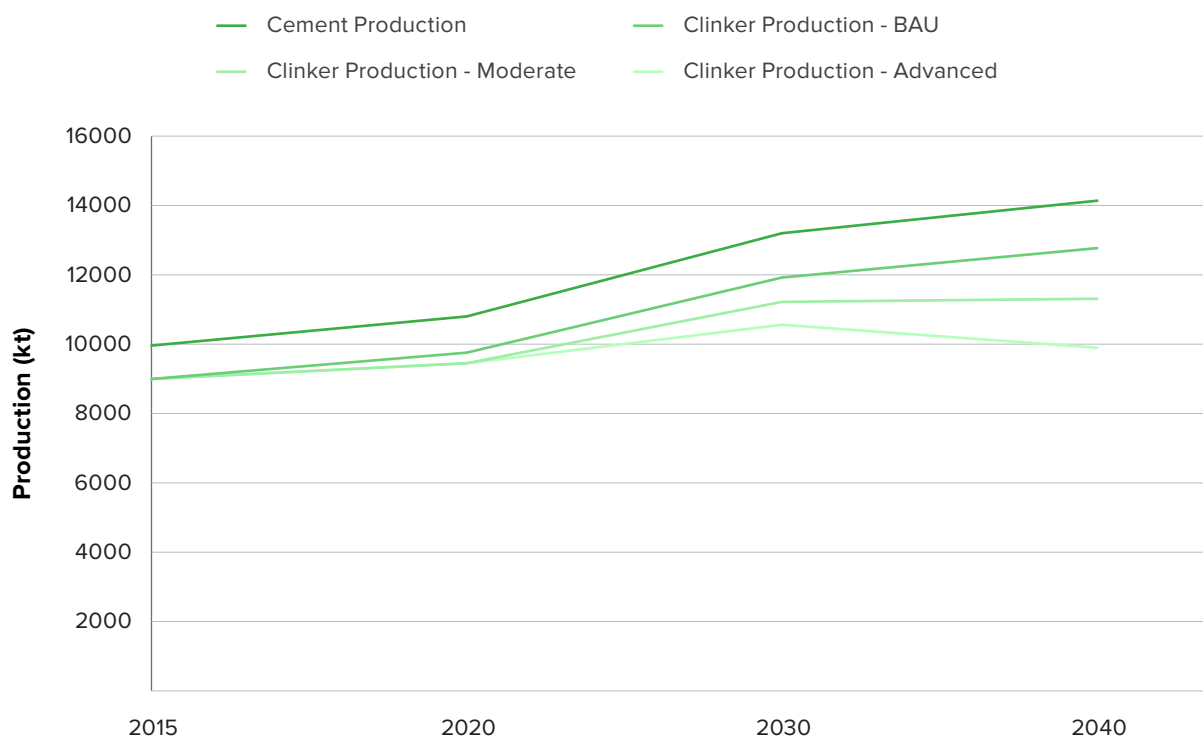


Figure 8. Annual cement and clinker production forecast for California, 2015-2040

Table 2 shows some of the key parameters and indicators for California’s cement industry and their projections up to 2040 under both the BAU, Moderate, and Advanced scenarios. We assumed that the clinker-to-cement ratio stays unchanged during 2015-2040 in the BAU scenario, which is a very likely assumption based on historical data (see Figure 2). In the Advanced scenario, however, this ratio decreases from 0.9 to 0.7. It should be noted that for this projection, we only accounted for supplementary cementitious materials (SCMs) that are added in the cement plants. As we explain in more detail in section 3.4, in the U.S. and California, unlike many other countries, a significant amount of SCMs are added during concrete production. We have considered the SCM production during the concrete production in CA in our analysis when assuming additional potential for increased use of SCM in California.

We assumed that the fuel intensity of California’s cement industry per tonne of clinker decreases by 8% and 19% between 2015 and 2040 under the BAU and Advanced scenarios, respectively. Further, we assumed that electricity intensity decreases by 14% and 41% between 2015 and 2040 under the BAU and Advanced scenarios, respectively. These energy intensities can be achieved by today’s commercially available technologies. For comparison, IEA/WBCSD (2018) assumes a fuel intensity of 3.1 GJ/t clinker and electricity intensity of 79 kWh/t cement in 2050 for their 2-degree scenario.

Table 2. Key parameters for California’s cement industry in the BAU, Moderate, and Advanced scenarios, 2015-2040

	Unit	2015	BAU Scenario			Moderate Scenario			Advanced Scenario		
			2020	2030	2040	2020	2030	2040	2020	2030	2040
Cement Production	kt	9,960	10,800	13,200	14,138	10,800	13,200	14,138	10,800	13,200	14,138
Clinker Production	kt	8,996	9,755	11,922	12,770	9,450	11,220	11,310	9,450	10,560	9,897
Clinker-to-cement ratio		0.90	0.90	0.90	0.90	0.88	0.85	0.80	0.88	0.80	0.70
Fuel Intensity	GJ/t clinker	3.81	3.71	3.60	3.50	3.70	3.56	3.40	3.65	3.41	3.10
Electricity Intensity	kWh/t cement	134	128	121	115	125	111	91	125	107	79
Process-related CO ₂ Emissions intensity*	kgCO ₂ /t cement	470	470	470	470	455	442	416	455	416	364
Fuel-related CO ₂ Emissions intensity *	kgCO ₂ /t cement	288	280	272	265	264	222	178	260	178	118
Electricity-related CO ₂ Emissions intensity *	kgCO ₂ /t cement	38	36	34	32	32	22	13	32	21	0.0

* These intensities are without application of CCUS.

In addition, we assumed a minimal amount of carbon utilization in the concrete industry and zero amount of carbon capture in the cement industry in California under the BAU. In the Moderate scenario we assumed in 2040, two CA cement plant has carbon capture technology, one with 50% and the other with 80% carbon capture efficiency. In the Advanced scenario, we assumed in 2040, six CA cement plants have carbon capture technology, three with 50% and the other three with 80% carbon capture efficiency. It should be noted that post-combustion carbon capture technologies can reach up to 95% capture efficiency, but because of the structure of cement kiln systems and the leakage that happen during carbon capture, it is hard to reach that high capture efficiency in cement plants. That’s why we have assumed 50% and 80% capture efficiency for cement plants in our study.

Finally, we made a projection of the fuel mix used in California’s cement industry (Figure 9) by shifting to lower carbon fuels. For example, in the Advanced scenario, we assumed the coal consumption in California’s cement industry will be reduced from 55% of fuel share to 5%, and petroleum coke use will be reduced to zero between 2015 and 2040, and natural gas, which has a much lower CO₂ emissions factor, will substitute these two fuels.

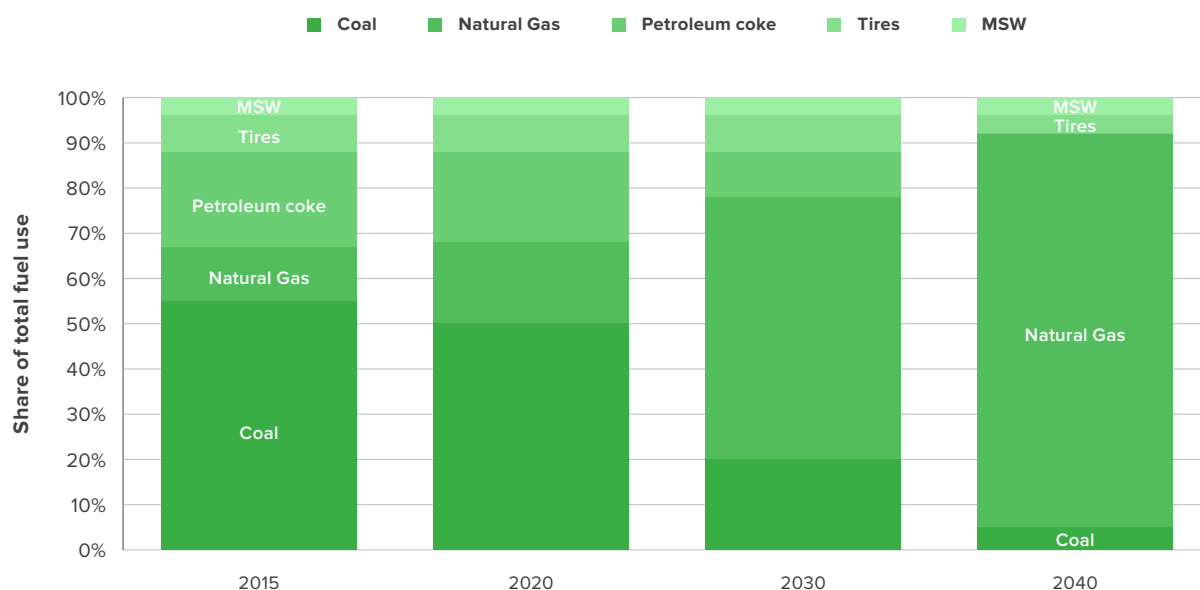


Figure 9. Fuel mix projections for California’s cement industry under Advanced scenario, 2015-2040

3.2. Decarbonization Roadmap

Based on the above assumptions, we forecasted the CO₂ emissions of California’s cement industry up to 2040 (Figure 10). In the BAU scenario, the CO₂ emissions of California’s cement industry increase by 36% between 2015 and 2040. In the Advanced scenario, however, the CO₂ emissions of the cement industry decrease by 68% from 7.9 MtCO₂ per year in 2015 to 2.5 MtCO₂ per year in 2040. This decrease in emissions occurs while cement production in California increases by 42% during the same period to continuously meet the needs of a growing population and expanding economy. The sharp reduction in the CO₂ emissions in advanced scenario in 2030 and 2040 is because of introduction of carbon capture in CA cement plants.

The Advanced scenario is completely achievable with commercially available and cost-effective technologies and measures except for CCUS technologies which are emerging technologies with some technologies requiring more demonstration and financial support. Policy tools such as the California cap-and-trade program, the Buy Clean California Act, and the 45Q tax credit for CCS should be leveraged to incentivize both cement and concrete producers to move towards low-carbon cement and concrete production. Policy, regulatory, and market implications of this study are discussed in more detail in the next chapter.

The difference between the CO₂ emissions of California’s cement industry under the BAU and Advanced scenarios in 2040 is equal to 8.2 MtCO₂ per year. This CO₂ emissions reduction is equal to emissions from around 1.8 million passenger cars per year or the annual electricity-related CO₂ emissions from around 4.9 million households in California.

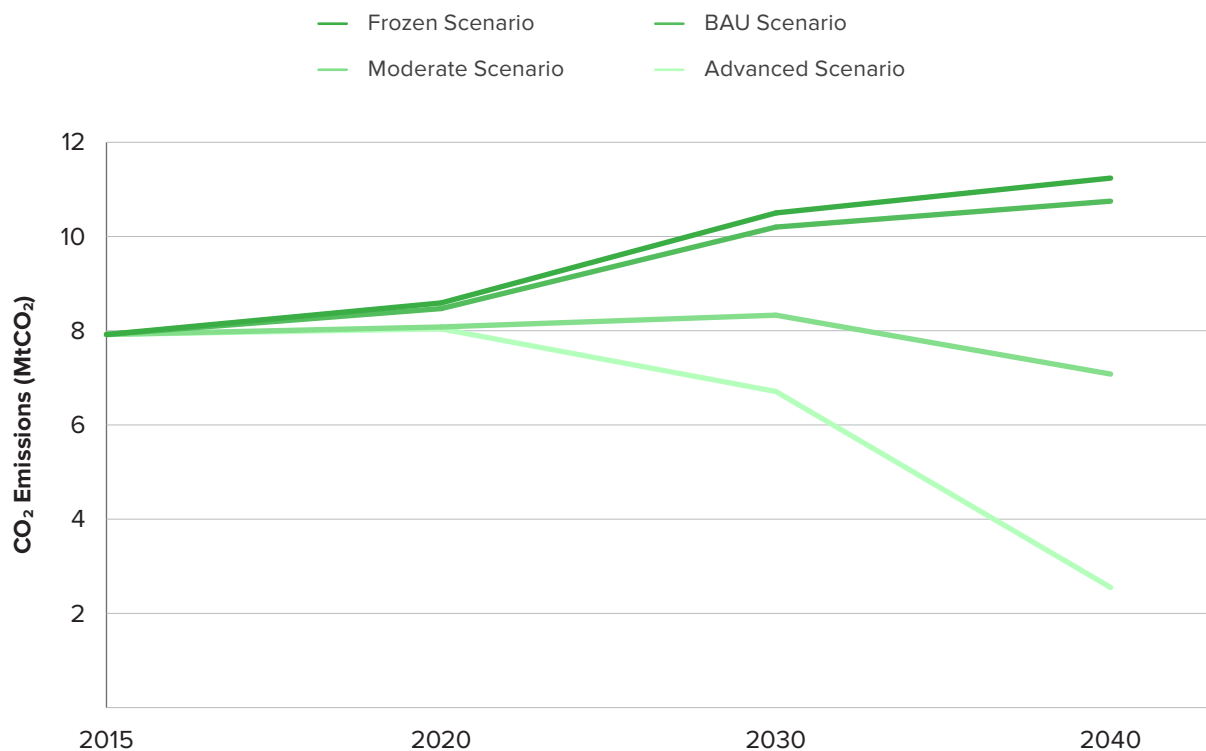


Figure 10. CO₂ emissions forecast for California’s cement industry by scenario, 2015-2040

If decarbonization levers are implemented more than BAU scenario, but at a slower pace and to a limited extent compared to that of Advanced scenario, then the CO₂ emissions reductions could be along the line of Moderate scenario, which will result in total CO₂ emissions in 2040 to be just slightly lower than 2015 level.

Different factors contribute to realization of CO₂ emissions reductions in the Advanced scenario. Figure 11 shows the contribution of each decarbonization lever (i.e. energy efficiency, clinker substitution, fuel switching, and CCUS) to reduction in the cement industry’s CO₂ emissions in California between 2015 and 2040. It is clear that CCUS makes the largest contribution to CO₂ emissions reduction, followed by clinker substitution (i.e. replacing clinker with SCMs for cement production) and fuel switching to lower carbon fuels. The impact of each of these decarbonization levers and the policy, market, and technical requirements for their adoption in California’s cement industry is discussed in detail in the following sections.

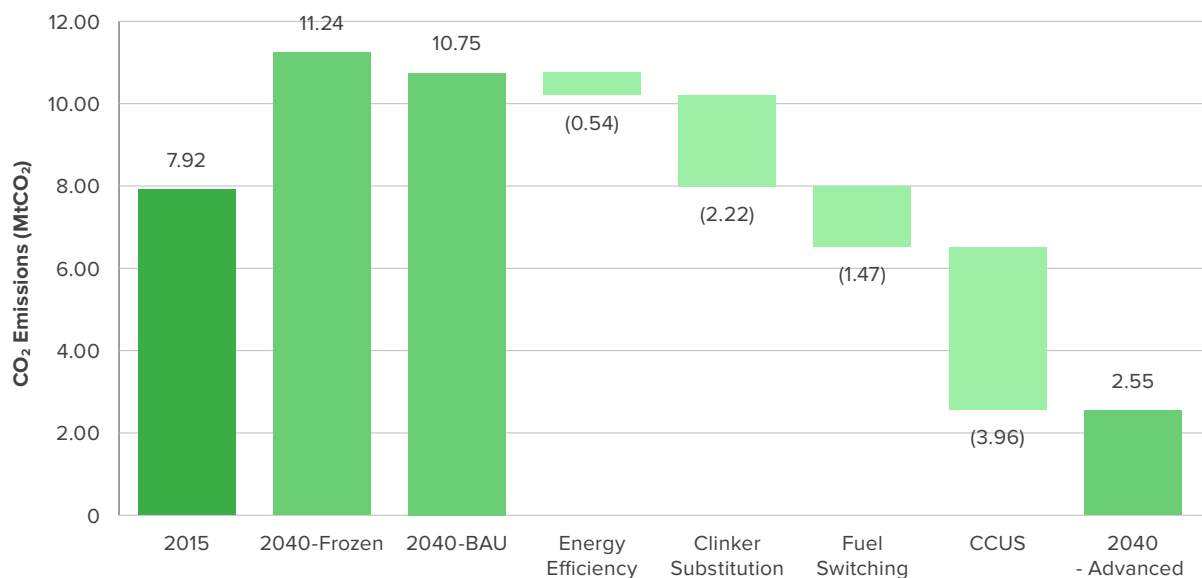


Figure 11. The impact of CO₂ emissions reduction levers on emissions of California's cement industry to 2040

3.3. Energy Efficiency Impact

Different studies have shown energy efficiency improvement opportunities in the cement industry around the world by implementation of commercially available technologies and measures (Worrell et al. 2013, Hasanbeigi et al. 2010, 2013, Morrow et al. 2014). Even so, Figure 11 shows that energy efficiency has the smallest contribution to CO₂ emissions reduction in California's cement industry up to 2040 compared to other decarbonization levers (0.54 MtCO₂ reduction per year in 2040 compared to the BAU scenario). This is mainly because process-related emissions from calcination account for around 60% of total CO₂ emissions from the cement industry and are not associated with energy use. As a result, energy efficiency measures only impact about 40% of the cement CO₂ emissions.

Among various energy efficiency technologies and measures, one important technology worth highlighting is waste heat recovery (WHR) power generation technology for cement plants. This technology uses a portion of the medium temperature (200-400°C) waste heat of kiln flue gases to generate electricity. Although it does not reduce the amount of electricity used at a cement plant, it uses the excess heat that otherwise would be wasted in order to generate electricity for on-site use or export to the grid. Typically, electricity generation by WHR power generation technology is around 10-25 kWh/t of clinker produced. The electricity output depends on various factors such as kiln configuration, the moisture content of the raw materials, preheater configuration, etc. Several countries such as China, India, Japan, and S. Korea have a high share of installation of WHR power generation technology ranging from 30% to 90% of each country's cement production capacity. China has the highest implementation of WHR power generation technology in the cement industry, with around 90% of its domestic clinker production capacity equipped with this technology (IEA/WBCDS 2018). This technology has a very low adoption rate in the U.S. cement industry and there is no WHR power generation implemented in California's cement plants.

All of California's cement plants now use the dry process with multi-stage preheater/precalciner systems (Van Oss 2018c, CARB 2013). Improving energy efficiency beyond the levels we have assumed in our Advanced scenario in 2040 will require new technological development and a significant overhaul of existing equipment in some of the cement plants in California and large capital investments by 2040, which is less likely to happen. Also, there are other more cost-effective options for California to consider in the short and medium term such as clinker substitution and fuel switching that will result in larger CO₂ emissions reductions. Our finding on the potential contribution of energy efficiency to decarbonization of the cement industry is also consistent with the International Energy Agency findings for the world's cement industry (IEA/WBCSD 2018).



3.4. Clinker Substitution Impact

All the fuel use and around 60% of the electricity used in a cement plant is 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 materials such as fly ash, blast furnace slag, natural pozzolans, ground limestone, and calcined clay can help to significantly reduce energy intensity per tonne of cement produced. Figure 11 shows that clinker substitution makes the second largest contribution to CO₂ emissions reductions in California's cement industry up to 2040 (around 2.2 MtCO₂ reduction per year in 2040 compared to the BAU scenario).

China has the lowest clinker-to-cement ratio (0.58), while the U.S. and California's cement industry have one of the highest clinker-to-cement ratios (0.9) (IEA/WBCSD 2018, van Oss 2018a). In other words, China uses a higher share of SCMs in cement production, while the U.S. and California use significantly less SCMs during cement production.

However, unlike many other countries, in the U.S. and California, the common practice is that SCMs are mostly added during concrete production and not cement production. Other countries also do add SCMs during concrete production but not as much as concrete plants in the US. 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. This is an important factor to consider when assessing California's cement industry energy use and emissions. Also, this is the primary reason why the concrete industry is included within the scope of this study. When we suggest or assume higher use of SCMs, this increase can be either in the cement plants or concrete plants in California. Either way, it will result in a decrease in the energy and carbon footprint of the final product (i.e. per m³ of concrete). In our Advanced scenario, we assumed the clinker-to-cement ratio decreases from 0.9 in 2015 to 0.7 in 2040. Assuming 5% use of gypsum in cement production, this will result in an increase in the use of SCMs in California cement plants from 5% in 2015 to 25% in 2040. It should be noted that, as mentioned above, another 13% of SCMs are added during concrete production. That will give a total proportion of 38% SCMs in concrete in 2040, which is still lower than today's SCM use in China, but is a significant improvement.

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. Below we briefly discuss availability and some other issues related to each of these SCMs.

It should be noted that while fly ash and GGBFS have been used as SCMs for many years around the world, there are eco-toxicity concerns among environmentalists for the use of these two materials as SCMs. Therefore, required protocols need to be in place and followed for handling and processing of these two SCMs to avoid any negative environmental impact.

Fly ash is separation of dust particles from flue gases produced mainly in coal-fired power plants. The use of fly ash is usually limited to 25-35% on a mass basis in cements for technical performance reasons (IEA/ WBCSD 2018). Around 45% of fly ash generated in the U.S. is re-utilized, of which about 50% is used in concrete production (Obla et al. 2012). In the U.S., fly ash production is projected to remain at the current level in the medium-term (Figure 12) (ARTBA 2015). Since only less than half of the fly ash available is currently utilized, there is good potential for increased beneficial use of fly ash. ARTBA (2015) predicts an increase in the utilization rate of fly ash up to 2033, primarily driven by use of fly ash in ready-mixed concrete (Figure 13).

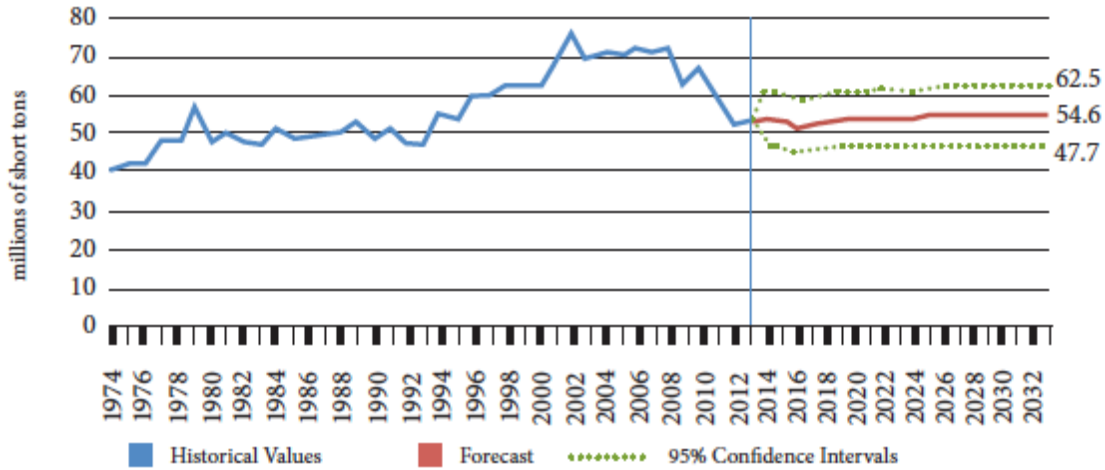


Figure 12. Fly ash production in the U.S., 1974-2033 (ARTBA 2015)

Fly ash costs less than Portland cement. Although the specific costs of fly ash will vary from state to state. For example, since there are no coal power plants in California, there are other issues that are unique to California that relate to the transportation logistics of moving fly ash to California from other states where it is predominantly produced. The transportation costs will lead to an increased price for fly ash upon delivery in California. Northern California fly ash is supplied from Arizona and Wyoming, while southern California sources fly ash from Arizona, Nevada and Utah (Caltrans 2016). Also, there will be a significant decline in the use of coal in the US electric power sector in coming decades, which will limit the availability of fly ash in the U.S. There is also abundant fly ash available in China and other countries that can be imported by California if needed. A detailed study needs to be done to quantify the cost and GHG emissions implications if California were to import fly ash from other countries.

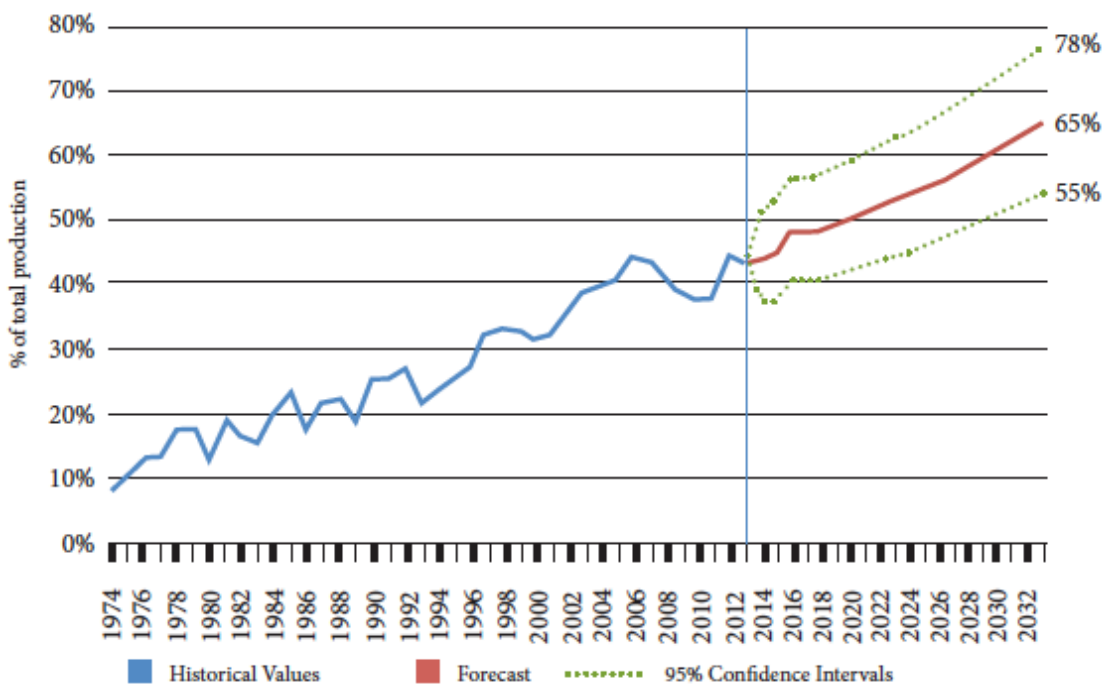


Figure 13. Fly ash utilization rate in the U.S., 1974-2033 (ARTBA 2015)

It should be highlighted that this study does not recommend or advocate for coal-fired power generation for the purpose of fly ash availability for cement and concrete production. However, there will still be coal-fired power generation in the U.S. and other countries in near-and medium-term. The fly ash produced as waste by these coal power plants can be beneficially used in production of cement and concrete and help to reduce the GHG footprint of these products. In the longer-term, we recommend the use of other naturally available SCMs such as natural pozzolans, calcined clay, and ground limestone.

Another common SCM is ground-granulated blast-furnace slag (GGBFS). It is a coproduct from integrated iron and steelmaking plants. GGBFS can be integrated at higher proportions in cement and concrete than fly ash and other SCMs. European standards allow several cements with up to 95% GGBFS on a mass basis (IEA/WBCSD 2018), but usually a lower amount of GGBFS is used. Since less than 30% of the steel production in the U.S. is produced from integrated plants using Blast Furnace- Basic Oxygen Furnace (BF-BOF) process (with the remainder of steel being produced by the electric arc furnace (EAF) process), there is limited GGBFS available in the U.S. In addition, only two U.S. blast furnaces are equipped with granulation cooling and can readily produce GGBFS (van Oss 2018c). There is no local production of GGBFS in California since there is only one steel plant in CA and it uses the EAF process. Therefore, GGBFS has to be imported for use in cement and concrete production in California. There is a significant amount of GGBFS available internationally, since around 70% of world steel production uses the BF-BOF process, which produces substantial amount of GGBFS. In China, more than 90% of steel is produced by the BF-BOF process. It should be noted that decarbonizing the steel sector results in shifting away from blast furnaces, which will affect the availability of GGBFS worldwide in coming decade. However, this shift will be slow and gradual and, in the meantime, there is a good amount of GGBFS that will be available to be used as SCM in order to reduce carbon footprint of cement and concrete.

Natural pozzolans are another type of SCM that can be used worldwide in cement and concrete production. Natural pozzolans are mined from natural deposits. There are large natural pozzolan deposits in California. Natural pozzolans require drying and grinding before being used in cement or concrete production. This will require both fuel and electricity. Waste heat from cement plants can be used for drying. The electricity needed for grinding of natural pozzolans is almost the same amount as that for grinding the clinker that the natural pozzolans are substituting for. Therefore, the net increase in electricity use is negligible. However, natural pozzolans show different characteristics with water demand when used in concrete, so the use of admixtures may be necessary. There will be a learning curve for the use of natural pozzolans by cement and concrete producers in California, but fortunately there is abundant amount of experience available worldwide (Caltrans 2016).

Ground limestone is another common SCM and it appears to be the dominant SCM currently use by cement plants in California. Typically, the mass content of ground limestone in such cements is 25-35%, but in California it is usually below 15% (van Oss 2018c). It is estimated that cements using limestone as a filler represent 25-30% of global cement production, and that the share will increase by around 50% by 2050 (IEA/WBCSD 2018). Limestone is also the raw material for clinker production, so it is usually available near cement plants. Limestone needs to be ground to finer particles before being used in blended cement or concrete production, but limestone is much easier to grind than clinker. Therefore, there is no energy penalty when replacing clinker with limestone. The use of ground limestone in cement plants in California as SCM was about 20 kt in 2015 (van Oss 2018c). Substantial potential exists in increasing the use of ground limestone in cement and concrete production in California. Figure 14 shows ground limestone filler content in cement production in for selected regions of the world (UNEP 2016).

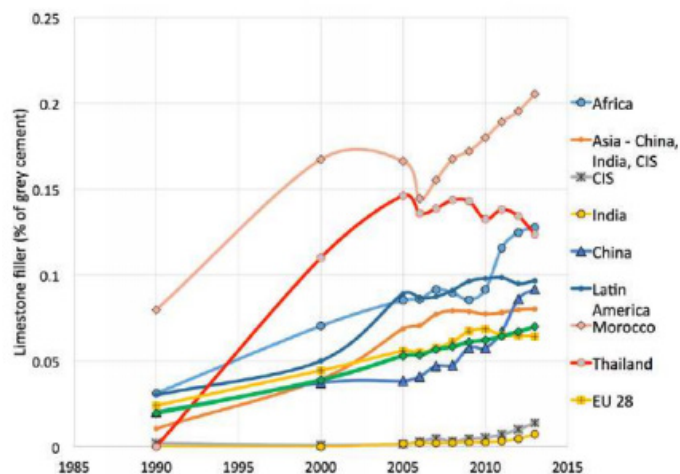


Figure 14. Ground limestone filler content in grey cement for selected regions (UNEP 2016)

Calcined clay is another SCMs that can be used in cement production to substitute for clinker. Brazil has been producing about 2 Mt of calcined clay per year since the 1970s. Early compressive strength of cement decreases with greater portions of calcined clay used due to the slower reaction kinetics of this cement constituent compared to clinker. However, recent developments suggest an optimized combination of calcined clay and ground limestone as cement constituents, potentially resulting in up to 50% clinker displacement without affecting cement properties (LC3 2018). IEA/WBCSD (2018) suggest that cements based on calcined clay and ground limestone will account for more than a quarter of cement in the world in 2050.

Clay is available abundantly in California and many regions in the U.S. It should be noted that energy is needed to calcine the raw clay before using it in blended cement production. However, the energy needed to calcine a tonne of raw clay is lower by far than the fuel needed for production of the clinker that calcined clay would be replacing.

Unlike many other countries where SCMs are mainly 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) conducted a survey of ready-mixed concrete producers in the U.S. on barriers to increased use of SCMs. Many participants listed lack of education on the part of specifiers and owners regarding the benefits of use of SCMs as the most important barrier to increased use of SCMs. As a result, stringent procurement criteria that do not favor higher share of SCMs in concrete production is considered as a major barrier. Some respondents listed cost and performance issues such as setting time and early age strength. A few mentioned lack of availability but that might have been a local issue, as availability of SCMs depends on the type of SCMs and the location of the plant. New standards and codes for increased use of blended cement and SCMs in cement and concrete production need to be developed in order to transform the market.



3.5. Fuel Switching Impact

Of total heat used (excluding electricity) in California's cement industry in 2015, around 55% came from coal combustion and 21% from petroleum coke. These are two of the most carbon-intensive fossil fuels. A shift away from these two fuels to less carbon-intensive fuels such as natural gas can significantly reduce GHG emissions from the cement industry. Our analysis (Figure 11) found that fuel switching can make the third largest contribution to CO₂ emissions reductions in California's cement industry up to 2040 (1.47 MtCO₂ reduction per year in 2040 compared to the BAU scenario).

Switching away from coal and petroleum coke to natural gas that is available in large quantity and can be easily used in cement plants with current technology is the main fuel switching option. The CO₂ emissions intensity of natural gas (kgCO₂/GJ) is less than 60% of coal and petroleum coke. Despite the significant reduction in the price of natural gas in recent years, there are still market barriers to natural gas use in California’s cement industry.

People or groups who oppose the use of natural gas in the cement industry, they practically support the use of much dirtier coal and petroleum coke.

According to energy prices published in the Annual Energy Outlook by the U.S. Department of Energy’s Energy Information Administration (U.S. DOE/EIA 2019), the price of coal and natural gas for the industrial sector in the Pacific region of the U.S. (which includes California) in 2018 were at \$4.6 and \$4.4 per MMBtu, respectively. However, U.S. DOE/EIA (2019) predicts that the price of natural gas will increase at a higher rate compared to the coal price for industry up to 2040 (Figure 15). This is explained by reduction in coal demand from the power sector, while natural gas demand increases for both the power and industry sectors. In addition, the projections point to larger natural gas exports (mostly to Asia), which will drive the natural gas price upwards. However, several other sources predict much lower rate of natural price increase in the U.S. by 2040 (World Bank 2018, McKinsey&Company 2018). Therefore, in our analysis, in addition to EIA’s natural gas price forecast, we also assumed a different scenario with slightly lower natural gas price increase up to 2040 compared to the prices given by EIA.

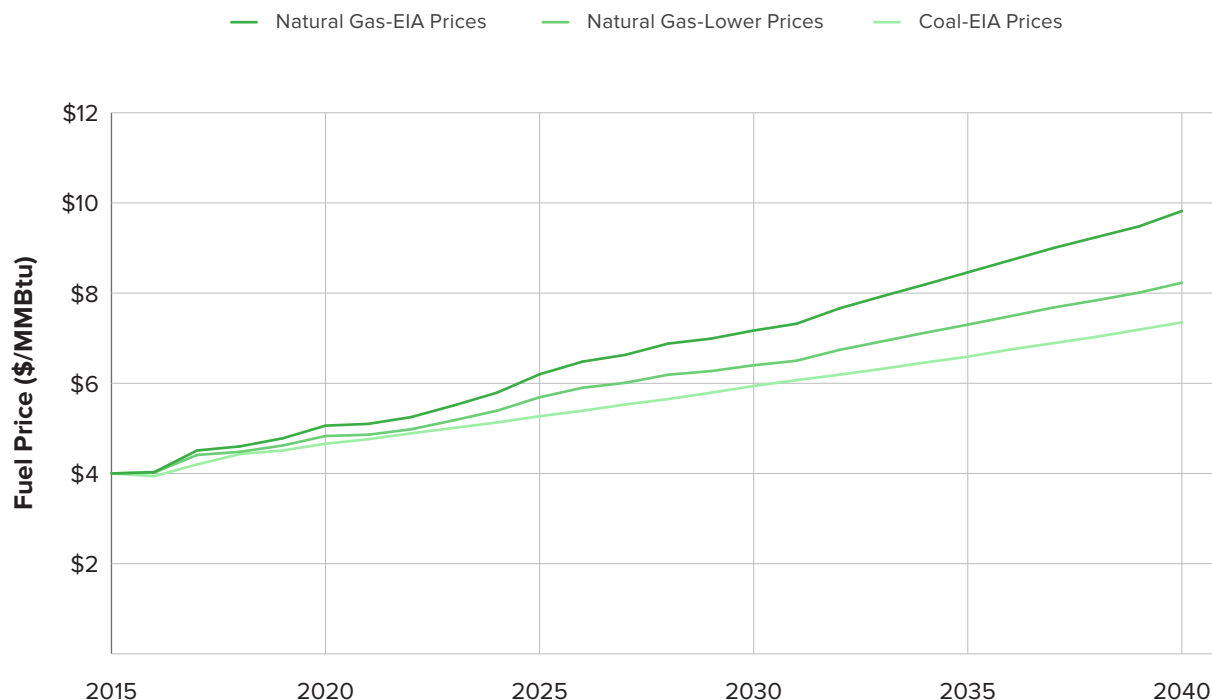
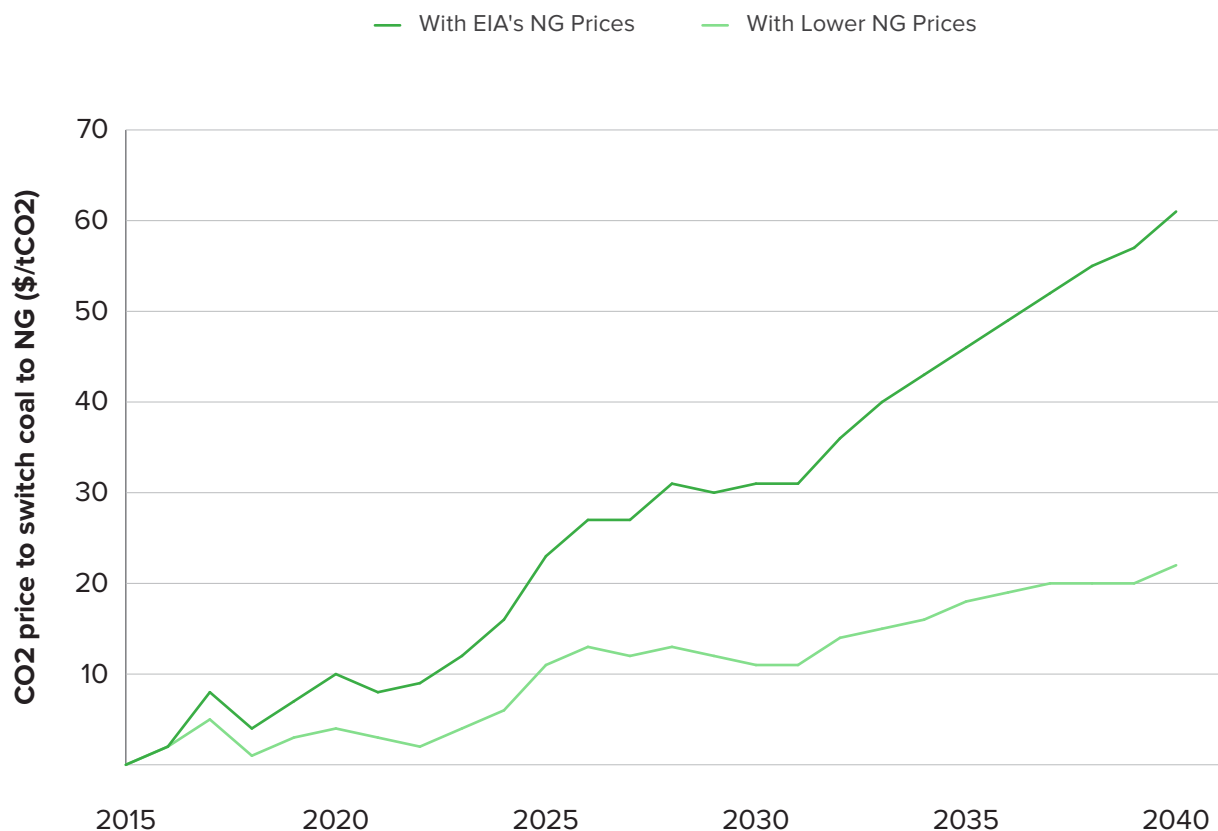


Figure 15. Projected price of coal and natural gas for industry sector in the Pacific region of the U.S., 2015-2040 (U.S. DOE/EIA 2019)

It should be noted that cement plants often have long term contract for fuel purchase. Since price of fuel paid in those contracts are not public information, we could not do our analysis using the actual price of energy paid by California cement plants. While this is a simplified analysis, it shows how carbon tax or credit policy and price on carbon can stimulate shift away from dirty coal and petroleum coke to cleaner natural gas in the cement industry.

Given the coal and natural gas price projections, in case of higher rate of natural gas price increase predicted by U.S. DOE/EIA (2019), it is unlikely that market forces alone will lead to switching from coal to natural gas in California’s cement industry. Therefore, there is a need for policy intervention to incentivize this fuel switching. One such policy could be through some form of a carbon tax or credit. We used the coal and natural gas prices for the industry sector in the Pacific region of the U.S. given by U.S. DOE/EIA (2019) as well as differences in the carbon intensity of coal and natural gas to calculate the carbon price needed for the California cement industry to switch from coal to natural gas. As can be seen from Figure 16, the carbon price (US\$/tCO₂) needed to switch from coal to natural gas in California’s cement industry increases from \$0 in 2015 to around \$60/tCO₂ in 2040 with EIA’s natural gas prices forecast or \$22/tCO₂ in 2040 with lower natural gas prices forecast. The price of carbon in California’s cap-and-trade program in the first quarter of 2018 was around \$15/tCO₂ (CCD 2018).



Note: These carbon prices are calculated for two scenarios based on fuel prices projections by U.S. DOE/EIA (2019) as well as our assumed lower prices for natural gas under one of the scenarios. Any change in fuel price projections can significantly affect the carbon price needed for switching from coal to natural gas in California’s cement industry.

Figure 16. Carbon price needed to switch from coal to natural gas in California’s cement industry, 2015-2040.

Borenstein et al. (2017) predict a probability-weighted expected carbon price in California in 2040 of \$52/tCO₂ in 2015 real dollars. Assuming a 2% annual average inflation rate during 2015-2040, this translates into a 2040 carbon price in California of \$70/tCO₂ in nominal dollars, which is much higher than the \$60 carbon price shown in Figure 16. Thus, it is possible that the carbon price in 2040 will exceed even our higher threshold price of \$60/tCO₂ and incentivize fuel switching. The energy and carbon prices given in Figure 15 and Figure 16 are all in nominal dollars.

It is worth mentioning that unlike coal and petroleum coke that need preparation (e.g. coal grinding) prior to burning in the kiln, natural gas does not need such preparation. Retrofits might be needed to install required natural gas pipelines to cement plants if they do not already have sufficient natural gas transport capacity, and in some cases, new kiln burner may be required.

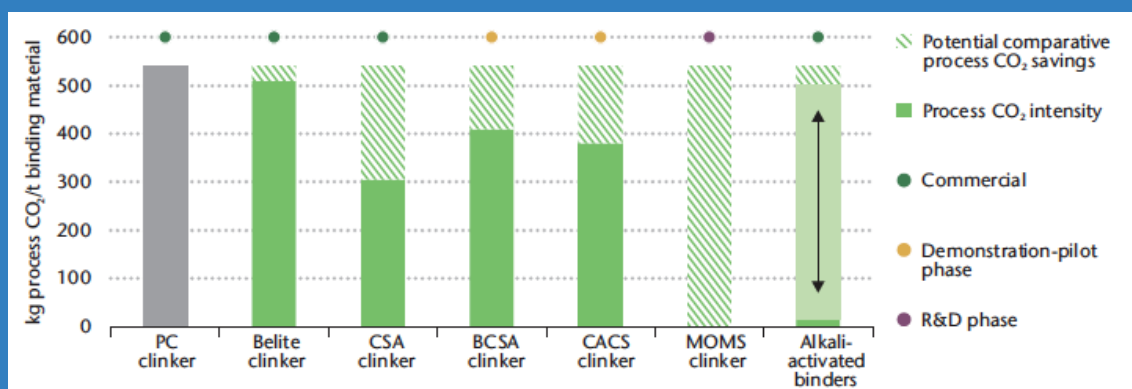
The shift from coal and petroleum coke to natural gas that is already occurring in the broader U.S. cement industry is even more proof that there are no technical barriers. According to the Portland Cement Association's labor-energy survey, in 2016 coal and petroleum coke had their lowest share of total energy use in the U.S. cement industry since 1976 and natural gas had its highest share since 1980.

In addition to decarbonization levers included in our analysis and discussed above, there are other options for reduce the CO₂ emissions footprint of cement and concrete production. For example, alternative raw materials and products for cement production (Box 1) can help to reduce CO₂ emissions from the cement industry. Also, significant efforts are needed to reduce the demand for cement and concrete products (Box 2).

Box 1. Alternative Raw Materials and Products for Cement

Process-related CO₂ emissions from calcination of limestone in cement production account for around 60% of the total CO₂ emissions from the cement industry in California. Alternative cement products that are different from Portland cement can help to reduce CO₂ emissions per tonne of cement significantly. The use of SCMs instead of clinker to produce blended cement helps to reduce CO₂ emissions intensity.

In addition, there are alternative binding materials that use different raw materials than Portland cement that are commercial or are being tested and developed by the cement industry in order to reduce process-related CO₂ emissions (Figure 17). Hasanbeigi et al. (2012) has described a list of alternative raw materials and products for cement that can replace Portland cement and reduce the carbon footprint of cement and concrete production. However, more research and development (R&D) is needed before these products are widely used by the industry. Further studies are needed on the cost, technical performance, potential applications, and regulatory and standardization issues for these alternative raw material and products.



Notes: BCSA = belite calcium sulphoaluminate, CACS = carbonation of calcium silicates, CSA = calcium sulphoaluminate, MOMS = magnesium oxide derived from magnesium silicates, PC = Portland cement.

Figure 17. Alternative binding materials for cement and their process-related CO₂ emissions (IEA/WBCSD 2018)



3.6. Carbon Capture, Utilization, and Storage (Ccus) Impact

Our analysis finds that CCUS technologies in the Advanced scenario will result in around 4 MtCO₂ emissions reduction per year in 2040 compared to the BAU scenario, which do not have any carbon capture and storage (Figure 11). This is about half of total CO₂ emissions reductions in the Advanced scenario compared to BAU scenario in 2040.

CCUS technologies are emerging for the cement industry that capture and compress CO₂ emissions and permanently store them. The carbon capture technologies are still emerging technologies and are at pilot and demonstration stage, while some carbon utilization technologies are fully commercialized and adopted in many plants such as CarbonCure technology that is installed in over hundred ready-mix concrete plants. Hasanbeigi et al. (2012) reviewed some of the major CCUS technologies as well as other emerging technologies for the cement industry. Because the majority of CO₂ emissions from cement production originate from limestone calcination (and not fuel combustion), pre-combustion technologies do not significantly decrease the CO₂ emissions of cement plants; therefore, pre-combustion CO₂ capture technology is not suitable for the cement industry. It is more appropriate to consider post-combustion CO₂ capture technologies in the context of the cement production process.

Oxy-fuel technology uses oxygen instead of air in cement kilns, which results in a pure CO₂ exhaust stream, which is easier to capture. Oxy-fuel technology is currently being demonstrated in small-scale plants. CalPortland 's Mojave Plant has piloted this technology in California (van Oss 2018c). Further research is required to make this technology a viable option for the cement industry. Post-combustion technologies are end-of-pipe mechanisms that do not need to be fundamentally altered for the clinker-burning process, so these technologies are appropriate for new kilns as well as retrofits (WBCSD/IEA 2009). In addition, cement plants have abundant amount of low and medium temperature waste heat, which can be used in post-combustion carbon capture process and bring down the operational cost of the process (\$/tCO₂-captured) significantly.

Heidelberg Cement at Lixhe in Belgium with support from The EU-supported LEILAC (Low Emissions Intensity Lime And Cement) project is at the final stage of construction of post-combustion carbon capture technology (HeidelbergCement 2019; Construction Climate Challenge 2018). In China, Anhui Conch Cement Company's Baimashan Cement Plant in Wuhu, Anhui Province has also installed world's largest post-combustion carbon capture plant for the cement industry with 50,000 ton per year CO₂ capture capacity that started operation in 2018 (Global Institute 2018)

Captured CO₂ can be geologically stored either permanently or over geological time scales, and either directly or after a commercial application. For instance, CO₂ can be used in the concrete curing process (e.g. CarbonCure 2018), production of aggregate and construction materials (e.g. Blue Planet 2018, Solidia Technologies 2018), to cultivate algae biomass, for production of chemicals and fuels by reacting it with hydrogen (IEA/WBCSD 2018), and other applications. Most of the carbon utilization technologies for the cement and concrete industry are at the pilot or development stage (Hasanbeigi et al. 2012), although some companies are beginning to scale up productions and operations today.

While carbon capture technologies for the cement industry most likely will have very slow commercial-scale deployment until 2030, some of the carbon utilization technologies for the cement and concrete industry are at a more advanced development stage. For example, CarbonCure says that their technology that helps to utilize and store CO₂ in concrete during the concrete curing process has been installed in around hundred ready-mixed concrete plants in North America.

The large-scale commercialization and adoption of CCUS technologies in the cement and concrete industry will likely not happen without substantial policy interventions. Significant policy intervention is especially needed to fully commercialize and deploy post-combustion CCS technologies, which are capital intensive but can significantly reduce CO₂ emissions from cement plants. One of such recent policy interventions is the expanded 45Q tax credit, which would provide \$50/tCO₂ revenue stream for projects larger than 100,000 tCO₂/year (EFI, 2018). Similarly, the low-carbon fuel standard, administered by the California Air Resources Board (CARB), is expected to enable CCS credit market access at a price between \$100-200/ tCO₂, however, the low-carbon fuel standard does not currently involve cement plants as sources, and would require a substantial modification by the Board in order to provide policy support to cement producers for CCS.

Without such policies, cement plants in California that invest in expensive carbon capture technologies will be at a disadvantage compared to their competitors in other states or countries. California policy makers will need to provide sufficient CO₂ credit incentives to cement plants in the state to adopt carbon capture technologies. It is a great opportunity for California to be a leader one more time in deploying carbon capture technologies in most of its cement plants as soon as possible, thereby paving the way for full commercialization and wide adoption of these technologies in other states and countries around the world.

When it comes to CCS, in addition to carbon capture which happens at the cement plants, we will need infrastructure for transport and storage of captured carbon. Since the volume of captured carbon is quite high, it is less likely that carbon utilization technologies and companies can absorb all the captured carbon. Therefore, there is a need for suitable site for safe geological storage or carbon captured from cement plants.

Depleted oil and gas fields are among the top candidate for geological storage of carbon around the world including in California. As shown in Figure 1, most of cement plants in California are in southern California where most of state's oil fields also are located. This could potentially provide a suitable storage site for captured carbon from cement plants. More detailed analysis needs to be done on this subject, which is beyond the scope of this study.

Carbon utilization technologies that use captured carbon from industrial plants or the power sector for production of construction material, fuels, and chemicals also will need policy support to penetrate the market. Carbon taxes or carbon credits applicable to carbon utilization technologies and products along with the development of relevant regulation and standards for the use of these products can transform the market and increase the use of carbon utilization technologies by 2030 and beyond.

Box 2. Product Demand Reduction

One of the substantial ways to reduce CO₂ emissions associated with the cement and concrete production is to reduce the demand for these products. This topic was outside the scope of this study, but below we briefly list a few actions that industry and California government can take to reduce the demand for cement and concrete.

- Industry should work along the construction value chain to use cement and concrete more efficiently.
- The California government should work with industry to set standards and codes in order to reduce waste, encourage recycling of concrete, and maximize design lifetime of construction.
- The California government should support R&D for the use of alternative materials to Portland cement and concrete for construction projects. Construction material produced by emerging carbon utilization technologies, cross-laminated timber, recycled plastic, fly ash-based concrete, etc. can help to reduce demand for conventional concrete in California. Further R&D is needed in potential applications and properties of final products for these alternative construction materials.



The CO₂ emissions reduction identified in this study under Advanced scenario cannot be achieved without substantial deployment of new policy mechanisms in California. Below we list some of the policy options that can support the implementation of decarbonization levers analyzed in this study. The policy mechanisms listed either do not currently exist in California or require significant improvement and expansion to address the CO₂ emissions from the cement industry.

Energy Efficiency Improvement:

- The California government agencies such as the California Energy Commission can set a minimum energy performance standard equal to best available technology (BAT) energy intensity for any new cement plants to be built in California.
- For existing cement plants, the California government can set targets for electricity intensity and fuel intensity reduction by 2040.
- The California government agencies such as the Air Resources Board can use policy mechanisms such as direct regulation or carbon price/tax, emissions standards, tax-exempt debt financing, low interest rate loans, and other fiscal incentives to stimulate investment in energy efficiency technologies and measures, especially WHR power generation in cement plants. Electric utilities can also provide fiscal incentive for energy efficiency retrofits.
- The cost savings from cost-effective efficiency measures can bring down the cost of conserved energy (US\$/GJ or kWh-saved) of many measures that are not currently cost-effective. This indicates that effective incentive programs by government or utilities should bundle efficiency measures, which will maximize savings and allow the savings to pay for non-cost-effective measures whenever possible.

Clinker Substitution and Use of SCMs:

- The California government agencies such as the California Department of Transportation (Caltrans) should develop new standards and codes for increased use of blended cement and SCMs in cement and concrete. These standards will need to ensure the performance and reliability of final products.
- The California government should encourage the use of blended cement with high shares of SCMs by setting requirements for such products in public procurement policy. The Buy Clean California legislation (AB 262) is an example of existing framework for this intervention. Some cities in California have already started such practice.
- The California government agencies such as the Department of General Services (DGS) should work with industry, universities and other third-party organizations to fund R&D projects for the use of blended cement in a wide range of applications.

- The California government agencies such as Caltrans and DGS and industry should work with third parties to conduct a series of seminars with the target audience of specifying engineers, contractors, and concrete producers, and government staff in order to: 1) replace specification restrictions on SCM amounts and minimum cement contents with concrete performance requirements; 2) share laboratory/field data showing acceptable concrete performance with higher amounts of SCMs; and 3) share best practices for successfully incorporating higher amounts of SCMs and achieving concrete performance requirements.
- The California government agencies such as Caltrans and DGS should use regulatory mechanisms to reward ready-mixed concrete companies and plants that maximize the use of SCMs in order to reduce the carbon footprint of the concrete produced.

Switching to Lower-Carbon Fuels:

- California government and its agencies should employ policy mechanisms such as carbon tax, emissions standard, and tax incentive to encourage the industry to move away from coal and petroleum coke (together accounting for more than 80% of total fuel used in the California cement industry) and use lower carbon fuel.
- The appropriate California government agencies, including the Air Resources Board, should set guidelines for the use of alternative fuels with lower carbon content based on international best practices to ensure safe pre-processing and co-processing of alternative fuel in the cement plants.

Support Carbon Capture, Utilization, and Storage (CCUS) Technologies:

- The California government agencies such as the Air Resources Board should work with the cement and concrete industry to increase the R&D investment for pilot and demonstration of CCUS technologies in the cement and concrete industries.
- Universities and research institutions in collaboration with industry should increase R&D for post-combustion carbon capture technologies for the cement industry to be available and fully commercialized by 2030. This requires increased government funding for R&D for this technology.
- The California government agencies such as the Air Resources Board should work with industry and U.S. DOE to support a demonstration project for post-combustion carbon capture in a cement plant in California.
- Carbon utilization technologies to use carbon for production of construction materials, chemicals, fuels, etc. are also emerging technologies at different commercialization stages. These technologies will require further R&D investment support from government and third parties.
- The California procurement authorities should develop and use new guidelines such as the ones being developed under California Buy Clean Act (AB262) in order to stimulate the use of carbon utilization technologies and products.
- The California government agencies such as Caltrans and DGS should set new standards and codes for the use of products produced by carbon utilization technologies.

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Appendix 1. Description of Cement and Concrete Production

Portland cement was invented in Britain during the late 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 CO₂ emissions impacts of cement production processes.

A.2.1. Cement Production Processes

Mining and Quarrying

The most common raw materials used for cement production are 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 CO₂ 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 the 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), 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 pre-heater 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 2023). 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 CO₂ 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 A.1 shows the detailed steps of the cement production process using a rotary kiln.

Figure A.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.

³ Calcination is the process of heating a substance to drive off structurally-bound volatiles.

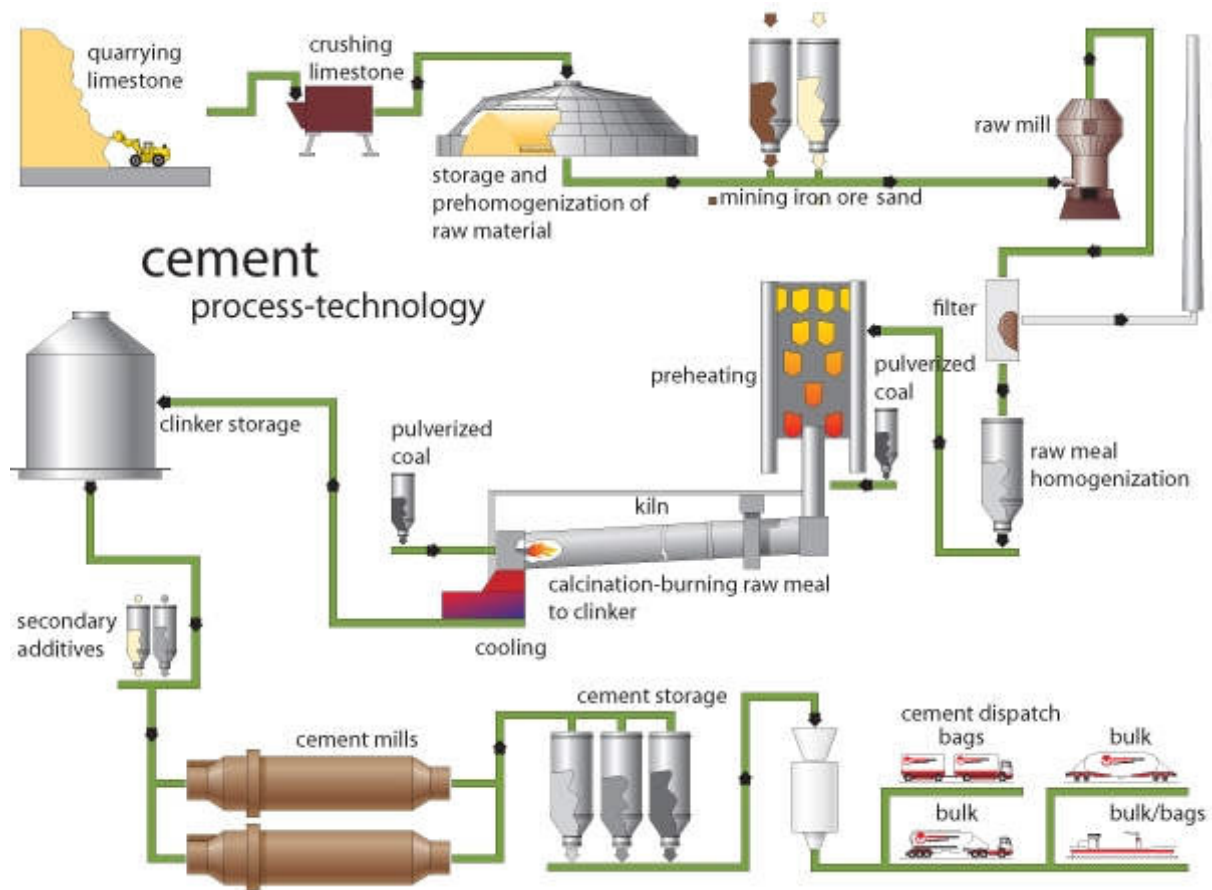


Figure A.1. Steps in the cement production process using the rotary kiln (HJM 2018)

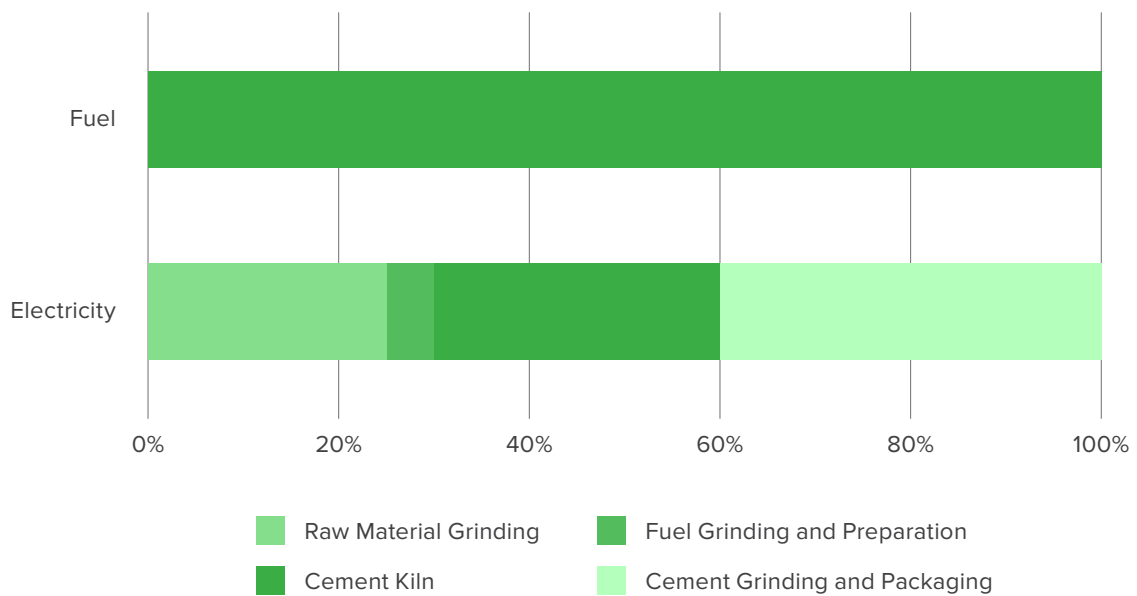


Figure A.2. Share of energy use by process step in a typical cement plant with a rotary kiln (IEA/WBCSD 2018)

A.2.2. CO₂ impact of cement production

The production of 1 metric tonne of cement releases an estimated 0.50 to 0.95 tCO₂/t cement depending on the clinker-to-cement ratio, fuel efficiency, fuel mix, and other factors. More than 50 percent of the CO₂ released during cement manufacture, or approximately 520 kg CO₂ per tonne of clinker (CARB 2018), is from calcination in which limestone (CaCO₃) is transformed into lime (CaO) in the following reaction:



The rest of the CO₂ 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 CO₂ emissions from electricity use is, on average, 5 percent of the total CO₂ 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 CO₂ emissions are associated with quarry mining and transportation (WWF 2008).

A.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 A.3 shows the typical share of each component in concrete production.

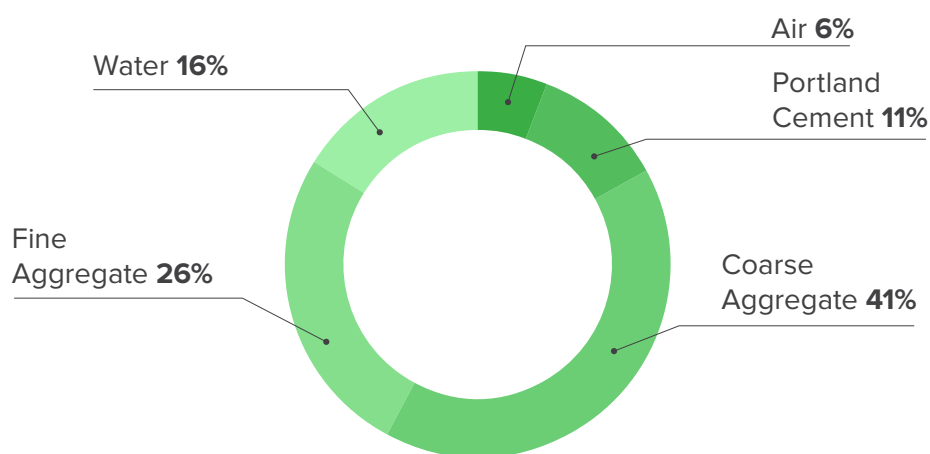


Figure A.3. The typical volumetric ratio of each component in concrete production (PCA 2012)

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.

Appendix 2. List of Acronyms

ASTM	American Society for Testing and Materials
BAU	Business as Usual
BF-BOF	Blast Furnace- Basic Oxygen Furnace
CaCO ₃	limestone
CaO	lime
CCUS	carbon capture, utilization, and storage
CO ₂	carbon dioxide
CO ₂ e	carbon dioxide equivalent
EAf	department of general services
EAf	electric arc furnace
GGBFS	ground granulated blast furnace slag
GJ	gigajoules
GHG	greenhouse gas
kg	kilogram
kt	kilo tonne
kWh	kilowatt-hour
MMBtu	million metric Btu
Mt	million metric tonnes
MSW	municipal solid waste
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
WHR	waste heat recovery

Appendix 3. List of Figures and Tables

Figure 1. The map of cement plants and cement terminals in California (PCA 2017)	8
Figure 2. Cement and clinker production in California, 2000-2015 (van Oss 2017, 2018a)	9
Figure 3. Fuel and electricity intensity of the cement industry in California, 2000-2015	10
Figure 4. Energy mix in California's cement industry in 2015 (van Oss 2018a)	11
Figure 5. Sources of CO ₂ emissions in California's cement industry in 2015	11
Figure 6. CO ₂ emissions in the cement industry in California by emissions source, 2000-2015	12
Figure 7. Fuel and electricity-related CO ₂ emissions intensity in the cement industry in California, 2000-2015	13
Figure 8. Annual cement and clinker production forecast for California, 2015-2040	17
Figure 9. Fuel mix projections for California's cement industry under Advanced scenario, 2015-2040	19
Figure 10. CO ₂ emissions forecast for California's cement industry by scenario, 2015-2040	20
Figure 11. The impact of CO ₂ emissions reduction levers on emissions of California's cement industry to 2040	21
Figure 12. Fly ash production in the U.S., 1974-2033 (ARTBA 2015)	24
Figure 13. Fly ash utilization rate in the U.S., 1974-2033 (ARTBA 2015)	24
Figure 14. Ground limestone filler content in grey cement for selected regions (UNEP 2016)	26
Figure 15. Projected price of coal and natural gas for industry sector in the Pacific region of the U.S., 2015-2040 (U.S. DOE/EIA 2019)	28
Figure 16. Carbon price needed to switch from coal to natural gas in California's cement industry, 2015-2040.	29
Figure 17. Alternative binding materials for cement and their process-related CO ₂ emissions (IEA/WBCSD 2018)	31
Table 1. Plant-level GHG emissions of cement plants in California in 2016* (CARB 2017)	14
Table 2. Key parameters for California's cement industry in the BAU and Advanced scenarios, 2015-2030	18