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China Cement Association

Toward Net Zero: Decarbonization Roadmap for China's Cement Industry

Report / December 2022

About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and nongovernmental organizations to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing, People's Republic of China.

About China Cement Association

China Cement Association (CCA), established in 1987 in Beijing, is a social organization with independent legal status. CCA is a voluntary industrial organization consists of producers of cement and related products, research and engineering design enterprises, investment consulting enterprises and other entities. With wide representation, CCA serves as a bridge between businesses and the government, and provides technical and policy consulting services for businesses, the government and the whole society. We cooperate with businesses, the government, research and design institutions and builders to promote the green, low-carbon and sustainable development of the cement industry.

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Preface

The cement industry is a key factor in China's transition to carbon neutrality. China's cement production and consumption account for more than half of the respective global totals, and the industry's carbon emissions are the third largest in the country — after power and steel — accounting for about 13% of total carbon emissions. One challenge of decarbonizing cement is its massive process emissions, which requires transformational technologies to substitute raw materials and ingredients on a large scale. Another challenge comes in switching from coal to low-carbon energy sources. In addition, given the young assets of the industry, there is a high risk of stranding assets in a rapid transition. A relatively low market concentration rate among top cement companies also impedes the scaling up of transition technologies.

Under its carbon-peaking and carbon-neutrality goals, China is building a "1+N policy" framework, which includes the formulation of carbon-peaking action plans for key industries, including the building materials industry, in which cement is a major component. The low-carbon transition of downstream industries such as construction, along with development of environmental policies, and the growth of the nationwide carbon market will all accelerate the transition to carbon neutrality in the cement industry.

This report, which is coauthored by RMI and the China Cement Association (CCA), provides a thorough discussion of the net-zero transition of the cement industry. Our analysis shows that achieving carbon neutrality will require synergy among various approaches, including demand reduction, fuel switching, changes to cement chemistry, increased energy efficiency, and carbon capture and utilization (CCUS) or carbon capture and storage (CCS). The demand for cement is likely to decline in China due to slowing urbanization, weakening construction, phasing out of substandard production capacity, and improvements in building-material efficiency. Alternative fuels will play an important role in reducing emissions, and some are already being applied. Changing cement chemistry — by reducing the clinker-to-cement ratio, developing new low-carbon cements, and switching raw materials — will be important to reducing process emissions. CCUS could provide end treatment of the remaining carbon emissions; the location of suitable storage sites could influence the industry's future geographical distribution.

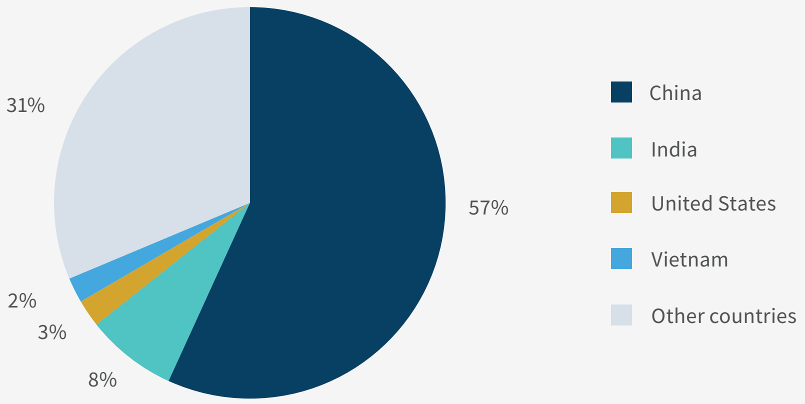
The cement industry's net-zero transition also requires the right pricing mechanism to ensure a cost advantage for low-carbon cement. The cement industry is closely tied to upstream and downstream industries — most notably fuel, concrete, and construction — so a systematic approach that integrates the whole value chain's net-zero transition is needed. However, because of the uncertainties in supply and demand, technological development, and cost, this study focuses solely on China's cement industry. It reviews the industry's short-, medium-, and long-term decarbonization strategies, technology deployment, and economics, within the time frame delineated by China's decarbonization goals (2020–60), to provide guidance for policymakers and market participants.

The Road to Carbon Neutrality for China's Cement Industry: Challenges and Opportunities

China produces and consumes half of the world's cement and clinker. Decarbonizing its cement industry has significant implications for global climate action.

China is the world's largest producer and consumer of cement. In 2021, China produced 57%[1] of the world's total (see Exhibit 1), or 2.363 billion tons of cement (see Exhibit 2, next page). In the same year, China consumed a total of 2.38 billion tons of cement,[2] accounting for more than half of the world's total.[i] In 2020, China's cement sector emitted 1.37 billion tons of CO_2 (see Exhibit 3, next page). The cement sector accounts for an estimated 13% of the country's total carbon emissions, making it the third-largest emitting sector following power and steel. Emissions reductions in the cement sector are crucial to meeting China's carbon-neutrality goal.

Exhibit 1: **Major cement-producing countries in 2021**



Source: US Geological Survey, Cement Statistics and Information

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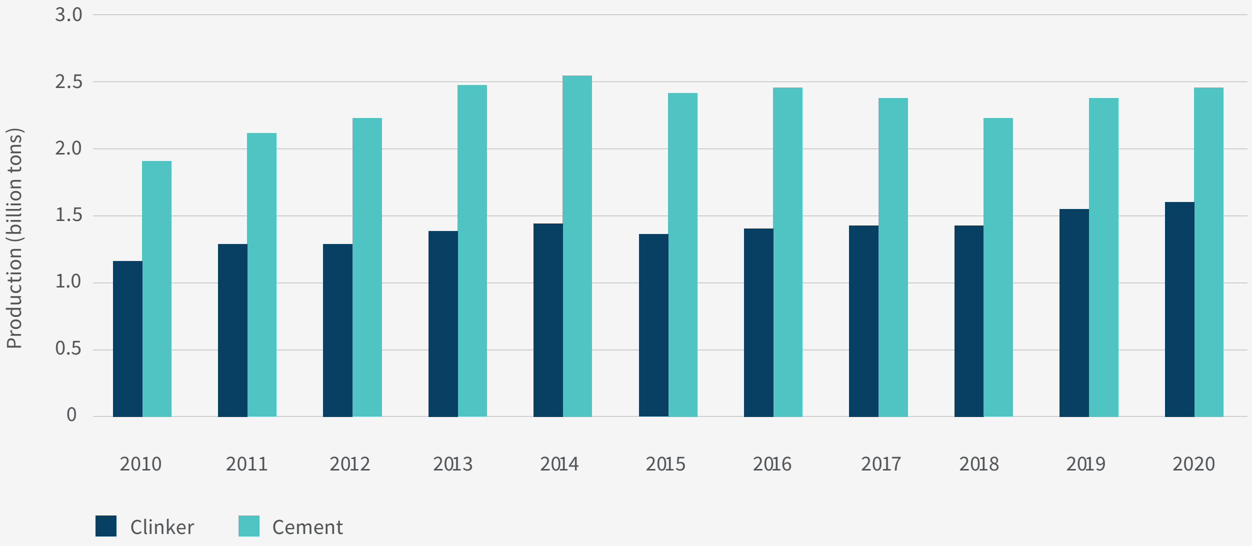
[i] According to *The Global Cement Report,* global cement consumption reached 4.14 billion tons in 2020. CemNet, September 2021.

Exhibit 2: Cement and clinker production in China, 2010–20



Source: RMI and CCA

Exhibit 3: CO_2 emissions of China's cement sector, 2010–20

Source: RMI and CCA

Challenges remain for China’s cement industry to transition toward carbon neutrality.

Process emissions are the biggest challenge to emissions reduction in the cement sector.

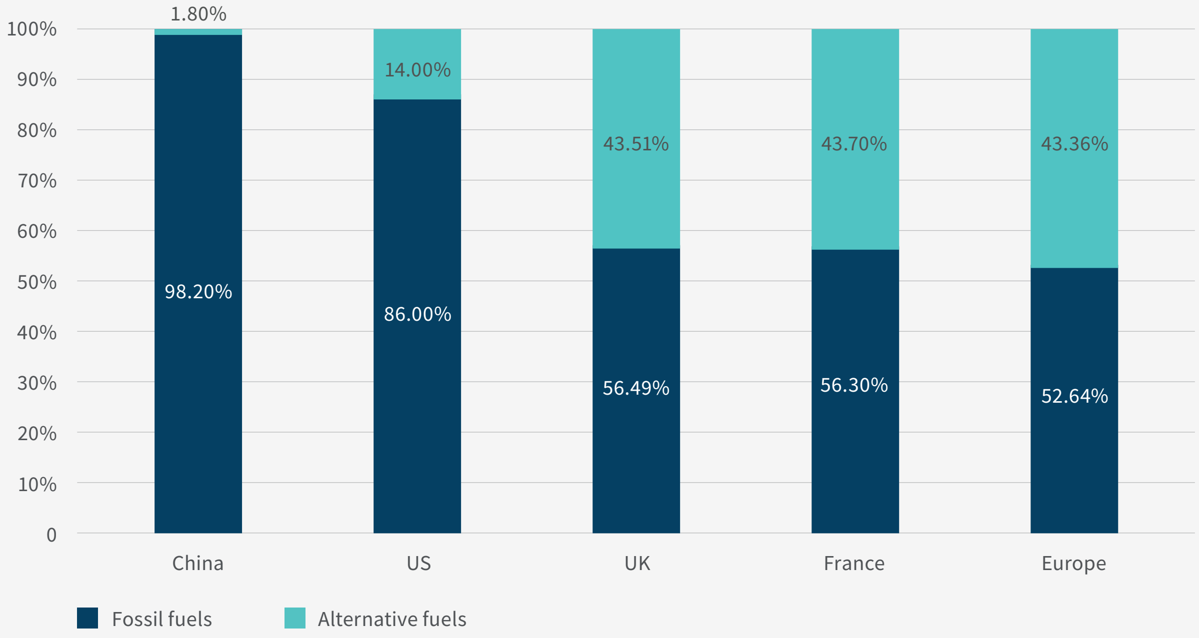
About 60% of the carbon emissions from cement production are process emissions — that is, CO_2 released from the decomposition of carbonates, mainly limestone. Constituting the core raw material of cement production, limestone is widely distributed, abundant, easy to access, and inexpensive. Assuming production of 1 ton of cement requires 1.2 to 1.3 tons of limestone,[3] China’s cement sector consumes 2 billion tons of limestone each year. Although there has been progress in identifying alternative raw materials, there is not yet an alternative raw material, production process, or binding material that can widely replace limestone. The large volume of these difficult-to-eliminate process emissions will be the biggest challenge on the road to carbon neutrality in the cement sector.

Cement production relies heavily on fossil fuels.

In cement production, fossil fuel combustion and electricity consumption account for about 30% and 5% of total carbon emissions, respectively. Fossil fuel combustion mainly occurs in the clinker-calcination stage, and electricity is mainly used for running machinery. Coal is the primary source of energy used in China’s cement production, whereas alternative energy is used at a very low rate in this industry. Only about 2% of China’s thermal energy use per ton of clinker comes from non-fossil fuels, compared to more than 40% in some European countries (see Exhibit 4, next page).[4]

In the cement sector, potential alternative fuels include solid waste and biomass. The application of new renewable energy such as hydrogen and green electricity in cement production is still in the early stages of development. The low share of alternative fuels used in China is mainly due to gaps in the waste treatment system, the lack of a waste-derived fuel industry, and low availability of biomass resources. Institutional, technical, and cost barriers need to be addressed to promote the use of alternative fuels in the cement sector.

Exhibit 4: **Thermal-specific energy consumption per ton of clinker in 2018**



Source: IEA and CCA

Newer cement assets face a high risk of being stranded in the industrial low-carbon transition.

Rapid infrastructure construction in China over the past 20 years, giving rise to strong demand for cement, has driven a dramatic expansion in cement production capacity. An estimated 90% of cement production facilities in China have been built in the past 20 years; 40% have been built in the past 10 years. The typical operating life of cement plants worldwide is 40 years.[5] The pursuit of carbon goals presents an increased risk that some existing cement production facilities will become stranded assets. Cement producers who decide to upgrade these relatively new facilities will face high costs.

A low degree of centralization in the cement sector makes it more difficult to engage in collective actions or promote new technologies.

The top 10 clinker producers in China's cement sector account for about 55% of total capacity. This low level of centralization is conducive neither to eliminating outdated production capacity, nor to centralizing R&D and large-scale deployment of new technologies. For new technologies such as carbon capture and storage (CCS), which requires significant infrastructure investment, the decentralized nature of cement production is an impediment to construction and sharing of infrastructure. The cost of CO_2 storage and transport caused by decentralized distribution, as well as the need for administrative coordination, may also hinder the large-scale adoption of such technologies.

Opportunities emerge for China’s cement industry to transition to carbon neutrality.

The dual carbon policy — supply-side reform and demand-side transformation — will drive the low-carbon transition in the cement sector.

As China’s economy shifts from a period of high-speed growth to a period of high-quality development, the cement sector and the downstream construction industry will also undergo a high-quality transformation. After 20 years of rapid development, China’s urbanization and infrastructure will level off, with a flat or even decreased demand for cement. At the same time, supply-side reforms, the implementation of environmental policies and industrial policies combined with carbon market–based measures will advance the low-carbon and carbon-neutral transition in the cement sector.

Favorable policies, broad market conditions, and innovation capacity are conducive to the promotion of new energy and new technologies.

China’s cement sector has advanced technology and equipment with world-leading production efficiency as well as a track record of innovating and applying new technologies. With the support of the government, new wind and solar power has achieved cost advantages over coal-fired power. In addition, China’s 14th Five-Year Plan calls for the pursuit of hydrogen technology as part of the industrial transformation. China’s Mid- to Long-Term Hydrogen Industry Development Plan (2021–35) issued in 2022 envisions application of hydrogen technology at scale to replace the use of fossil fuels in industry.[6] These factors will create favorable technical and cost conditions for the use of new types of energy in the transition of the cement sector.

Increased awareness in the construction industry will foster and strengthen the market for low-carbon building materials.

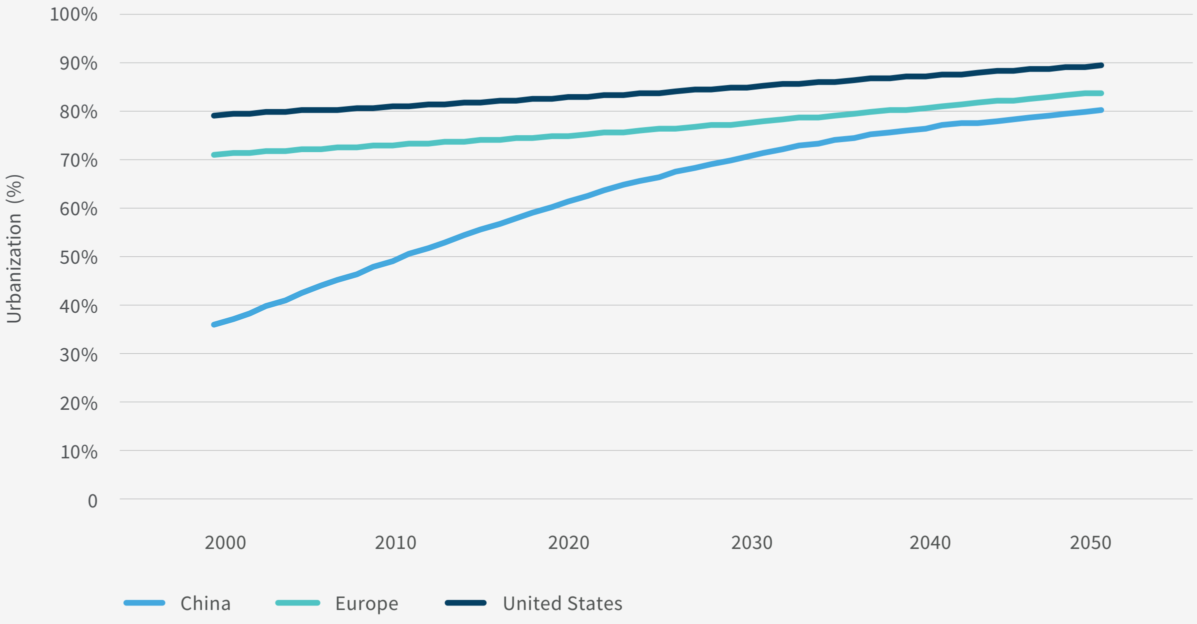
The construction industry will continue to deepen green reform and improve low-carbon standards, which will help bolster demand for low-carbon building materials, including low-carbon cement. In 2019, the Ministry of Housing and Urban-Rural Development issued the Standard for Building Carbon Emission Calculation, which includes carbon emissions from production of building materials.[7] The ministry stipulated that the calculation of carbon emissions will be mandatory for construction projects starting April 1, 2022.[8] Domestic real estate development companies have started to set goals as part of the nation’s dual carbon-reduction initiatives. Sino-Ocean Group, for example, has taken the lead in committing to carbon neutrality by 2050.[9] Ten real estate companies, including Vanke and China Jinmao, have publicly promised that 100% of their new buildings will meet green building standards.[10] Increased awareness in the construction industry will bring market power to the low-carbon transition of the cement sector.

Demand Outlook for Cement in a Carbon-Neutral Scenario

Slowing urbanization and infrastructure construction will constrain cement demand.

Demand for cement in China is driven mainly by construction of buildings and infrastructure, including urban roads, highways, and railways. China's population has entered a stage of low growth, and urbanization is expected to reach a mature level of more than 80% between 2035 and 2040. Declining population in the medium to long term and the slowing of urbanization (see Exhibit 5) as well as the housing stock accumulated in recent years by the rapid development of the real estate sector will depress demand for cement. Housing construction is expected to decline steadily from 2022 to 2030. After 2030, construction activities will mainly focus on the renovation of existing housing, and new housing development will continue to decrease.

Exhibit 5: **Rate of urbanization in China, Europe, and the United States**



Source: United Nations, *World Urbanization Prospects 2018*

After more than two decades of large-scale infrastructure building, China's overall infrastructure level is relatively high, but uneven regional and sectoral investment is still a serious problem. Strengthening weak links in infrastructure will be a key task for a long time to come. Therefore, the demand for cement in the infrastructure sector will remain high for at least a decade, even as the rate of construction gradually slows. For example, the total length of new highways increased by 1.2 million km from 2010 to 2020 but is expected to increase by 600,000 km in the decade from 2020 to 2030, reaching 5.8 million km.[11] Railways increased by 56,000 km from 2010 to 2020 and will increase by 54,000 km from 2020 to 2035, reaching 200,000 km.[12] A decline in demand for cement is inevitable as construction of buildings, highways, and railways slows.

Demand for cement clinker will decline two-thirds by 2050.

The outlook on demand for cement and clinker in the medium to long term is based on macroeconomic indicators related to cement consumption, such as gross domestic product (GDP), fixed-asset investment, population growth, and urbanization rates. China's economic development model is adjusting. The proportion of investment in construction is gradually decreasing, while investment in energy conservation and environmental protection, and technological transformation is increasing, resulting in a continuous decrease in demand for cement. After China reaches the economic level of moderately developed countries — a goal set for 2035 — local infrastructure construction and repair, and renovation and upgrading of existing buildings will become the main types of construction, leading to further decline in cement consumption.

Fixed-asset investment will also slow in the future. The proportion of fixed capital formation as a portion of GDP in China has remained high for half a century — especially since 2000 — and is much higher than that of other countries, indicating that investment plays a very important role in driving China's economic growth. However, the economy is shifting from high-speed growth to high-quality development, which is expected to limit fixed-asset investment. RMI expects average growth in fixed capital formation to remain high until 2025, then shift to a moderate rate from 2026 to 2035. After 2035, fixed capital formation is expected to grow at a low rate.

Cement consumption in China peaked in 2014 at 2.48 billion tons, with per capita consumption of nearly 1,800 kg — well above the peak levels in developed countries. From 2015 to 2021, China's per capita cement consumption has been hovering at 1,600–1,700 kg, with cement consumption at the peak plateau stage, while clinker consumption continued to rise. As the experience of developed countries shows (see Exhibit 6, next page), per capita cement consumption usually fluctuates at a high level for a period after peaking, and then declines until it reaches a more stable state.

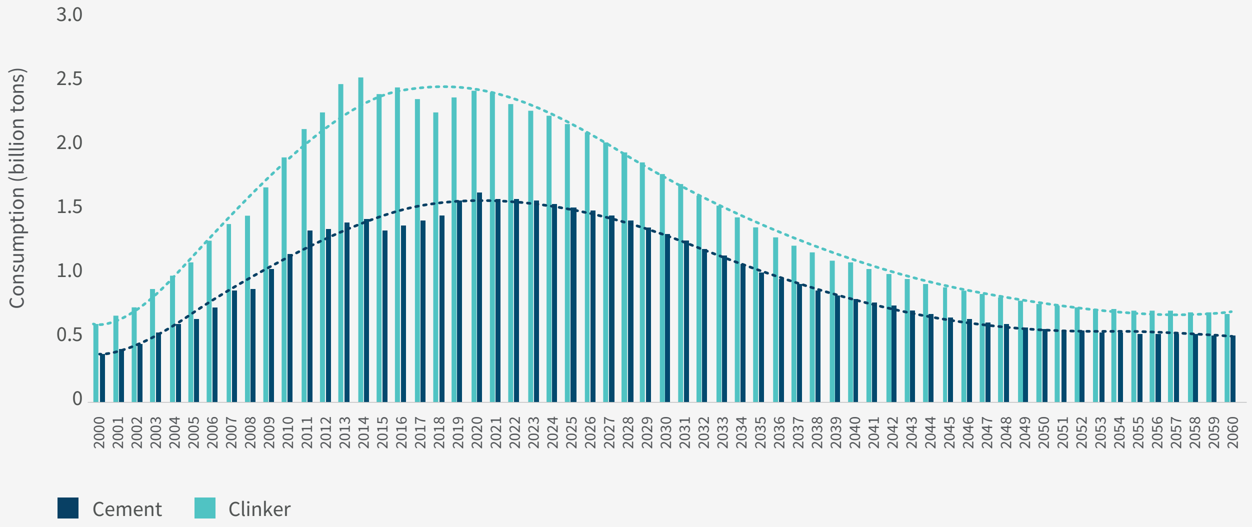
Exhibit 6: Per capita cement consumption after its peak in select countries

	Peak cement consumption per capita (kg)	1–5 years after the peak		6–10 years after the peak	
		Average value (kg)	Percent of the peak	Average value (kg)	Percent of the peak
United Kingdom	357	283	79.3	243	68.1
France	593	526	88.7	445	75.0
Japan	729	657	90.1	579	79.4
South Korea	1,348	1,027	76.2	1,111	82.4

Source: RMI and CCA

RMI's forecast assumes that China's clinker demand will decline by about two-thirds, to 560 million tons in 2050 from 1.55 billion tons in 2021. Cement demand is forecast to decrease to 750 million tons in 2050 from 2.365 billion tons in 2021, based on the assumption of an increasing clinker coefficient (see Exhibit 7). The reduction in demand for cement will have a significant impact on overall carbon emissions of the cement sector.

Exhibit 7: Historical and future consumption of cement and clinker in China



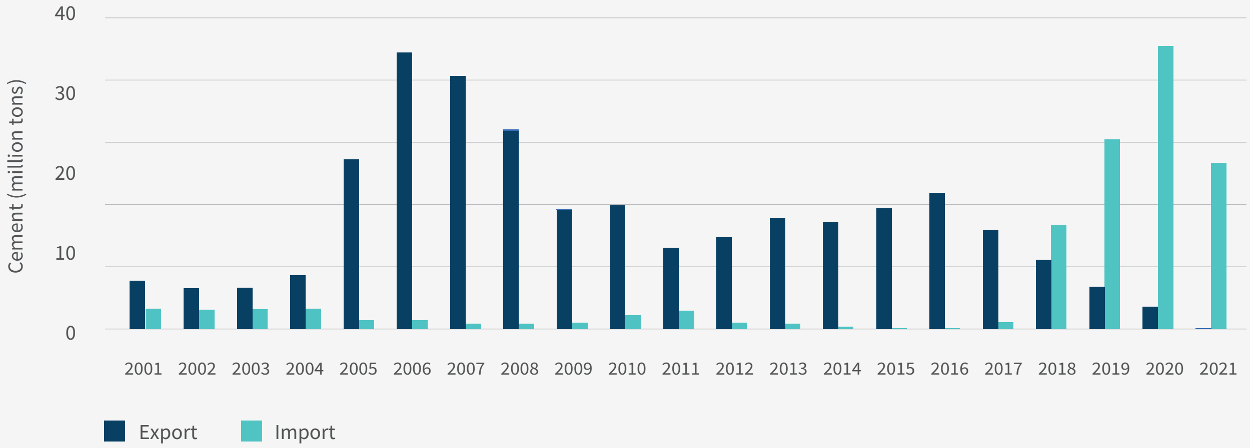
Source: RMI and CCA

Imports and exports will have limited impact on carbon emissions of the cement industry.

The cement sector is characterized by local production and national distribution due to its sensitivity to transportation costs. Traditionally, the transport radius of cement is about 300 km; cement production is normally close to consumer markets and concentrated in densely populated and rapidly urbanizing areas. China's dependence on imported cement is low.

However, since 2018, China has transformed from a cement exporter to a cement importer (see Exhibit 8) for a variety of reasons. First, supply-side structural reform and measures such as staggered peak production and production restriction have led to regional and periodic cement shortages and price spikes. In addition, cement plants in Southeast Asia, particularly Vietnam, are producing over capacity and exporting their product to China at a competitive price. China's import of cement clinker is likely to expand further amid structural adjustment in the domestic industry, increased pressure for environmental protection, and higher labor costs. China's clinker imports are expected to be about 30–40 million tons per year in the future. But the share of imports remains modest, at 2%–8% of annual demand.

Exhibit 8: **Import and export of cement and clinker in China, 2001–20**

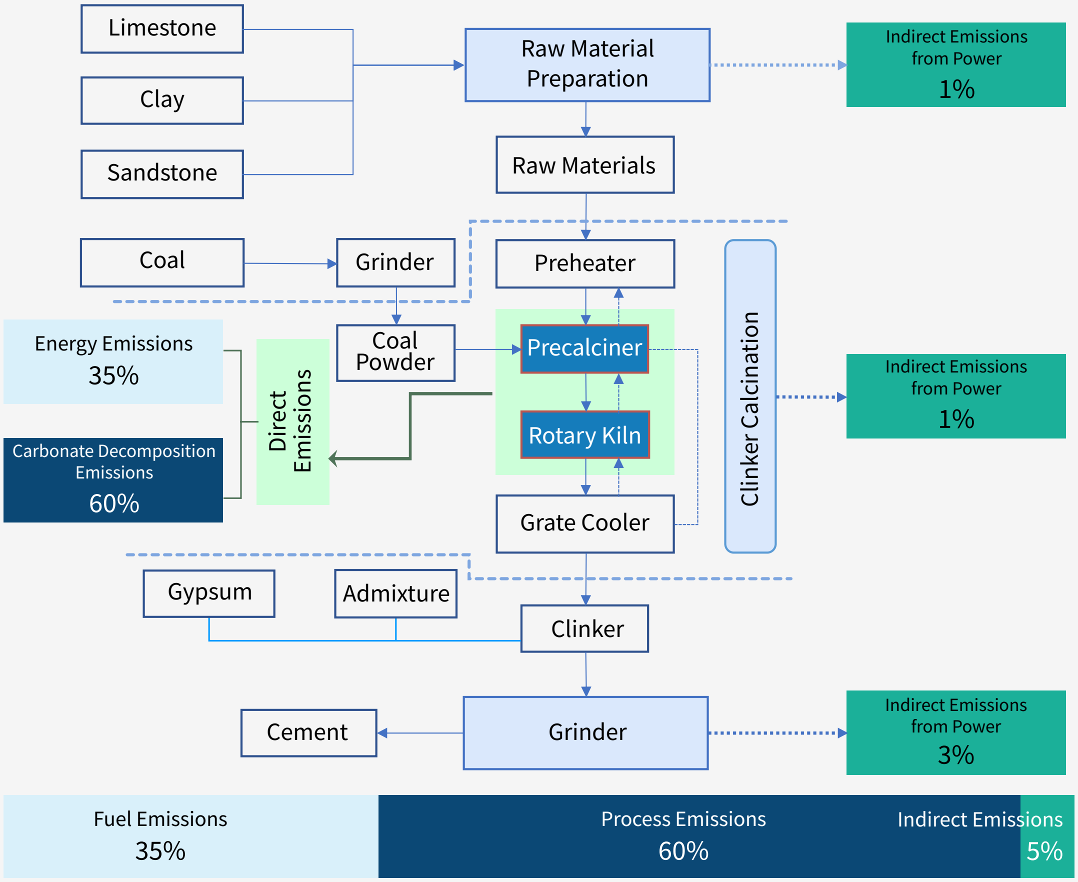


Source: RMI and CCA

Technical Pathways to Decarbonizing the Cement Industry

The process of cement production can be roughly divided into three stages: raw material preparation, clinker sintering, and cement grinding. Carbon emissions from clinker sintering account for more than 95% of the total — mainly from fossil fuel combustion (combustion emissions) and CO_2 generated by decomposition of carbonate raw materials (process emissions) (see Exhibit 9). Combustion emissions account for about 35% and process emissions account for about 60% of carbon emissions from cement production. Given the current level of cement production technology in China, the carbon intensity of cement is about 0.58 tons CO_2 per ton, and that of clinker is about 0.86 tons CO_2 per ton.

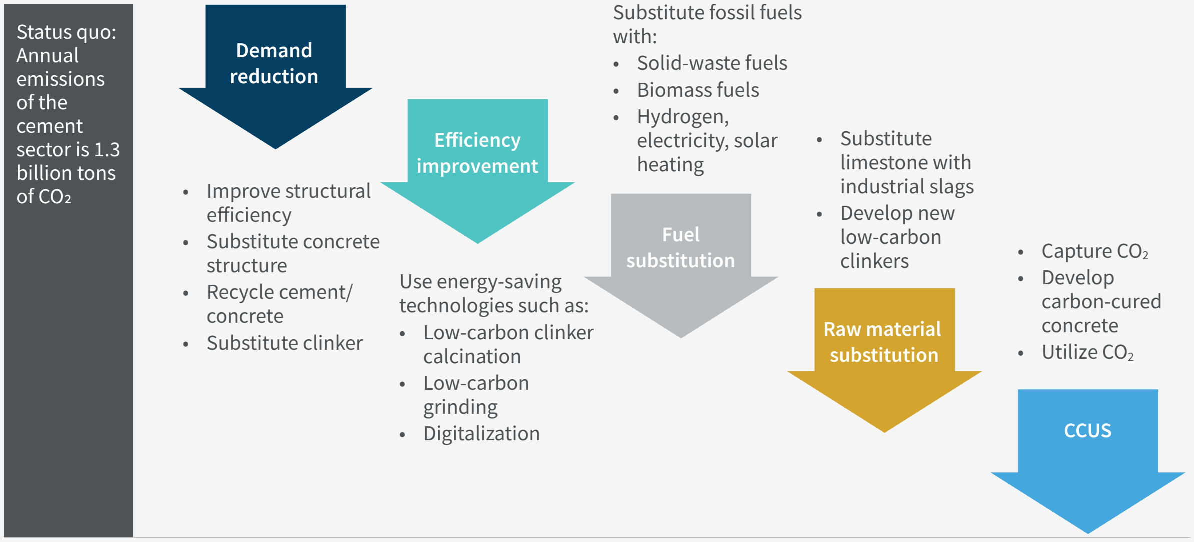
Exhibit 9: **Major sources of CO_2 emissions in the cement sector, 2020**



Source: RMI and CCA

At present, lowering carbon emissions in cement production in China is achieved mainly by improving the burnability and grindability of raw materials and improving the production processes and equipment to reduce energy consumption. Although emissions reductions can be achieved by these measures, it is difficult to achieve the long-term net-zero emissions goal of the cement sector by relying only on existing technology. Full decarbonization of the cement sector requires a set of transformational approaches (see Exhibit 10), including reducing cement consumption, innovating low-carbon cement varieties, increasing the substitution rate of low-carbon energy in fuel and electricity use, adjusting clinker and raw material ratios in cement production, and promoting CCUS technologies to offset hard-to-eliminate process emissions.

Exhibit 10: Major approaches for the cement sector to achieve carbon-neutral goal



Status quo: Annual emissions of the cement sector is 1.3 billion tons of CO_2

Demand reduction

- Improve structural efficiency
- Substitute concrete structure
- Recycle cement/ concrete
- Substitute clinker

Efficiency improvement

Use energy-saving technologies such as:

- Low-carbon clinker calcination
- Low-carbon grinding
- Digitalization

Substitute fossil fuels with:

- Solid-waste fuels
- Biomass fuels
- Hydrogen, electricity, solar heating

Fuel substitution

- Substitute limestone with industrial slags
- Develop new low-carbon clinkers

Raw material substitution

- Capture CO_2
- Develop carbon-cured concrete
- Utilize CO_2

CCUS

Note: Arrow size does not indicate the proportion of emissions reduction potential.

Source: RMI and CCA

Demand management is an important lever to reduce emissions in the cement industry.

Reduced production is expected to be the most significant factor in driving down total emissions in the cement sector. According to our projections, cement clinker production in China will fall to 560 million tons per year by 2050 — about one-third of 2020 levels — which will help reduce carbon emissions in this industry by about 67%. The main drivers of reduction in cement demand and production are slightly different in the short and long term. In the short term, the elimination of outmoded production and excess cement capacity will be the main means of reducing carbon emissions in the cement sector and reaching peak carbon emissions as soon as possible. At present, staggered peak production and volume-reduced capacity replacement are two major policy means to reduce excess capacity. In late 2020, the Ministry of Industry and Information Technology and the Ministry of Ecology and Environment jointly issued the Notice on Further Improving the Normalization of Cement Peak-Shifting Production, requiring that all cement clinker production lines should transition to peak-shifting production. Shortening the operation time of cement clinker units can effectively reduce excess capacity and lower carbon and pollutant emissions in the cement sector.

In the long term, slowing urbanization and construction will be the main factors behind the decline in cement demand. In this process, some important policy and technical factors will drive down demand for conventional cement and help drive emissions reduction in the sector.

By following good urban planning, the construction industry can avoid unnecessary large-scale demolition and rebuilding, improve the service life and reuse value of existing buildings, and thereby reduce unnecessary cement consumption. The average life span of buildings in China is 30 years — just half or even one-quarter of that in developed countries — in large part because of large-scale demolition.[13] Extending the life of buildings will reduce unnecessary consumption of building materials.

Second, through modification of the architectural design code and the construction code, and industrialization of prefabricated buildings, the demand for concrete could be reduced by structural substitution and optimization. Renewable building materials such as steel and new composites can be used to replace concrete structures and reduce carbon emissions. At present, the penetration rate of a steel structure building in China is only 10%, and the new composite material is just beginning to make market inroads, so there is potential for large-scale substitution. In addition, improved building design can save up to 70% of concrete slab-floor mass, achieving materials saving and carbon reduction.[14]

Third, the reuse of cement and concrete can replace part of the clinker. The hydration of cement is generally regarded as an irreversible process, but about 30% of the concrete is not hydrated and can be extracted and reused.[15] After crushing, 85% of the waste concrete can be reused as recycled aggregate in roadbed construction.[16] The recycling rate of construction waste in developed countries is as high as 70%–90%,[17] but the proportion of standardized treatment and reuse in China is low, so there is room for improvement.

Fourth, the emergence of new low-carbon clinkers and binding materials will reduce the demand for portland cement. The International Energy Agency (IEA) summarized new binding materials that could be used as alternatives, such as commercially available belite clinker, calcium sulfoaluminate clinker, and alkali-activated clinker-free cement. However, these new binding materials have different sources of raw materials, emissions reduction effects, and applications, making it very difficult to replace portland cement entirely.

Technologies are available for a net-zero cement industry.

Fuel substitution is critical to cement decarbonization.

About 35% of carbon emissions from cement production come from fuel combustion. Using low-carbon fuel to replace fossil fuel is an important means of cement emissions reduction. The technologies currently being developed or adopted mainly use solid waste, biomass, and other new fuels such as hydrogen and electricity as substitutes.

Solid waste fuel is a commonly used alternative. The classification of solid waste fuels that can be used as alternatives in cement production is complex. The primary forms are tire-derived fuel (TDF), spent pot liner (SPL), meat and bone meal (MBM), dry sewage sludge (DSS), biomass, solid recovered fuel (SRF), municipal solid waste (MSW), refuse-derived fuel (RDF), and secondary coal and plastic waste (see Exhibit 11). Among them, the most abundant source is MSW, which can be rendered more stable when processed into RDF.

Exhibit 11: **Solid-waste alternative fuels in cement production**

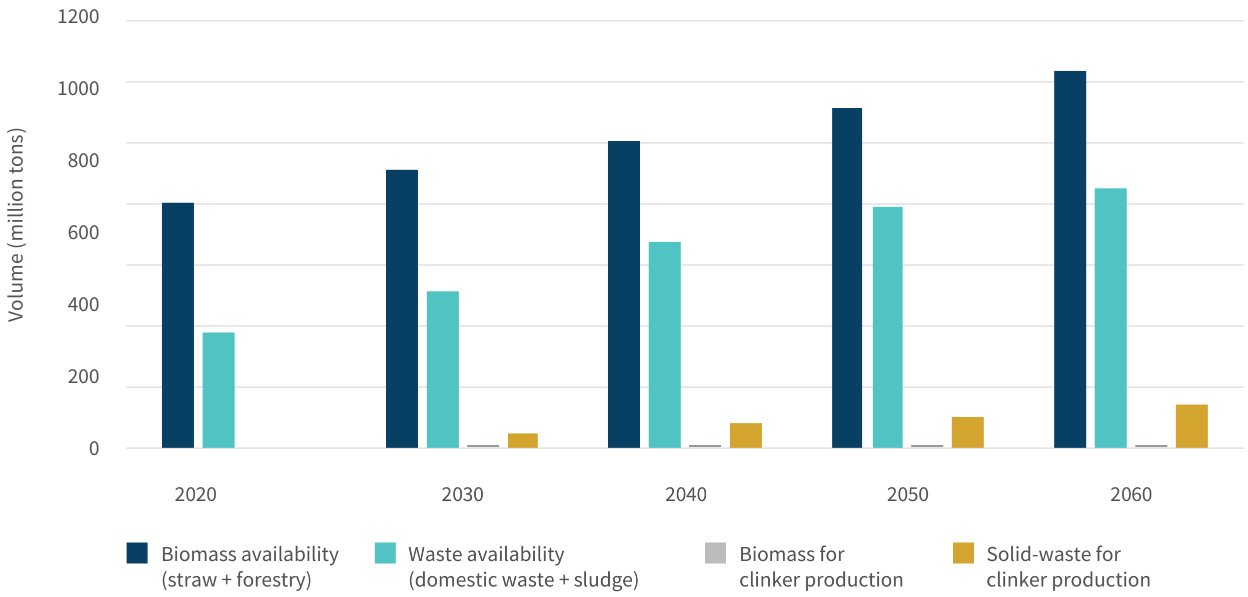
Type	Caloric value (MJ/kg)	CO_2 emissions	SO_2 emissions	Heavy metal emissions	Max substitution rate, %	Impact on clinker quality	Cost
TDF	35.6	Lower	Higher	Lower	30	None	Low
SPL	9.29	Lower	Undetected	Undetected	8	None	Low
MSW	15.4	Lower	Higher	Higher	30	Little	High
MBM	14.47	Lower	Lower	Undetected	40	Little	Medium
DSS	15.28	Lower	Higher	Same	5	Little	High
Crops (rice husks, straws)	14–21	Lower	Lower	Lower	20	None	Low
Waste plastics	29–40	Lower	Higher	Higher	—	Moderate	Medium
Waste oil and solvent	43–45	Lower	Undetected	Lower	—	Little	Low

Source: RMI and CCA

China got a late start in development of alternative fuels in its cement sector. The existing technology is mainly cement kiln coprocessing technology, which is a primary stage of solid waste utilization and paves the way for further development of alternative fuels. By the end of 2020, about 17% of China's cement production lines had been equipped with coprocessing capabilities. In 2020, about 310 million tons of domestic waste was produced in China.[18] Assuming the caloric value of RDFs after pretreatment of 1 ton of domestic waste is 300 kg standard coal equivalent, that 310 million tons of domestic waste could replace 90 million tons of standard coal. The peak potential of domestic waste generation in 2060 is expected to be about 1.005 billion tons, with a collected volume of 586 million tons. In 2020, sludge production in China exceeded 60 million tons. Assuming the caloric value of 1 kg of sludge is 0.2 kg standard coal equivalent, that 60 million tons could replace about 12 million tons of standard coal. Solid waste has great potential as an alternative fuel for China's cement clinker production and their availability will be sufficient to meet the demand for cement industry (see Exhibit 12) — representing 170 million tons of standard coal equivalent.

Exhibit 12:

Total volume of biomass and solid-wastes vs. volume required for clinker production



Source: 3060 Zero-Carbon Biomass Energy Development Potential Blue Book

Advanced international cement producers have achieved high fuel-substitution rates (see Exhibit 13), dominated by solid waste fuels. EU producers have significantly increased the fuel substitution rate to an average of nearly 40%, which can be used as a reference for China's development of alternative fuels in the industry (see Box 1, next page).

Exhibit 13: Types and shares of alternative fuels used by leading cement producers

Plant/Company	Holcim	Cemex	Heidelberg	Italcementi	Lafarge
Waste oil	5%		3.7%	8.5%	22.1%
Waste liquid and solvent	11%		4.7%	21.9%	
TDF	10%	16%	11.6%	14.9%	19.7%
Waste plastics	9%		26.4%	4.7%	33.1%
Industrial and municipal waste (solid)		65%		13.8%	
Industrial waste and other fossil fuels	30%				
MBM	2%	4%	6.1%	15.7%	
Crops	9%	10%	4.2%	11.1%	
Chips and other crops	21%	5%	24.5%		25.1%
Sewage sludge	2%		4.2%	1.7%	
RDF				7.8%	
Other alternative fuels			14.6%		

Source: International Finance Corporation, *Increasing the Use of Alternative Fuels at Cement Plants: International Best Practice*

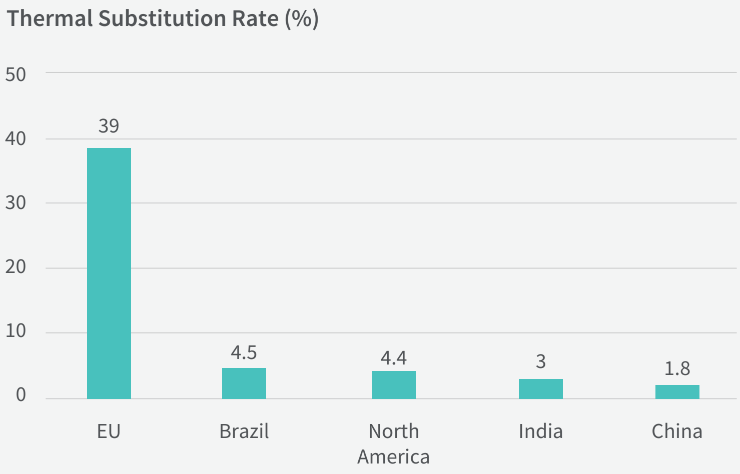
Box 1:

Promote alternative fuels in the cement sector: A European case study

The EU has the highest fuel-substitution rate in the cement sector in the world, and its development is worth studying (see Exhibit 14). In Germany, for example, combustible waste captured the attention of experts in the country's cement sector in 1985. The technology was still in the initial stage of development, and the national heat-replacement rate was just 2%, which is very similar to China's current use of combustible waste. By 1990, almost every cement plant in Germany was equipped with a combustible waste pretreatment system, similar to the coprocessing system used in China's cement kilns. However, during subsequent development, the disadvantages of this application gradually became clear: low processing capacity, high investment cost, and extremely low efficiency. With the maturity of alternative fuel technology and the adoption of relevant policies, the heat replacement rate of alternative fuels in Germany's cement sector rapidly increased, growing more than 10% a year for a time, to reach 68.3% in 2017. The alternative fuels used by Germany's cement sector are mainly SRFs and RDFs, and their use is gradually increasing.

Exhibit 14:

Fuel substitution rates in caloric value by region



Source: RMI and CCA

There are three important contributing factors to this development, the first of which is the formation of an alternative fuel industry supply chain. In the 1980s, EU countries started to establish a complete waste recycling and nontoxic waste treatment industry chain, and constantly developed and improved the treatment technology of combustible waste and the conversion of combustible waste into SRFs and RDFs. In Germany, cement producers can use alternative fuel without the need to invest in additional equipment. The purchase and use of alternative fuels are not much different from those of coal and less expensive for German cement producers.

The second factor is the landfill bans implemented in most European countries, which sparked the alternative waste industry as a means of trash disposal. For example, the landfill ban released in 2013 in Poland has increased the alternative fuel substitution rate from less than 20% in 2007 to over 50% in 2015, and relevant technologies have developed rapidly.

The third factor is the national quality control system for alternative fuels. Germany designed a series of standards for alternative fuels, including waste framework standards, industrial pollutant discharge standards, and waste transport standards. The implementation of this system helps ensure that alternative fuels in the market comply with relevant product standards and minimizes the impact of alternative fuel use on cement clinker production.

Solid waste as an alternative fuel is technically feasible and has significant emissions reduction implications. However, the heat replacement rate of cement production in China is relatively low compared with other countries where the rate is commonly over 50% — and as high as 85% in some — so there is still much room for improvement.

The use of solid waste alternative fuels faces several obstacles. First, current standards regard coprocessing by cement kilns as waste disposal rather than fuel replacement. Their management, therefore, is according to standards of waste rather than fuels, resulting in bureaucratic obstacles such as the need for interregional transport permits, which is not conducive to the promotion of cement kiln coprocessing as an emissions reduction technology in the sector.

Second, China has not established a mature solid waste collection, classification, and derived-fuel-processing industry. As a result, domestic waste varies widely in quality, caloric value, and water content, which can affect the processing of waste by cement kilns as well as clinker production capacity, limiting the efficacy of alternative fuels.

Third, there is a risk of toxic components in solid waste flowing into cement products, making it difficult to promote large-scale production for the market. Therefore, in order to promote solid waste fuel substitution, it is necessary to solve the problems of waste fuel positioning, pretreatment technology, cement quality control, and market acceptance. RMI believes solid wastes have great potential for application after relevant standards and technology are improved.

Using biomass fuel to replace traditional fuel does not require a large-scale retrofit of cement kilns — and potentially, in combination with carbon capture technology, could represent a negative-carbon system. One project demonstrating the promise of this technology in China is Conch Zhuyang Cement Plant, which replaces some of the coal burned in the decomposing furnace with crop straw, processing 200 tons of straw waste per day. This project shows that it is technically feasible to partially replace coal with biomass blending. However, large-scale adoption of biomass fuel replacement depends on having the fuel readily available and attractively priced. The cement industry is also faced with competition from other industries that seek to use biomass as fuel.

Cement producers are also exploring the value of photovoltaic thermal, hydrogen, and electricity as alternative fuels. Exhibit 15 (next page) shows some of the new fuel substitution technologies for cement kilns that are in the development and pilot stages. Hydrogen combustion in cement kilns requires significant modification of the existing cement kiln structure and sufficient hydrogen supply, and the thermodynamic properties of hydrogen flame and steam generation make it inconducive to direct heating, so the utilization of hydrogen in cement production still faces hurdles. Cement kilns have high operating temperatures (1,300°C–1,450°C), and the use of electric heating also requires a complete renovation of the existing kiln structure. However, the potential of new energy sources and technologies in the production of low-carbon cement cannot be ruled out.

Exhibit 15: Major alternative fuels for cement production

	Municipal solid waste fuels	Biomass fuel	New renewables such as hydrogen, electricity, and solar thermal
Potential	• China generates 310 million tons of domestic waste and 14 million tons of sludge every year • By 2060, domestic waste will surpass 1 billion tons/year • Caloric value: 1 ton of domestic waste = 300 kg coal, saving about 90 million tons of coal • Reduced CO_2: Emissions factor is 8% lower than that of coal, while also reducing greenhouse gas emissions from landfills	• Straw: 829 million tons per year, of which 694 million tons can be collected • Forestry residues: 9.604 million tons available for energy use • Biomass can become a carbon negative when combined with CCS	• Hydrogen is being developed as a clinker sintering fuel in China • International companies are also exploring solar heating (Synhelion) and other technologies
Maturity	• Waste coprocessing technology is approaching maturity • About 17% of clinker production lines have coprocessing capacity • Systems for collecting, sorting, and preprocessing waste are still in development • Production of RDF is in its early stages, with only a few production lines • There is still a need to improve the technology for using waste as an alternative fuel	• Pilot project: A cement company in China uses 200 tons of straw waste every day, with a heat replacement rate of 10%	• R&D phase (China) and early demonstration phase (international) • Heidelberg Cement piloted a technology to use hydrogen, biomass from other industries, and glycerin as fuels in cement production • CEMEX and Synhelion use solar energy to heat a mixture of CO_2 and water vapor for clinker calcination • Both CemZero in Sweden and a project in Norway in 2018 demonstrated the technical feasibility of combining cement production with electric heating • LEILAC technology incorporated electric heating into its alternative energy plans
Constraints	• Solid waste has not been officially recognized as an alternative fuel • RDF industries and standards need to be established, especially for waste pretreatment • Cement produced from waste has low market acceptance due to potential health risks • Incinerators and waste-to-energy plants use waste competitively, and current subsidies discourage the use of waste as an alternative fuel	• The cost of collection and transport is high • Limited resources and competitive use of biomass fuels (for power generation, heating, etc.) • Availability fluctuates seasonally • The high water content in biomass fuel may affect clinker productivity	• Uncertainty of the development and application of new technologies in the cement sector • If combusted in a cement kiln, hydrogen may not meet the thermal requirements • Hydrogen combustion produces water vapor, which affects clinker production capacity

Source: RMI and CCA

Energy efficiency can be further improved.

The China cement industry has been a global leader in energy efficiency. Comprehensive energy consumption of 1 ton of cement clinker is 90–136 kg of coal equivalent (kgce)/t (2.6–4.0 gigajoules [GJ]/t), which is comparable to or better than the level of 126–130 kgce/t (3.7–3.8 GJ/t) in Europe and the United States.[19] In 2019, there were 26 Chinese cement producers that had comprehensive clinker energy consumption of 100 kgce/t (2.9 GJ/t) or less, reaching the world's advanced level. At present, there are three commonly used low-carbon cement technologies: low-carbon clinker calcination, low-carbon grinding systems, and digitalized cement production. Exhibit 16 (next page) highlights typical projects that demonstrate use of these technologies and their technical and economic indicators.

Even so, China still has some producers in the cement sector that are highly inefficient energy consumers and are in urgent need of technical transformation. Therefore, the cement sector should continue to promote energy-efficient technologies and improve the average energy consumption level of the industry. Based on the new version of the Norm of Energy Consumption Per Unit Product of Cement (GB 16780-2021) released in 2021,[20] about 75% of the clinker production lines in China meet the Level 3 energy consumption per unit product of clinker of 117 kgce/t (3.4 GJ/t). If all clinker production lines are upgraded to Level 1 (100 kgce/t, or 2.9 GJ/t) from the current Level 3, this equates to a reduction in energy consumption and emissions of approximately 14%. With the current trend of technical development, Level 1 energy consumption is close to the limit of energy-efficiency improvement.

Exhibit 16: Technical and economic indicators of major low-carbon cement technologies

Technology	Application case	Investment (million RMB)	Energy-saving capacity (tons of coal equivalence per annum [tce/a])	Emissions reduction (t CO_2/a)	Penetration potential (%)	Expected emissions reduction potential (million tons CO_2/a)
Low-carbon clinker sintering						
High-efficiency low-resistance preheater system with staged combustion	5,000 tons per day (t/d) clinker production line of a cement producer in Shandong	20	6,200	16,120	90	23.0
High-performance heat insulation material technology	5,000 t/d clinker production line of a cement producer in Henan	4	6,318	16,426	90	16.1
New cement clinker cooling technology	A cement producer in Hebei	11–24	8,155	22,600	100	15.7
Oxy-fuel combustion	4,500 t/d clinker production line in Anhui	23–30	5,000	13,000	50	11.0
Low-carbon grinding system						
Cement vertical mill final grinding technology	1 million tons per annum cement producer	69	934	2,428	80	11.5
Roller press raw material final grinding technology	2,500 t/d clinker production line in Anhui	26	1,342	1,489	90	12.3
Digitalized cement production						
Intelligent optimization system for kiln and grinding	• Intelligent optimization system for kiln of a cement producer in the Northwest • Intelligent optimization system for cement grinding of a cement producer in Heilongjiang	2.7–3.5	2,223	5,780	100	15.5

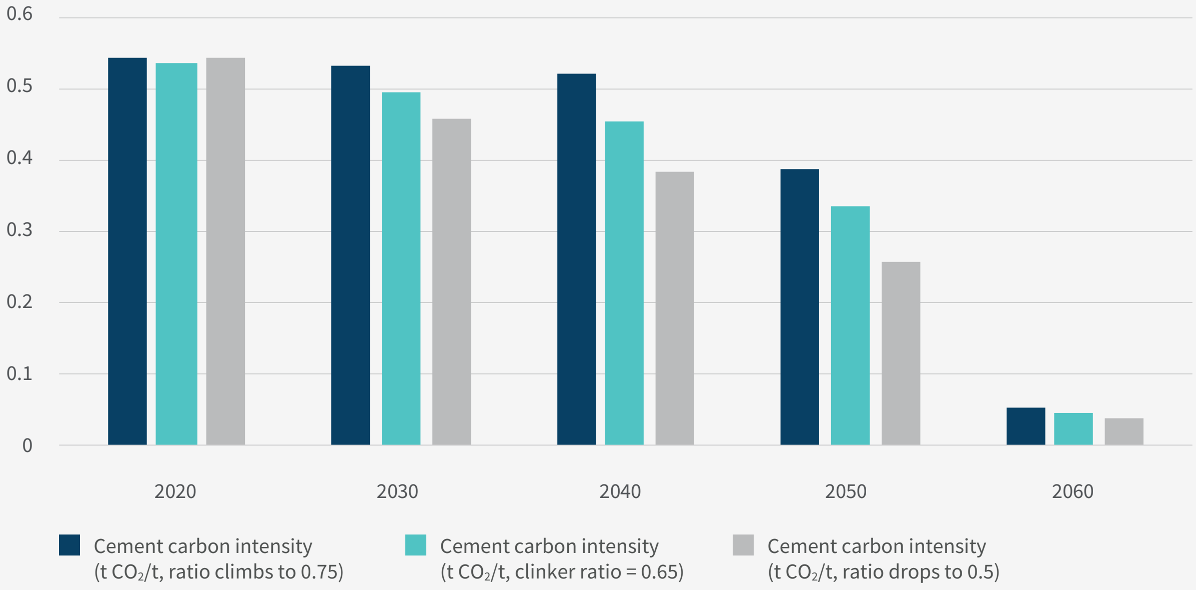
Source: RMI and CCA

Change cement composition for carbon reduction.

There are three ways to change cement composition to achieve carbon reduction: clinker substitution, that is, to control the amount of clinker used and reduce the carbon intensity per unit of cement; raw material substitution, that is, to replace part of the limestone with other materials and reduce the process emissions; and to develop new types of low-carbon cement using new clinker systems not based on calcium silicate.

Proper control of the clinker-to-cement ratio (clinker coefficient) can reduce the carbon content of cement products. Over the next 10 years, the global average clinker coefficient is projected to decrease from the current 0.72 to 0.65. Historically, China's clinker coefficient has been low compared with European and US levels and has noticeably increased with the adjustment of cement standards, reaching about 0.65 in 2020. In the future, changes in the clinker coefficient will impact the carbon intensity of cement (see Exhibit 17). Considering that low clinker content can aid in carbon reduction and can be applied without compromising quality, a revision to the current cement standard should be considered to legalize use of cements with lower clinker contents in building and infrastructure projects.

Exhibit 17: **Carbon intensity of cement with different clinker-to-cement ratios**



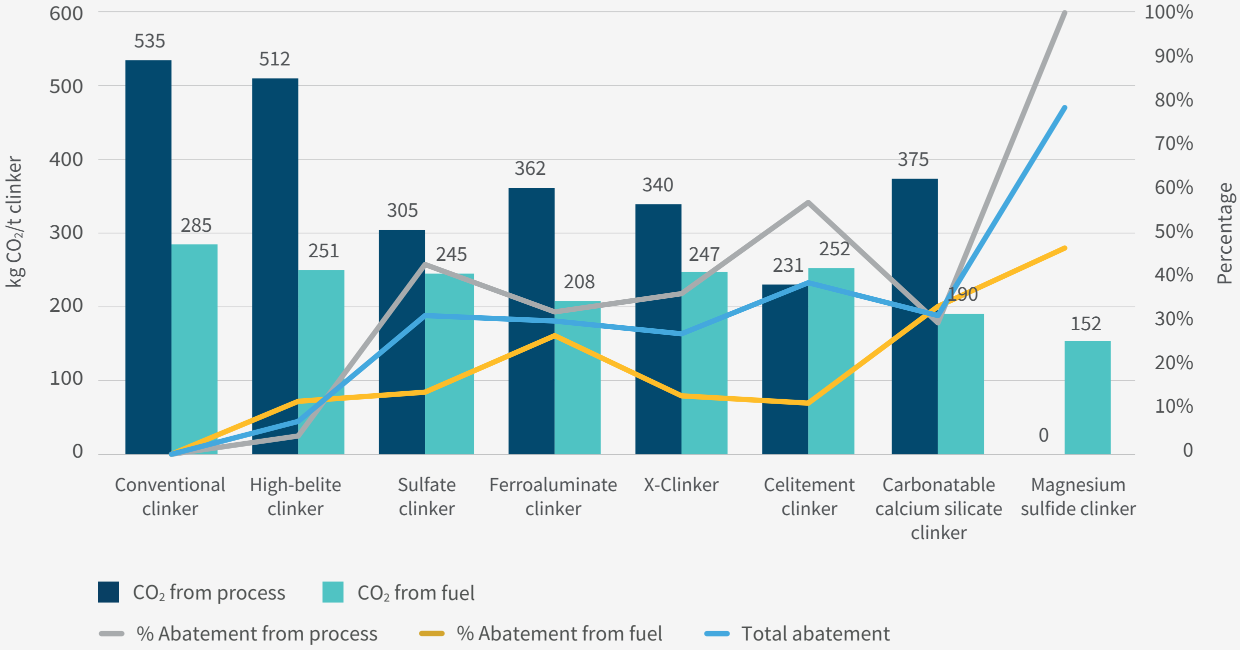
Source: RMI and CCA

Traditionally, the admixture used to replace clinker is mainly industrial waste containing calcium such as coal ash and blast-furnace slag. A lower clinker-to-cement ratio means an increase in the use of admixture. However, as heavy industry undergoes decarbonization, the availability of industrial waste residue will decline. Some new admixtures are under development, such as calcined clay and fine powder of carbonized concrete.

Replacing part of the limestone with low-carbon raw materials helps reduce process emissions. Industrial waste slag containing calcium such as steel slag, calcium carbide slag, silica-calcium slag, and fly ash can replace some of the limestone used in cement production, thus reducing emissions from limestone decomposition in the process of cement calcination. The effect of raw material substitution on carbon reduction depends on the substitution rate. China has abundant industrial waste residue resources that can be used as alternative raw materials in the near term. However, as the industry decarbonizes further, the availability of alternative raw materials will become a challenge. Therefore, raw material substitution is more suitable as a short-term measure to reduce the carbon intensity of clinker.

The development of new clinker or clinker-free cement formulations also opens up possibilities for low-carbon cement. The new low-carbon clinker system is not based on calcium silicate clinker and has low CaO (calcium oxide) content, a low sintering temperature, and low carbon emissions (see Exhibit 18). Examples of low-carbon cement composite materials include high-belite cement, sulfoaluminate cement, Solidia cement, Celitement cement, X-Clinker cement, and magnesium sulfate cement. The application potential of new cement types is still uncertain, and reliant on the availability of raw materials, cement stability and durability, productivity, and price. As pressure increases for emissions reduction in the cement industry and demand grows for low-carbon building materials, alongside the adoption of intelligent production systems, it is reasonable to expect that new varieties of low-carbon cement will occupy an increasing share of the market.

Exhibit 18: Carbon emissions and emissions reduction using replacement cement composite materials



Source: Monica Antunes et al., *Alternative Clinker Technologies for Reducing Carbon Emissions in Cement Industry: A Critical Review*

CCUS technologies are crucial for carbon neutrality in the cement industry.

About 60% of the carbon emissions from cement production come from the thermal decomposition of carbonate in the raw materials. CCUS technologies are essential to achieve cement carbon neutrality because there is currently no alternative process that can completely replace limestone on a large scale. The primary carbon capture technologies applied in the cement sector include oxygen-rich combustion, calcium looping, membrane separation, and Low Emissions Intensity Lime and Cement (LEILAC) — most of which are in the trial or preliminary commercialization stage. By comparing the applicability, energy consumption, and cost of different carbon capture technologies (see Exhibit 19), RMI believes that liquid chemical absorption technology, calcium looping technology, second-generation oxygen-rich combustion technology, and LEILAC technology have the greatest potential to add value in the cement sector.

Exhibit 19: **Major carbon capture technologies applied in the cement sector**

Technology	Applicability	Energy-savings rating	Cost rating	Pros	Cons	Development stage
Pre-combustion capture	4	—	—	Can capture carbon emissions from fossil fuel combustion	Cannot capture carbon emissions from calcium carbonate decomposition	Commercialized
Chemical chain combustion	4	—	—	Can capture carbon emissions from fossil fuel combustion	Cannot capture carbon emissions from calcium carbonate decomposition	Pilot
Liquid chemical absorption	8	7	10	Mature technology, low equipment cost	High energy consumption by desorption tower, high cost of operation and steam	Commercialized
Split calcium looping	9	8	9	Inactive absorbent can be used as raw material for clinker production, high waste heat to power generation, negative electricity cost	High reactor cost, difficult reactor design, high energy consumption of desorption reactor, high equipment cost	Pilot
Integrated calcium looping	10	8	9	Inactive absorbent can be used as raw material for clinker production, low equipment cost, high waste heat to power generation, low electricity cost	Difficult reactor design, high energy consumption of desorption reactor, high equipment cost	Pilot

Membrane separation	8	10	7	Small space requirement, low energy consumption	Gas separation membrane should be replaced regularly, high energy consumption of auxiliary equipment, high equipment cost, high electricity cost, high fixed operating cost	Industrial demonstration
Ionic liquid-based carbon capture	6	—	—	Low absorbent loss	Immature technology	Basic research
Oxy-fuel combustion	8	10	10	Low energy consumption, low cost of equipment	Significant equipment modification	Industrial demonstration
Second-generation oxy-fuel combustion	8	9	9	Low energy consumption, low cost		Pilot
Physical absorption	6	—	—	Simple equipment	High energy consumption	Industrial demonstration
Adsorption	6	—	—	Simple equipment	High energy consumption, high operational cost	Industrial demonstration
LEILAC	9	9	9	Possible application of sustainable energy in clinker production, low cost, low energy consumption, available sustainable energy alternatives	Complex reactor design, carbon capture is only applied in the calciner and needs to be combined with other technologies, capture rate is low at present	Pilot

Source: RMI and CCA

There are challenges to adopting CCUS on a large scale. The costs of achieving emissions reduction with CCUS are still high. Transportation costs for CO_2 are high because cement plants are geographically dispersed. CO_2 concentration in cement kiln flue gas is usually less than 30%, which makes effective capture difficult, and the cost of capture after purification is higher than that of chemical plants. Some leading cement producers in China have begun to pilot CCUS demonstration projects. Conch Cement has built the world's first cement kiln flue gas CO_2 capture and purification demonstration project, with an annual output of 50,000 tons of industrial-grade CO_2 products and 30,000 tons of food-grade CO_2. As the technology matures and the scale effect unfolds, gradually reducing the cost of emissions reduction, CCUS technologies could become essential for the cement sector to achieve carbon neutrality.

CO_2 from cement kilns can also be used in conjunction with the downstream concrete industry. CO_2 mineralized curing concrete technology involves injecting CO_2 into freshly mixed concrete. Through chemical reaction, CO_2 is permanently sequestered in concrete, reducing CO_2 emissions from the concrete production process by 25% or more and resulting in concrete that is more than 10% stronger.[21] China's Zhejiang University team, Solidia Tech in the United States, and CarbonCure Technologies in Canada have all developed CO_2 mineralized concrete technology. Huaxin Cement and Hunan University jointly developed the world's first brick production line absorbing the carbon dioxide from cement kiln, which can replace the traditional clay brick and concrete brick processes, achieving energy savings and carbon reduction. CO_2 curing technology can achieve both carbon-negative CO_2 production and high-quality concrete, providing environmental and commercial value to the cement sector.

CO_2 produced by cement kilns can also be used in geological, chemical, and biological applications. Consider the example of a carbon-neutral consortium in Germany made up of a cement producer in Rudersdorf, electrolyzer producer Sunfire, and renewable energy company Enertrag. Sunfire uses renewable power to produce hydrogen and syngas, and supplies part of the hydrogen for the cement plant to produce calcine clinker. The cement plant supplies CO_2 to Sunfire to produce methanol and other chemicals, achieving carbon reduction and industrial symbiosis.

Zero-carbon cement can be economically viable with carbon pricing and technology development.

The transition to carbon-neutral cement production requires consideration of changes in up-front capital investment and clinker unit cost. The up-front investment required for equipment transformation in cement plants ranges from 1 million renminbi to hundreds of millions of renminbi, depending on the plant. Innovative production facilities under early-stage development require even higher R&D and construction costs. Therefore, the transformation of the cement sector will require investment by cement producers as well as outside investors.

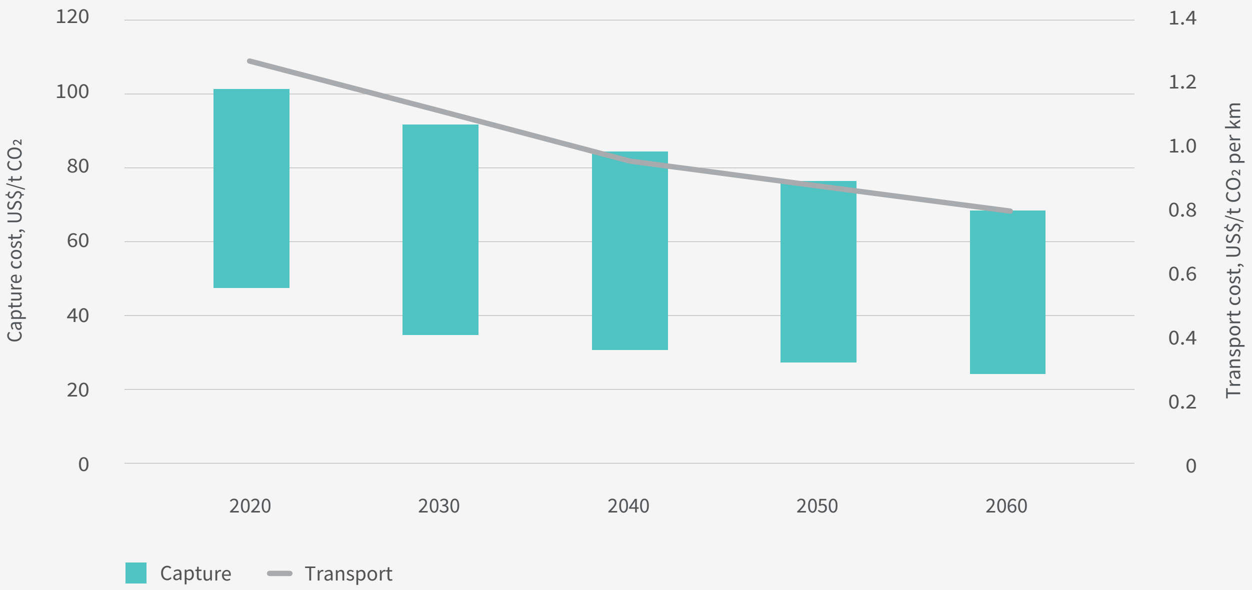
Fuel costs are a major component in the current unit cost for clinker, accounting for more than 50% of the total. Thus, the cost of alternative fuel — whether biomass, solid waste, hydrogen energy, or green electricity — is the most significant cost factor in transition. The second most important factor is the cost of capturing carbon emissions that are difficult to eliminate. The remaining factor is the cost of retrofitting existing cement plant equipment. With increased consolidation in the industry and the development of cement equipment, high-capacity production lines will gradually become dominant, leading to lower equipment costs per unit clinker (below RMB 10/ton). Therefore, the cost of fuel and CCS will continue to be the most significant factors.

The combination of technologies for carbon reduction in cement is complex. To simplify the discussion, we look at the cost of five different routes for producing zero-carbon cement[ii] based on fuel and CCS technologies, assuming the basic components of cement remain unchanged: (1) Coal + CCS, (2) biomass (mainly biomass molded fuel) + CCS, (3) solid waste (mainly RDF) + CCS, (4) hydrogen + CCS, and (5) electrification + CCS.

CCS cost will significantly impact the cost of zero-carbon cement. There are two main factors influencing the cost of CCS in the future: the decline of CCS cost due to technology maturity and scale, and variations in cost depending on the distance of CO_2 transport. The current cost of carbon capture is between RMB 300 and RMB 650 per ton of CO_2 captured. With the maturity and industrialization of carbon capture technology, the cost of CO_2 capture applied to cement is expected to decrease 30%–40% by 2050, to RMB 170–RMB 480 (see Exhibit 20, next page). The transportation cost depends mainly on the distance between the cement plant and carbon storage site. For example, when the transportation distance reaches 200 km, this cost will account for half of the total. The cost of CCS can be greatly reduced if cement producers adopt on-site storage or utilization.

[ii] The term “zero-carbon cement” used in this report refers to cement with near-zero-carbon intensity. Carbon intensity here refers to net emissions, which are the original emissions minus the carbon sequestration. In this report, Scope 1 and Scope 2 emissions are considered in cement production, including direct emissions from cement production and electricity emissions. Due to an unclear accounting boundary, this report does not consider the emissions from using CCS technology.

Exhibit 20: **Cost of carbon capture and transport in the cement sector**



Source: RMI and CCA

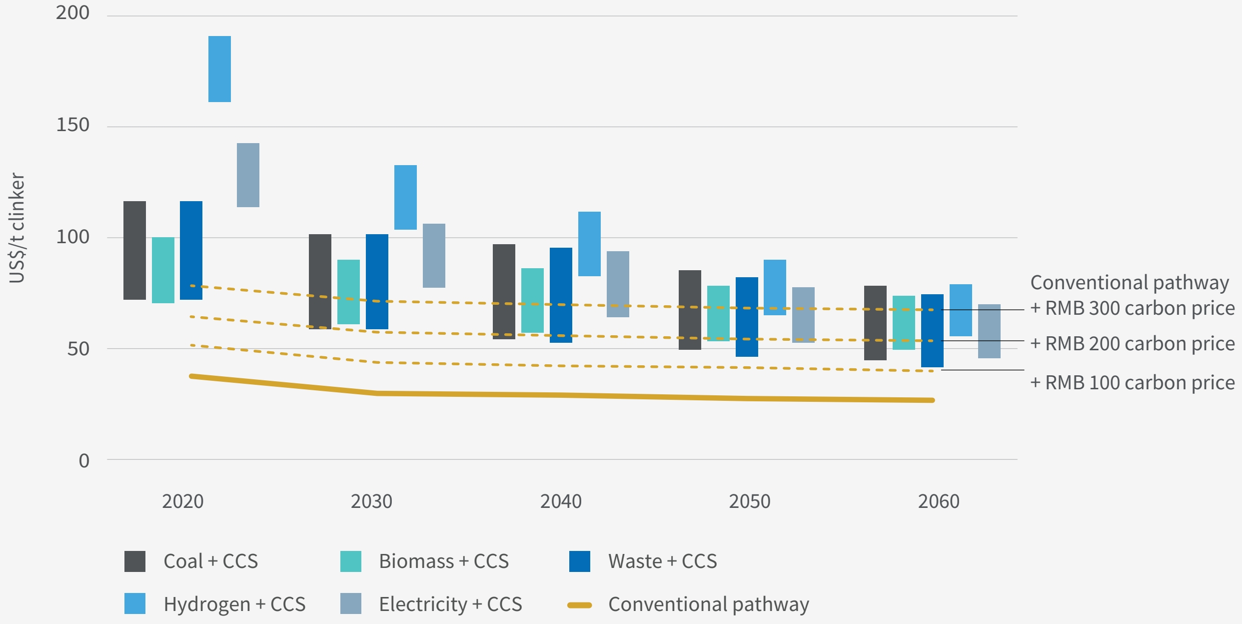
Due to the high cost of alternative fuels and CCS technology, there is a premium of 90%–480% for producing zero-carbon cement (see Exhibit 21, next page). Assuming cement kilns with different fuels produce similar yields, the cost of producing cement using hydrogen and green electricity is significantly higher, with a premium of 200%–400%. The costs of using biomass + CCS, coal + CCS, and solid waste + CCS are similar. The application of solid waste as an alternative fuel in cement production needs to be phased in gradually. At present, when blending small amounts of solid waste, the cost structure is similar to using coal.

Although the cost of the coal + CCS route is similar to that of biomass and solid waste fuel in the short term, two factors need to be considered: First, coal prices will rise with the strengthening of coal control policies, and coal-based production will gradually lose its economic advantage. Second, continued use of coal will increase the emissions from cement production, which will require more CCS and infrastructure investment, increasing the cost of the low-carbon transition of the sector.

By 2050, the premium for zero-carbon cement could fall further as alternative fuels and CCS scale up and become less expensive and CO_2 on-site utilization becomes a possibility. With technological progress and large-scale development, the cost of CO_2 capture and storage will decrease by about 40%. At the same time, the costs of green hydrogen and green electricity will fall by about 65% and 60%, respectively, over the next three decades. This could bring the low-carbon cement premium down to around 70%–240% by 2050. Meanwhile, technological progress is expected to close the cost gap among different zero-carbon cement production methods. The hydrogen- and electricity-based routes will gradually become advantageous when the cost of green hydrogen or electricity is low enough. It is estimated that hydrogen-based cement production will reach cost parity with the solid waste fuel–based route when the price of green hydrogen is less than RMB 5,300/ton, and electricity-based cement production will reach cost parity with the solid waste fuel–based route when the price of green electricity is less than RMB 0.13/kWh.

Exhibit 21:

Costs of various zero-carbon clinkers compared with conventional clinker



Note: Cost estimates are shown as ranges for new pathways due to uncertainties of CCS cost. Cost projections in this figure assume constant coal and raw material costs and constant clinker composition. The prediction of clinker cost in this paper includes the main, but not all, cost factors of clinker, and is only used for comparison. In practice, clinker costs vary among different production lines.

Source: RMI and CCA

Although the cost of zero-carbon cement will approach that of traditional cement in the future, reaching cost parity is unlikely. Therefore, the carbon market and carbon pricing are important enablers for the zero-carbon transition of cement. The cement industry is well placed to be integrated into the national carbon trading market due to good data availability and quality. China's carbon market will gradually cover multiple energy-intensive industries including cement. In the future, carbon pricing will play an important role in promoting emissions reduction of the cement sector. For example, when the carbon price is RMB 100/ton, the cost of producing conventional cement will rise to about RMB 250/ton of clinker, making zero-carbon cement produced from solid waste cost-effective in 2050.

In the short term, reasonable waste disposal subsidies can help incentivize cement producers to use solid waste as an alternative fuel and reduce the cost of solid waste–based production. Currently, local governments give cement factories subsidies of RMB 75–RMB 140 per ton for handling MSWs. The subsidy is lower than that of other waste-treatment approaches such as incineration (RMB 250–RMB 350 per ton) or waste-to-power (about RMB 180/ton) and can barely reach the break-even point (the waste-treatment cost of a cement plant is RMB 130–RMB 200 per ton).[22] Appropriate pricing mechanisms and subsidies for waste processing would make solid waste more economically attractive as an alternative fuel for cement production.

With the combined influence of technological progress, carbon pricing, and financial incentives, the production of cement clinker using solid waste fuel, biomass, electricity, and hydrogen has the potential to become economically feasible and cost-effective compared to traditional cement clinker production.

The Carbon-Neutral Road for China's Cement Industry

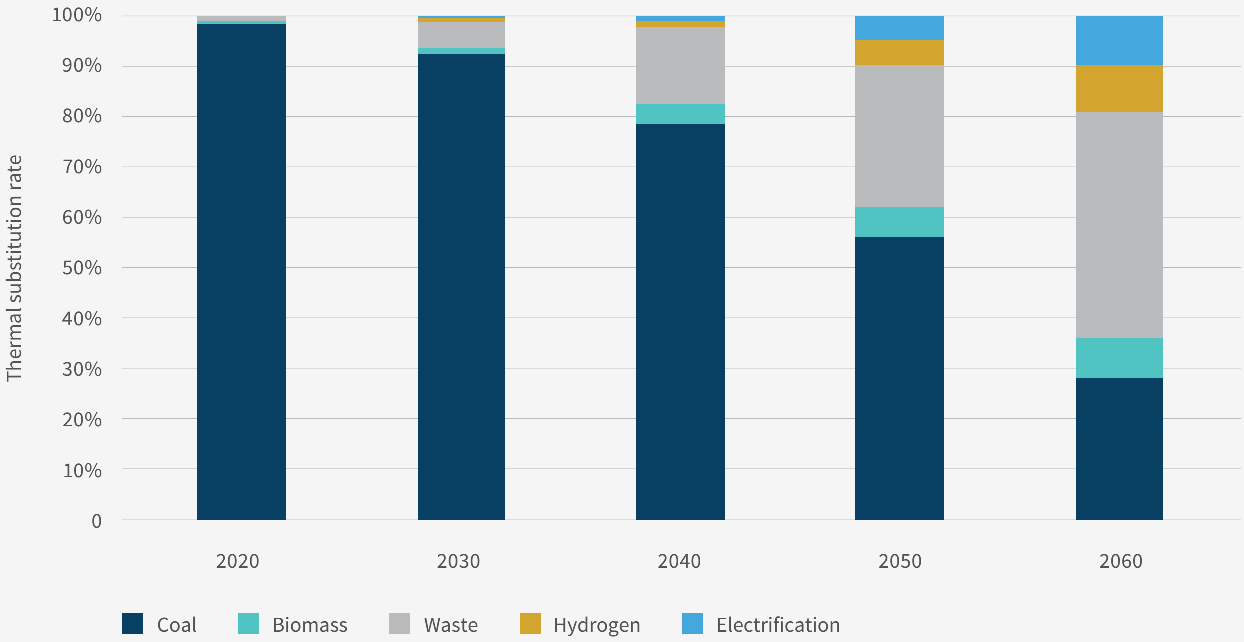
Transition to carbon neutrality gets underway now with mature technologies and reaches near zero by 2060.

In a carbon-neutral scenario, China's cement sector will shift from coal to alternative fuels for clinker production (see Exhibit 22, next page). At present, more than 90% of the energy used in clinker calcination in China comes from coal. Coal will continue to have cost and technological advantages until 2040, but its use will steadily decline. By 2050, when alternative fuels are fully developed, the cement sector can achieve a fuel substitution rate of about 50%, and a rate of about 70% by 2060.

In the development of alternative fuels, solid waste fuels have the first-mover advantage. Coprocessing of solid waste is an existing technology and some domestic cement production lines already have coprocessing capacity, which lays the technical foundation for the development of solid waste–based fuel substitution. With the establishment and improvement of waste management and utilization systems, solid waste pretreatment and fuel production technologies will mature and be standardized in the next decade. With favorable policies and financial leverage, solid waste fuels (including TDFs, RDFs, and SRFs) may become the main alternative fuels due to cost, availability, and other factors, reaching nearly 30% heat replacement rate by 2050 and nearly 45% by 2060.

New alternative fuel technologies will develop and gain initial commercial application in the next two decades. Applications of electricity and hydrogen in cement production are still in the early stages of development. As traditional cement kiln equipment is retired and new cement kiln technology based on hydrogen and electricity is developed and becomes more cost-effective, these systems will occupy a greater share of the cement sector. In the long term (beyond 2050), hydrogen- and electricity-based production are projected to reach a heat replacement rate of 20%–30%. The promotion of biomass as a fuel for production depends on its availability. Due to the competition for biomass fuels from other industries and limited blending rates, the heat replacement contribution of biomass in the cement sector is likely to be limited (about 5%).

Exhibit 22: Fuel use in China's cement industry, 2020–60



Source: RMI and CCA

The road to carbon neutrality in the cement sector can be roughly divided into the following stages (see Exhibit 23, next page).

In the near term (2020–30), the focus of cement decarbonization will be demand reduction and efficiency improvement, helping the sector to achieve an early and high-quality peak in carbon emissions. Biomass and solid waste fuels could serve as viable alternative fuels during this period, reducing the industry's reliance on coal. Technology and standards for solid waste fuels will be gradually established and improved. Hydrogen- and electricity-based technologies will be under development. Early CCUS projects will be developed and demonstrated. By 2030, about 5% of the emissions in the sector could be captured using CCUS, and clean energy will account for about 40% of electricity consumption.

In the medium term (2030–40), demand management, alternative fuels, and CCUS will work together to drive emissions reductions. CCUS technologies will be mature and could capture about 10% of the emissions in the cement sector. Standardization and commercialization of solid waste collection, sorting, and pretreatment will be achieved, with solid waste fuels achieving mass production by 2040. Pilot and demonstration projects of hydrogen- and electricity-based cement production technologies will be established. The share of clean energy in electricity consumption will rise to 55%.

In the long term (2040–50), alternative fuels and CCUS will become more cost-effective and play a bigger role in reducing emissions. With the carbon pricing mechanism, zero-carbon cement will have a cost advantage. By 2050, 30% of the CO_2 emitted by the cement sector will be captured. Most existing cement kilns will reach the end of their service life by 2040, requiring significant reinvestment, and production routes based on new kiln structures such as hydrogen-to-cement, electric kilns, and LEILAC technology will achieve greater penetration. About 50% of combustion heat will be replaced by sustainable energy sources. Carbon emissions from cement production will fall to less than one-sixth of current levels, and the carbon intensity of a ton of cement and a ton of clinker would fall by about 50% compared with current levels.

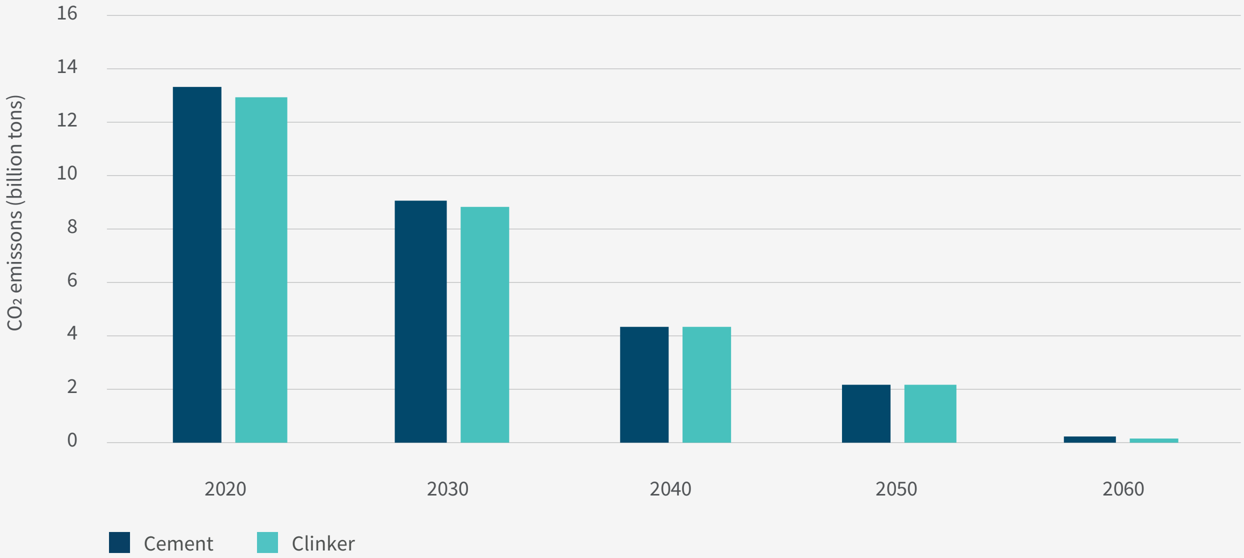
From 2050 to 2060, new alternative fuel technologies such as hydrogen- and electricity-based routes will mature and achieve commercialization. The share of coal as a cement fuel will decline. The fuel substitution rate of the cement sector will reach 70%. Ninety percent of CO_2 produced by the cement sector will be captured. Net CO_2 emissions from the cement sector and carbon intensity of cement products will be close to zero (see Exhibits 24 and 25, next page).

Exhibit 23: Deployment of key technologies on the road to carbon-neutral cement

Levers	Actions	Deployment over time				
		2020	2030	2040	2050	2060
Demand reduction	Reduce cement demand in buildings (mitigation effect)					10%
	Extend building life span (mitigation effect)					5%
	Recycle and reuse cement/concrete (recycling %)	40%				70%
Fuel substitution	Use solid-waste fuels (thermal substitution %)		5%	15%	28%	45%
	Use biomass fuels (thermal substitution %)					8%
	Use hydrogen and electrical kilns (thermal substitution %)			10%		25%
Energy efficiency	Apply clinker calcination energy-saving technologies (application %)	30%	60%	70%	80%	90%
	Apply grinding system energy-saving technologies (application %)		40%	60%	70%	80%
	Apply digitalization (application %)			100%		
Low-carbon cement composition	Reduce clinker-cement ratio			No higher than current national standard		
	Replace raw materials (substitution rate %)			15%		
	Develop low-carbon cement clinker (market share %)					10%
CCUS	Apply carbon capture (CO_2 captured %)		5%	10%	30%	90%
	Produce carbon-cured concrete			Commercialization		
	Make use of CO_2			Commercialization		

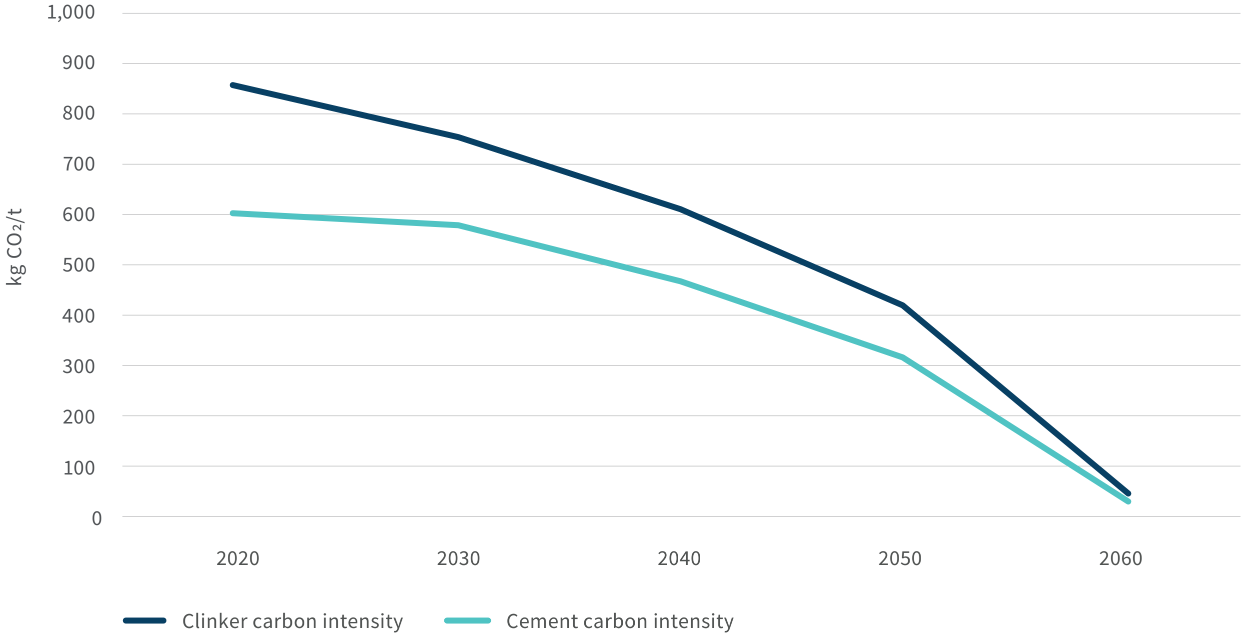
Source: RMI and CCA

Exhibit 24: Carbon emissions from China’s cement and clinker production



Source: RMI and CCA

Exhibit 25: Carbon intensity of China’s cement and clinker

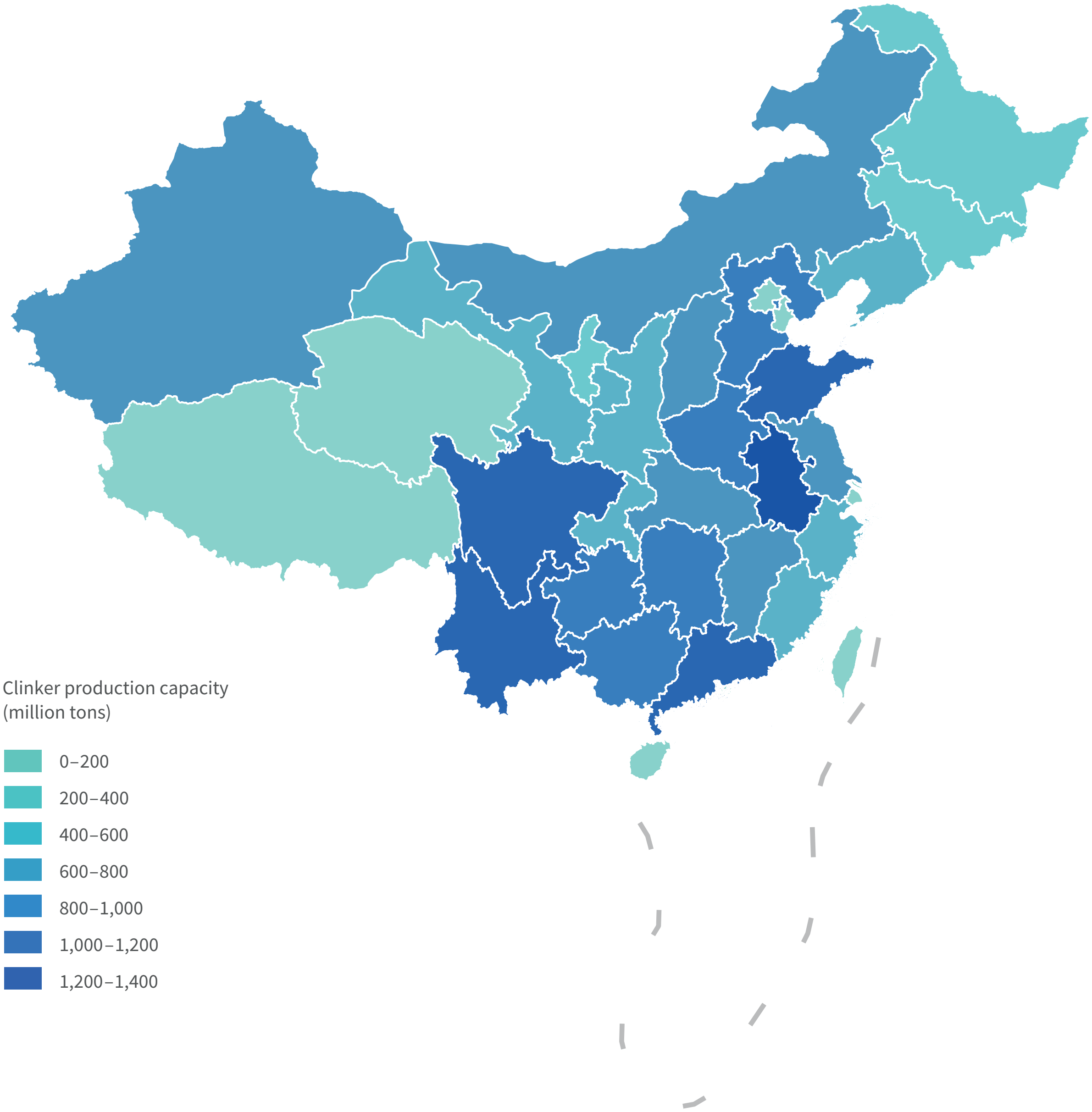


Source: RMI and CCA

Sustainable resources will influence the geographic distribution of low-carbon cement plants.

The geographic distribution of the cement industry in China is relatively dispersed (see Exhibit 26), with production capacity in most of the country's provinces. The main reasons are the national distribution of limestone resources and the need for proximity of cement production to demand. Areas with large construction volumes, such as east and central China, especially in coastal areas and the Yangtze and Yellow River basins, have correspondingly higher cement production capacity.

Exhibit 26: **Distribution of clinker production capacity in China's provinces, 2021**



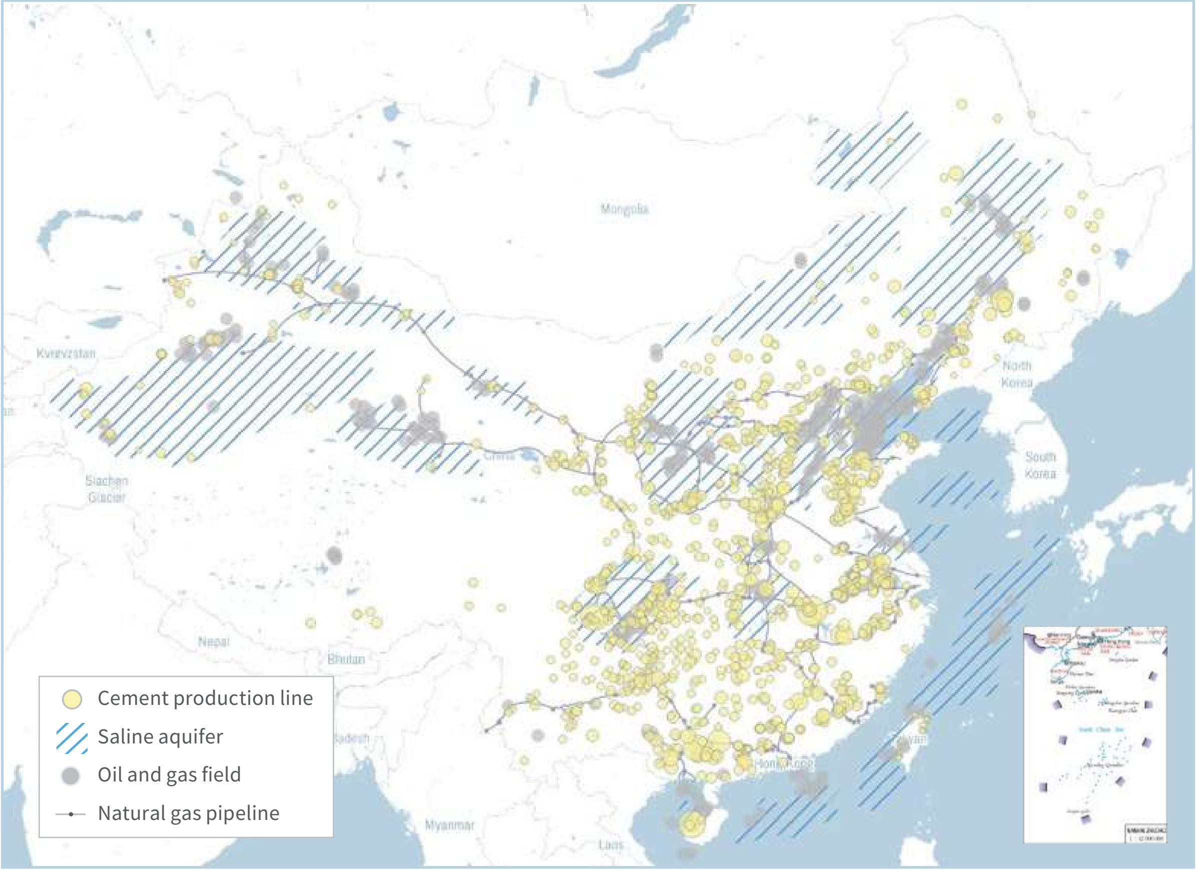
Source: RMI and CCA

The main factors affecting the geographic distribution of zero-carbon cement production capacity in the future will be market demand, raw materials, low-carbon energy availability, and geographic carbon sequestration resources. Carbon sequestration resources will become a major factor in determining the distribution of zero-carbon cement plants, especially due to the wider use of CCS technology under the net-zero scenario.

In terms of construction demand, China's urbanization will continue to be concentrated in coastal areas in the east and emerging central cities. Development envisioned in the 14th Five-Year Plan does not change the outlook for geographic distribution of demand. In the future, the dominant areas of urban construction in China are still expected to be the eastern coastal areas and the central plains. The impact of demand on the geographic distribution of cement capacity will not change much.

There are three main options for carbon sequestration and utilization, namely, deep saline aquifers, oil and gas fields, and natural gas pipeline networks (see Exhibit 27, next page). China's main CO_2 sequestration locations include the Northwest and Qinghai-Tibet Region, Ordos Basin, Bohai Bay Basin, South China Sea Basin, Sichuan Basin, East China Sea Saline Area, and the Pearl River Mouth Basin, while the cement production capacity is mainly concentrated in Anhui, Sichuan, and Shandong provinces. Therefore, different storage technologies should be adopted according to the characteristics of the different geographical locations and geological conditions. There are a large number of oil and gas production fields in Bohai Bay Basin and Ordos Basin, where CO_2-enhanced oil-recovery technology can be gradually used to increase CO_2 sequestration. The southern coastal areas can use the abundant deep saline aquifers (mostly offshore) and offshore oil and gas fields in southern China as well as inland CO_2 storage sites in the Sichuan Basin for future sequestration.

Exhibit 27: **Cement plant and carbon storage site distribution**



Source: RMI and CCA

The construction of China's CO_2 transportation network could follow the example of the natural gas pipeline network. The layout of CO_2 pipelines should consider the geographical location and geological conditions of carbon-intensive industries such as cement plants. CO_2 trunk-line operators could be established in different areas to collect captured CO_2 in trunk lines to reduce the overall cost of pipeline construction.

In terms of new energy resources, North China has rich wind and solar resources, while Southwest China has abundant hydropower resources, and these regions have policy mechanisms to reduce the price of renewable power. Biomass resources are abundant in South China. Cement plants in these areas could explore technological routes for producing zero-carbon cement from green electricity, green hydrogen and biomass.

In the near term, cement production lines located in North China can actively develop fuel substitution based on solid waste and biomass and CCS technology, and in the long term develop clean production systems based on green hydrogen or green electricity using renewable power. Cement production lines located in Southwest and Central China can develop solid waste– or biomass-based systems or use hydropower to develop green hydrogen or green electricity to produce cement and use saline aquifers for CO_2 sequestration. Due to limited CCS resources in East, Southeast and Central South China, cement producers there should consider biomass- and wind-to-hydrogen-based production while using natural gas pipelines for long-distance CO_2 transportation or offshore storage or utilizing CO_2 with other industries in their locality.

Carbon neutrality can transform the industry landscape and nurture new business models.

China's current cement production capacity is relatively dispersed, with the 10 largest producers accounting for 57% — about 1 billion tons of capacity per year — of the national total. Going forward, the cement sector will develop higher industrial concentration, balanced environmental and economic benefits, and closer to zero-carbon resources. In the near term, the transition of the cement sector will focus on capacity structure optimization. To avoid stranding assets as much as possible, cement production lines with earlier commission dates should be prioritized for retirement. Because large-scale production lines often have more advanced production technology, small-scale cement production should be prioritized for retirement, which will also accelerate concentration of the industry. In order to reduce pollution and decarbonize, cement plants with high energy consumption and high carbon emissions that cannot meet environmental protection standards should be prioritized for retirement. Meanwhile, retiring cement production capacity in resource-deficient and ecologically fragile areas will help maximize environmental benefits.

In the medium and long term, the transition of the cement sector will be driven by the availability of zero-carbon resources, including renewable energy and CCUS resources, in places where cement production lines are located. The distribution of CO_2 storage and utilization sites should be considered when CCUS technologies are applied in cement plants. Cement production using biomass as an alternative fuel — which needs to account for the transport radius of biomass — will be developed mainly in areas rich in agricultural and forestry residues. Cement plants using new energy, electric heating, and green hydrogen could be located mainly in the west and other areas rich in wind, solar, and land resources.

The path to carbon neutrality will create new business models and industrial opportunities in the cement sector.

Possibility 1: Cement plants may integrate waste treatment and waste-derived fuel production.

Because cement plants have quality and quantity requirements for waste-derived fuels, capable cement plants could merge with waste treatment operators to produce standardized waste-derived fuels. Cement plants may receive government subsidies for waste treatment, while cities could reduce the ecological footprint of waste treatment.

Possibility 2: The cement industry could develop in coordination with the concrete industry.

CCUS is a necessary technology for cement decarbonization, and one of the more promising means of utilization is to produce mineralized concrete. This technology can increase the strength of concrete and reduce the volume of cement required. The coordinated development of the two industries could make mineralized concrete more cost-effective.

Possibility 3: Cement plants that go through a gradual transition could produce new low-carbon cement.

Non-portland cement and other new binding materials, although currently unable to replace conventional cement on a large scale, will see increased demand because of the impact of the carbon market and gain market share in the future. Developing new varieties of cement can help reduce process emissions and thus reduce the dependence on CCUS, which will be beneficial for the transition of cement production lines that lack access to CCUS resources.

Possibility 4: Cement plants could form symbionts with other industries.

Sharing industrial infrastructure (including CCUS facilities) could lower carbon reduction costs, and the CO_2 produced by cement plants can be raw materials for downstream industries, so cement plants can form a closed-loop symbiotic relationship of material flow and energy flow with other industries.

Accelerating Transition to Carbon Neutrality for China's Cement Industry: Policy Recommendations

Exhibits 28 and 29 (pages 47 and 48) provide recommendations for action by the government and the corporate sector in the short, medium, and long term to gear the industry toward a net-zero scenario. The key policy recommendations are as follows.

Accelerate the inclusion of cement industry in the national carbon trading market and leverage the role of carbon pricing.

Low-carbon cement production technology is likely to increase cement production costs — creating a green premium, particularly in the near and medium term. Leveraging carbon pricing and carbon trading could be the key to ensuring the low-carbon transition. As a high-carbon-emissions industry with good data availability and quality, cement is well placed to be included in the carbon trading market. From the government's aspect, a proper carbon price level is key to incentivizing companies to take action. Given the high cost of carbon reduction in the cement sector, especially when taking CCUS into account, the current carbon price is not enough to function as a market driver. On the corporate side, cement producers should get ready to be included in the carbon market, manage their carbon assets well, create carbon-emissions reduction targets and roadmaps, and actively participate in the monitoring, reporting, and verification of carbon emissions so they can lead in the transition.

Facilitate demand-side actions through carbon-linked green procurement policies and create a green building materials market and ecosystem.

One important driver for the carbon-neutral transition of the cement sector will come from the demand side, especially the concrete and building industries. These industries will be moving to improve structural efficiency, save on construction materials, recycle reusable construction waste, and purchase green and low-carbon building materials. At present, China's construction waste-recovery rate is low, and the green building materials procurement system has not been linked to carbon emissions, so there is untapped potential for demand to bolster the transition of the cement sector. In the short term, carbon-emissions accounting for buildings should include the carbon emissions of construction materials as embedded carbon. In the medium term, a carbon labeling system should be established for low-carbon cement products. Purchasing standards and policies for low-carbon building materials should be established as well. These initiatives could be applied starting with government procurement projects and leading real estate companies to cultivate the market and establish the supply chain for low-carbon cement and building materials.

Leverage green finance to support the green transition by cement producers.

Green financial instruments were created to provide capital for the transition of high-emissions companies and could guide and motivate social capital to participate in the low-carbon transition. In the cement sector, there is an urgent need for a large amount of investment for technical and commercial transformation. However, existing green financial instruments cannot effectively cover all the transition needs of high-carbon-emissions industries, including cement. It is of paramount importance to develop the financial support system for these industries. On the government side, a complete system of financial standards and tools should be introduced to provide a financial support framework for players pursuing a low-carbon transition. Corporations, meanwhile, should be preparing to apply for financial support by creating concrete short-, medium-, and long-term transition strategies or action plans, and improving carbon-emissions accounting and reporting.

Promote a circular economy to achieve large-scale production and application of solid waste fuels.

Solid waste fuel has great potential as an alternative fuel for emissions reduction in the cement sector — and could have a profound impact on the industry. The positioning of cement kiln coprocessing as waste treatment rather than alternative fuel in current standards may limit the development and large-scale application of solid waste fuel. The subsidy for waste treatment provides little economic incentive for cement producers. The government should improve the system of collection and classification system of MSW, encourage the establishment and standardization of the solid waste fuel industry, and provide a technical and administrative foundation for using solid waste as an alternative fuel. At the same time, the government should provide incentives, such as subsidies, to cement producers to promote the use of solid waste fuel. On the corporate side, cement producers could promote the establishment of relevant standards and industries by virtue of their demand for large volumes of high-quality solid waste fuels. Large cement groups, environmental industry companies, and infrastructure investment funds should be encouraged to engage in the deep processing industry of combustible waste and produce standardized alternative fuel products.

Exhibit 28: **Short, medium, and long term government actions for carbon-neutral development in the cement sector**

Type	Specific policy	Short term	Medium term	Long term
Mandatory policies	Strict project approval	★		
	Outdated capacity phaseout	★		
	Energy dual control and carbon-emissions dual control	★		
Incentive policies	Carbon pricing policy	★	★	★
	Tax credits for low-carbon technologies		★	
	Green finance	★	★	★
	Low-carbon product certification and procurement		★	
Supportive policies	Low-carbon industrial parks		★	
	Solid-waste collection and pretreatment system and solid-waste fuel system	★	★	
	Infrastructure for major innovative technologies such as hydrogen, solid waste, biomass, and CCUS		★	★
	Support for key technology R&D and demonstration	★	★	
	Refine cement certification system	★	★	

Source: RMI and CCA

Exhibit 29: Short, medium, and long term actions by producers for carbon-neutral development in the cement sector

Type	Specific policy	Short term	Medium term	Long term
Create carbon-neutral strategy and roadmap	Propose specific decarbonization target	★		
	Conduct research on the roadmap and timeline for decarbonization	★		
Promote R&D and application of key carbon-neutral technologies	Actions to improve energy efficiency	★		
	Actions to phase out outdated capacity	★		
	Actions to promote fuel substitution and renewable electricity	★	★	★
	Actions to promote raw material substitution		★	
	R&D of new binding materials and low-carbon cement		★	
	Carbon-sink projects	★	★	
	CCUS projects	★	★	★
Strengthen carbon-emissions management and policy creation	Establish corporate carbon-emissions management system	★	★	
	Establish corporate carbon-assets management system		★	
	Establish corporate response mechanisms to dual carbon policy, such as industry chain and carbon market	★	★	★
	External communications and cooperation	★	★	★
	Low-carbon innovation, R&D, and team cultivation	★	★	★

Source: RMI and CCA

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