Building Technologies & Urban Systems Division
Energy Technologies Area
Lawrence Berkeley National Laboratory

Evaluating Net-Zero Emission Pathways for China's Cement Industry

Hongyou Lu [1], Nan Zhou [1], Hon Leung Curtis Wong [1], Xian Zhang [2]

[1] Lawrence Berkeley National Laboratory, [2] The Administrative Center for China's Agenda 21

Energy Technologies Area
June 6, 2024

https://doi.org/10.20357/B75W27

This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy,
Building Technologies Office, of the US Department of Energy
under Contract No. DE-AC02-05CH11231.

No. 9-037-24 + Hongyou Lu

Evaluating Net-Zero Emission Pathways for China's Cement Industry

Hongyou Lu
Lawrence Berkeley National Laboratory
1 Cyclotron Road Mailstop 90R2121, Berkeley, CA 94720
Email: hylu@lbl.gov

Nan Zhou
Lawrence Berkeley National Laboratory
1 Cyclotron Road Mailstop 90R2121, Berkeley, CA 94720
Email: NZhou@lbl.gov

Hon Leung Curtis Wong
Lawrence Berkeley National Laboratory
1 Cyclotron Road Mailstop 90R2121, Berkeley, CA 94720
Email: curtis_wong@lbl.gov

Xian Zhang
The Administrative Center for China's Agenda 21
8 Yuyuantan South Road, Haidian District, Beijing, China
Email: zhangxian@acca21.org.cn

Abstract

China's cement industry emits over 1 Gt of carbon dioxide (CO_2) annually, or 3% of global CO_2 emissions. Urgent decarbonization efforts of the Chinese cement industry are needed to meet China and global community's climate commitments. Prior studies on this topic primarily relied on supply-side technologies and end-of-pipe solutions, presenting one singular pathway to net zero without exploring multiple trajectories.

This study adds value to the existing research by constructing and evaluating two different pathways toward net-zero emissions in China's cement industry: the Energy Technology Pathway (ETP) and the Circular Economy Pathway (CEP). Both pathways aim for net-zero emissions but diverge in their prioritization and emphasis. The Energy Technology Pathway focused on supply-side technologies such as green hydrogen and CCS, while the Circular Economy Pathway focused on demand-side strategies, centered on materials and resources.

The study showed both pathways can achieve a comparable level of emission reduction, reducing 94-95% of CO_2 emissions by 2060 from the 2020 level. Notably, the role of CCS is limited in the CEP, contributing only 5% and 22% of total emission reductions by 2030 and 2060, respectively. The majority of the emission reductions in CEP are achieved through a combination of material-focused innovations and circular economy strategies, such as increasing the use of supplemental cementitious materials (SCMs), advancing alternative cements, integrating material efficiency practices in product lifecycle phases, and adopting alternative fuels (e.g., industrial wastes and agricultural byproducts). Policy support on materials and the circular economy will be critical. We recommend updating codes and standards to allow performance-based cement products, providing R&D support on alternative cements, developing implementation guides to disseminate material efficiency practices, and improving material/waste collection, sorting, and recycling systems.

Introduction

Cement and cement products are foundational materials for society. They are used extensively in residential and commercial buildings, industrial facilities, highways and bridges, and other transportation systems, power plants, and infrastructure systems to distribute electricity, heat, gas, and water. Globally, the cement industry is one of the most energy and carbon-intensive sectors. It accounted for 7% of global carbon dioxide (CO_2) emissions (GCCA 2021), or about 3.5 gigatonnes (Gt) of CO_2 emissions per year.

China has been the world's largest cement-producing country for at least 20 years. In 2022 alone, it produced a total of 2.1 billion tonnes of cement, accounting for 52% of global production (USGS 2023). CO_2 emissions from the Chinese cement industry represented 13% of China's total CO_2 emissions in 2020 (Xinhua Net 2022). To achieve China's climate goals, i.e., carbon peaking before 2030 and carbon peaking before 2060 (or "Dual Carbon" goals), it is imperative to significantly mitigate China's cement industry emissions.

Most of the current research on decarbonizing China's cement industry focused on supply-side technologies and/or end-of-pipe solutions, which are complex engineering systems and capital intenvise. Prior research showed that technologies such as fuel switching and carbon capture, utilization, and storage (CCUS) will play significant roles in achieving near-zero emissions in China (He et al. 2023; RMI and China Cement Association 2022; Li 2021). Often, previous studies present only one pathway as the most plausible pathway to net-zero emissions, without exploring multiple pathways to deep mitigation.

This analysis adds value to the existing literature and studies on China's cement industry decarbonization. We developed three scenarios and compared two potential near-zero pathways – an Energy Technology Pathway (ETP), and a Circular Economy Pathway (CEP). Both pathways have the potential to reduce the cement industry's CO_2 emissions to near zero. However, the pathways differ in their prioritization and emphasis on decarbonization strategies, with the ETP focused on supply-side technologies such as green hydrogen and CCUS, and the CEP focused on demand-side and circular economy strategies such as material efficiency strategies, clinker substitution, and alternative cements.

First, we provided an overview of the current status of the Chinese cement industry. Then, we briefly summarized the modeling approach, including the modeling framework, scenario designs, and key characteristics of each of the scenarios. The Results Section presented the main findings of this analysis, highlighting the energy and emission implications and contributions from each of the decarbonization strategies. We discussed the policy implications for China and other emerging economies. The purpose of this paper is to develop a bottom-up decarbonization roadmap for China's cement industry. In addition, some of the policy findings may be also beneficial for other emerging economies, which are expected to have higher cement demand while meeting their climate change goals.

Cement Industry in China

The cement industry plays an important role in supporting China's economic growth and urbanization. With the development of China's economy and urbanization., China's cement production increased from 232 million tonnes (Mt) in 1990 to more than 2,100 Mt in 2022, growing 7.2% per year on average. By 2022, China's cement production represented 52% of the total production in the world. As shown in Figure 1, cement production in China seemed to have peaked in 2014 and then began to gradually decline at around 2% per year on average from 2014 to 2022 (NBS 2023). China's cement industry has pledged to achieve carbon peaking before 2023, ahead of China's national climate goal (CBMF 2022; China Government Website 2022). Most of the experts we interviewed agree that reaching carbon peaking is not a challenge for China's cement industry, given that both clinker and cement production seem to have already peaked, and further demand reduction is expected.

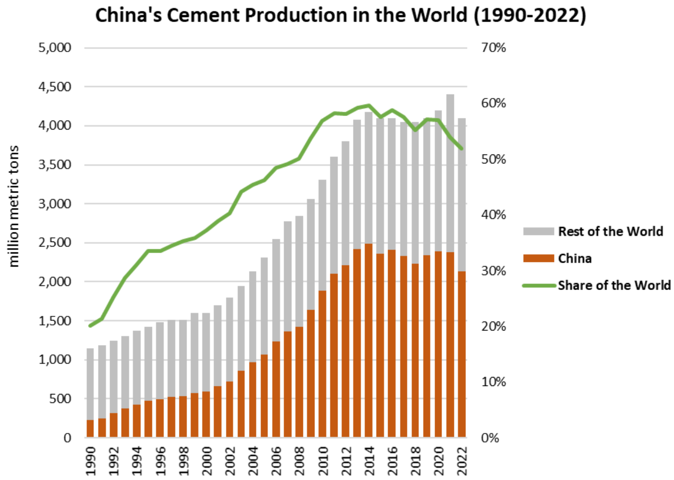

Figure 1. China's cement production in the world (1990-2022)

Sources: USGS 2023; NBS 2023.

China's cement production and consumption are strongly linked to real-estate industry development and fixed-assets investment. On average, about 40% of cement is used to develop urban buildings while another 35% is used for infrastructure systems, such as energy supply systems, railways, roads, pavements, and highways (Figure 2 top). The remaining 25% of cement is used in rural housing and infrastructure. Over the years of urbanization and economic development, the construction type of Chinese rural housing has been shifting from traditional brick and mortar walls to poured concrete walls. In addition, about 60% of the cement produced in

China is used to make concrete products. Mortar production and brick production each accounted for another 20% of cement consumption (Figure 2 bottom).

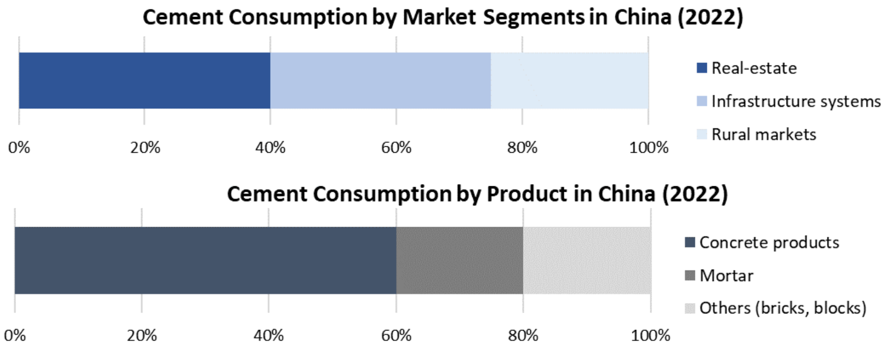

Figure 2. Cement consumption by market segments (left) and product (right) in China

Source: personal communication with the experts from the China Cement Association.

The cement industry is the second largest CO_2-emitting industry in China, after the iron and steel industry. By 2020, the cement industry contributed to 13.5% of China's total CO_2 emissions (Xinhua Net 2022). The process-related CO_2 emissions, i.e., calcination of limestone, represented 60% of total emissions. Onsite fuel combustion for cement production accounted for about 35% of total CO_2 emissions in the cement industry. Emissions associated with purchased electricity (Scope 2 emissions) represented about 5% of total CO_2 emissions in China's cement industry (He et al. 2023).

By the end of 2022, China had 1,572 rotary kiln production lines with a designed total clinker production capacity of 1.84 billion tonnes per year. The actual clinker production capacity is estimated to be more than 2 billion tonnes per year (Digital Cement 2023a). In the past 10 to 15 years, the Chinese government implemented policies such as "replacing small, inefficient with larger, efficient capacities" (Zhou et al. 2022; Xinhua Net 2018). Smaller kilns have been replaced with larger and newer capacities. By 2022, about 75% of the clinker capacity came from kilns with a capacity of 2,500 tonnes per day (tpd) or higher. About 69% of the clinker capacity was from kilns with a capacity of 4,000 tpd or higher (China Environmental Impact Assessment 2023).

The Chinese government has been encouraging industry consolidations to phase out inefficient capacities and improve efficiency. By 2022, about 58% of the clinker production capacity belong to the Top 10 largest cement manufacturers in China (Table 1). About half of the Top 10 cement companies are state-owned enterprises (SOEs), either at the central or provincial level, and these SOEs controlled almost 50% of the total clinker production capacity in China. It could be argued that these SOEs have more responsibility and pressure to decarbonize China's cement industry and support China's "Dual Carbon" climate goals.

Table 1. Top 10 Cement Companies in China (2022) by Clinker Production Capacity

No.	Companies [English]	Companies [Chinese]	2022 Clinker Production Capacity (Mt/year)	Share of National Total	Ownership
1	China National Building Materials Group	中国建材集团	385	21%	Central SOE
2	Anhui Conch Cement	安徽海螺水泥股份有限公司	221	12%	Provincial SOE (Anhui)
3	Tangshan Jidong Cement	唐山冀东水泥股份有限公司（含金隅）	109	6%	Provincial SOE (Beijing)
4	Hongshi Holdings Group	红狮控股集团有限公司	67	4%	Private
5	China Resources Cement	华润水泥控股有限公司	67	3%	Central SOE
6	Huaxin Cement	华新水泥股份有限公司	63	3%	Foreign with local SOE*
7	Shandong Shanshui Cement Group	山东山水水泥集团有限公司	54	3%	Private
8	Taiwan Cement	台湾水泥股份有限公司	43	2%	Foreign
9	Tianrui Cement Group	天瑞水泥集团有限公司	34	2%	Private
10	Asia Cement	亚洲水泥（中国）控股公司	22	1%	Foreign

Sources: Digital Cement 2023b; Downie 2021.

*Foreign with local (Huangshi City, Hubei Province) SOE as a minority shareholder.

Cement manufacturing in China is a localized production. Every province (or provincial-level municipality) has cement production (Figure 3). In 2022, Guangdong province produced the most, at 151 Mt, or 7% of the national total; while Beijing produced the least, at 2 Mt, or 0.1% of the national total. Cement production is more concentrated in the southeast region of China, but also significant in the southwest and central China.

This level of localization, partly based on the abundant availability of raw materials (e.g., limestone) and partly driven by the need to reduce transportation costs, should be considered when identifying potential technologies (e.g., green hydrogen or renewables) and strategies to decarbonize the cement industry. To rapidly decarbonize the cement industry, standards and regulations on cement (and cement-based products) need to think beyond national-level, "one size fits all" requirements, but allow cement production to be adaptive to local resources of raw materials and energy sources, as well as local specific applications.

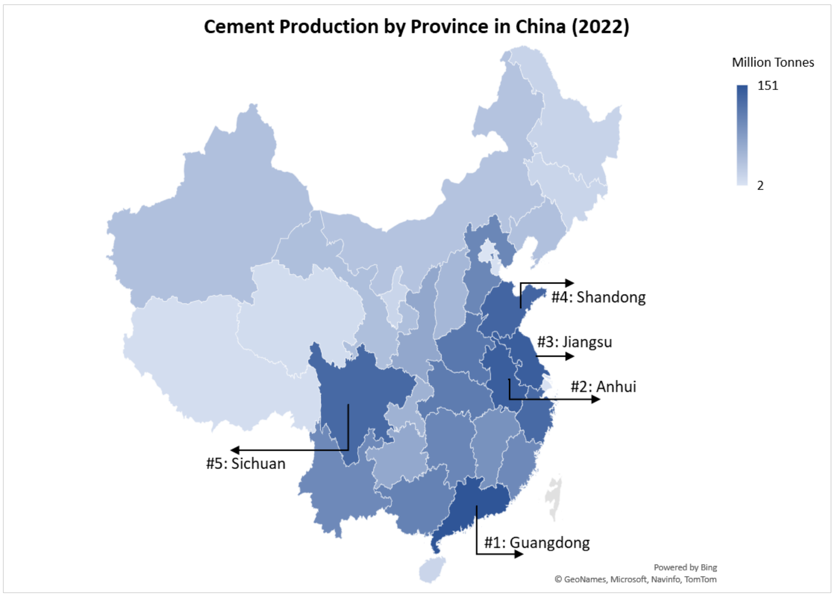

Figure 3. Cement production by province in China (2022)
Sources: NBS 2023; this analysis.

During the 14th Five-Year Plan (2021-2025), the Chinese government also established targets to improve the cement industry's energy efficiency, increase the use of alternative fuels, and limit clinker production capacity. This includes an energy intensity reduction of 3.7% by 2025 from the 2020 level for clinker production, increasing the share of production capacity to reach energy-efficiency benchmark levels to 30% by 2025, increasing the percentage of kilns that use alternative fuels to more than 30%, and limit clinker capacity to be no more than 1.8 billion tonnes by 2025 (Table 2).

Table 2. Energy and carbon targets for the cement industry in China

Categories	Indicators	Targets
CO_2 mitigation	Carbon peaking	Before 2023
Energy efficiency improvement	Energy intensity of clinker production	Reducing 3.7% by 2025 from 2020 level
	Share of production capacity reaching the announced benchmark level in energy efficiency (see Table 3 below)	30% by 2025
Alternative fuels	Share of kilns using alternative fuels	>30% by 2025
Limit production capacity	Clinker capacity	No more than 1.8 billion tonnes by 2025

Source: CBMF 2022; LBNL analysis.

Specifically, the Chinese government recently re-focused on improving industrial energy efficiency and indicated that it planned to leverage the actions of industrial energy efficiency to advance efforts on carbon mitigation. The National Development and Reform Committee (NDRC) of China announced guidance on *Promoting energy conservation and emission reduction in key sectors by strictly using energy efficiency requirements* in 2021 (NDRC 2021a). NDRC published *Energy Efficiency Benchmark and Standard Levels for Key Industrial Sectors (2023 version)* in June 2023 (NDRC 2023). The cement industry is required to have 30% of the clinker production capacity reach the energy intensity of 100 kilograms of coal equivalent (kgce) per tonne of clinker by 2025 (Table 3).

Table 3. Energy intensity benchmark and standard levels for clinker production in China

Key industry	Benchmark Levels	Standard Levels	Reference Standard

Clinker production	100 kgce/t clinker 2.93 GJ/t clinker	117 kgce/t clinker 3.42 GJ/t clinker	GB 16780

Source: NDRC 2023.

To achieve the target, NDRC requires local governments to develop a timeline and annual plans to either retrofit or phase out inefficient capacities. The Chinese government also encourages the local governments to use existing policy tools, such as loans, green credits, green bonds, climate finance, differential pricing, supervision and inspection, and enforcement of environmental protection laws.

However, specific policies on how to accelerate the cement industry to achieve net-zero emissions by 2060 seem lacking in China. Chinese experts that we interviewed for this study expect the cement industry to be included in China's cap-and-trade program soon. Discussions on low-carbon cement as well as the use of carbon capture, utilization, and storage (CCUS) are also ongoing. However, urgent policy actions are needed to expand beyond improving energy efficiency and tackle the decarbonization challenge using a portfolio of strategies from both the supply-side and demand-side solutions. Thus, we conducted this study, developed multiple pathways building on China's existing targets and policy guidance, and compared their differences in reaching near-zero by 2060. We especially highlighted the material-level, demand-side strategies that have not been emphasized by existing policies.

Modeling Approach

Modeling Framework

This study is developed based on the modeling work of the *China Energy Outlook 2022* (Zhou et al. 2022), which used Berkeley Lab's *China 2050 Demand Resources Energy Analysis Model* (China 2050 DREAM) to develop bottom-up scenario projections of China's future energy and emissions. The China 2050 DREAM follows a bottom-up energy end-use accounting framework of China's energy and economic structure built using Stockholm Environment Institute's Low Emissions Analysis Platform (LEAP). Using the LEAP platform, the China 2050 DREAM framework employs both macroeconomic and non-linear, physical drivers to model integrated feedback within and across buildings, industry, transportation, and energy transformation (primary energy supply including electricity) sectors.

China 2050 DREAM differs from most other integrated assessment models in that uses non-linear, physical drivers such as population, demographics, and land area to drive the future growth of energy-consuming activities in buildings, industry, and transport. In not relying solely on economic growth to drive future energy consumption, the use of these additional physical drivers helps capture potential saturation effects in energy equipment ownership and usage, living space and urban infrastructure, and fertilizer use that can contribute to the plateauing of energy demand. This unique approach also captures important cross-sectoral linkages that may not be in other models, such as how slowdowns in new building and infrastructure construction can reduce domestic cement, steel, and glass demand for construction. Lastly, the China 2050 DREAM incorporates decades of detailed Chinese energy-related statistics at sectoral and fuel-specific levels tracing back to 1980 and also characterizes the latest energy-consuming technologies in terms of energy efficiency and fuel mix for various end-uses.

For calculating and reporting primary energy consumption, the China 2050 DREAM uses the direct equivalent approach (consistent with the Intergovernmental Panel on Climate Change, IPCC) as the default for converting primary electricity, rather than the power plant coal consumption (PPCC) method used in Chinese statistics (Lewis et al. 2015). For calculating energy-related carbon dioxide (CO_2) emissions, China-specific fuel energy and heat content are entered into the model and multiplied by the IPCC default CO_2 emissions factors for specific fossil fuels (IPCC 2006). For other studies developed using China 2050 DREAM, please see Lu et al. 2022 and Khanna et al. 2019.

Scenario Design

To analyze the decarbonization pathways in China's cement industry, we constructed three scenarios and two of which have the potential to reach near-zero by 2060:

- **Reference Scenario**: assumes that China's cement production will slow down significantly driven by slowing urbanization, declining population, and a slower pace of economic development (He et al. 2023). It assumes no additional new policies, with gradual improvements in energy efficiency improvements and slow progress in energy transition.
- **Energy Technology Pathway (ETP)**: aims to achieve near net-zero emissions in China's cement industry by 2060. It considers all pillars of decarbonization from both supply and demand-side strategies.

However, this scenario emphasizes supply-side technology innovation, such as green hydrogen, renewable heating, and carbon capture, utilization, and storage (CCUS). It assumes major technology breakthroughs and aggressive adoption of these technologies, supported by significant investment and policy support.

- **Circular Economy Pathway (CEP):** aims to achieve near net-zero emissions in China's cement industry by 2060. It considers all pillars of decarbonization from both supply and demand-side strategies. But this scenario emphasizes demand-side deep mitigation measures, such as optimizing cement consumption throughout the product value chain, improving building design, increasing the use of prefabrication, extending building lifetime, increasing material substitution, and improving recycling, as well as circular economy strategies, such as the use of alternative fuels and low-carbon cements. It assumes major shifts in business and engineering practices, with significant regulatory and policy support.

Table 4 below summarizes the key decarbonization strategies and the emphasis of the measures in each of the three scenarios. The bolded areas indicate these strategies are prioritized in the respective scenarios.

Table 4. Decarbonization strategies of the cement industry and prioritization by scenario

	Material Efficiency	Energy Efficiency	Clinker Substitution and Alternative Cements	Fuel Switching	CCUS
	Improved building design; optimizing cement content in concrete	Improving thermal energy efficiency	Use of SCM: coal fly ash, blast furnace slags	Alternative fuels: industrial wastes, municipal solid wastes, agricultural byproducts	Post-combustion CO_2 capturing technologies
	Extending product lifetime; increased use of precast components and post-tensioning of floor slabs	Improving electrical energy efficiency	Use of SCM: calcined clay, end-of-life binder	Onsite renewables	Oxyfuel combustion CO_2 capturing or calcium looping
	Alternative materials (e.g., mass timber); additive manufacturing	Smart energy management	Use of SCM: other byproducts (e.g., silica fume, bauxite residue, agricultural byproduct ashes)	Hydrogen blending	Integrated calcium looping with the calcination process
	Recycling construction wastes; recycling concrete into recycled concrete aggregates	Integrative design/system optimization	Alternative cement chemistry	Concentrated solar	CO_2 mineralization (CO_2 mixing and curing)*
Reference Scenario	No adoption	Gradual improvement	The clinker-to-cement ratio stays at the 2020 level	Slow replacement of coal using alternative fuels	No adoption
Energy Technology Pathway	Moderate adoption	Approaching practical minimum levels	Moderately using clinker substitutions and alternative cements	**Aggressive implementation of zero-carbon sources (green H_2 and renewable heating)**	**Aggressive large-scale adoption**
Circular Economy Pathway	**Aggressive adoption**	Approaching practical minimum levels	**Aggressively reducing the clinker-to-cement ratio and increasing the development and use of alternative cements**	**Aggressively using low-carbon alternative fuels****	Limited adoption

Source: this analysis. *CO_2 mineralization potential is modeled at a high level in this paper. Technologies are grouped and called as "recarbonation" in the paper. ** Alternative fuels include industrial wastes, solid wastes, byproducts, agricultural residues, and municipal solid wastes. Notes: 1) SCM stands for supplemental cementitious materials. 2) Bolded areas are prioritized with high adoption.

Results

Improve material efficiency

Our modeling results show that China's cement production will significantly decline, mainly driven by a declining population, slowing urbanization growth, and the structural shift of the Chinese economic growth model from investment (e.g., in the real estate industry and infrastructure) to domestic consumption. In the Reference Scenario, total cement production declines from 2,130 Mt in 2022 to 1,608 Mt by 2030, and further to 747 Mt by 2060.

The trend of production decline deepens in the Circular Economy Pathway (CEP), where total cement production is 8% and 24% lower by 2030 and 2060, respectively, compared to Reference (Figure 4). This additional demand reduction is the result of the aggressive implementation of strategies that improve material efficiency of cement and cement-based products. For example, CEP expects that the average building lifetime in China will be more than doubled (from 30 years to 70 years by 2060) in 24% of the new buildings by 2030 and 80% of all new buildings by 2060 (Cao et al. 2019; Q. Wang 2010; Aktas and Bilec 2012; Sandberg et al. 2016). Prefabrication techniques will be widely adopted, reaching 80% by 2060 in all urban residential and commercial buildings. In addition, optimizing the amount of cement used in products to deliver the performance needed while minimizing consumption, reducing construction wastes, and recycling of concrete products are also aggressively adopted in this scenario.

In contrast, the Energy Technology Pathway (ETP) only moderately implemented strategies that can reduce material demand, e.g., the doubling of average building lifetime only affects 30% of the new buildings by 2060 and prefabrication only reached 50% of the urban buildings. This resulted in a 4% and 9% reduction of total cement production by 2030 and 2060, respectively compared to the Reference Scenario.

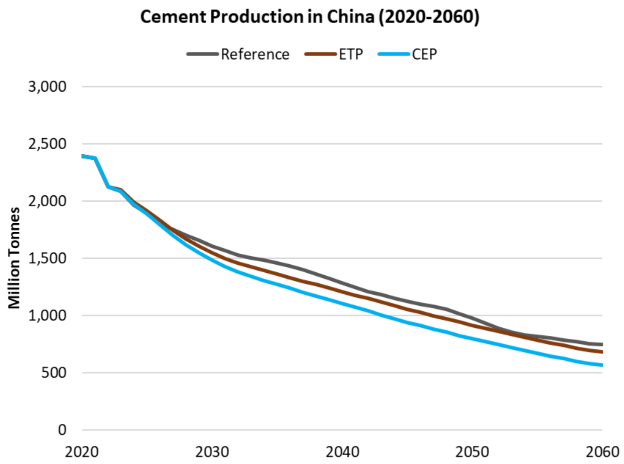

Figure 4. Cement production in China by scenario (2020-2060)

Use of SCM and alternative cement

One of the cost-effective ways to reduce emissions from the cement industry is to blend clinker with supplemental cementitious materials (SCMs), which not only reduces CO_2 emissions from thermal energy production but also process-related emissions. China's cement industry has been using SCMs, such as fly ash from coal-fired power plants and granulated blast furnace slags from the iron-production process. By 2020, China's clinker-to-cement ratio was 0.66 and stayed at this level through 2022. This is an increase from the historical low of 0.56 in 2013, where very low-quality cement was allowed and produced at a significant scale. To achieve near-zero emissions by 2060, our modeling showed that it is essential for the Chinese cement industry to continue using SCMs, expand the categories of SCMs (given the limited supply of fly ash and BF slag in the future), and adopt new SCM technologies. For example, studies show that silica fume, bauxite residue, agricultural byproduct ashes, forestry byproduct ashes, and end-of-life binders can also be used as SCMs (Shah et al. 2022). Calcined clay in combination with limestone (LC^3 technology), which has a technology readiness level (TRL) of 9[1], can reduce up to 50% of the clinker content and cut CO_2 emissions by up to 40% (Scrivener et al. 2018; Scrivener, John, and Gartner 2016). LC^3 technology has been adopted in several countries, such as Brazil, Cuba, India, the United States, and the European Union.

Alternative cement technology, i.e., 1) producing clinkers with different chemistries to Ordinary Portland Cement (OPC), and 2) producing OPC with alternative processes is another important strategy to decarbonize the cement industry emissions. Examples of alternative clinkers include Belite-Rich Clinkers, calcium sulfoaluminate (CSA), Belite-Ye'elimite-Ferrite (BYF), Solidia Cement, Celitement, X-Clinker, magnesium-based cement (Antunes et al. 2021), and geopolyemers (Singh and Middendorf 2020). Belite-rich Clinker and CSA are a mature technology and have already been widely used while other alternative clinkers are less mature and yet to be proven at scale. In addition, alternative cement with the same clinker composition as OPC can also

[1] Technology readiness level (TRL) provides a framework to assess and compare the maturity of a technology. It is now being widely used by research institutes and technology developers to set research priorities and design research & development programs. TRL levels ranges from concepts stage (TRLs 1-3) to prototype (TRLs 4-6) to demonstration (TRLs 7-8) to early adoption (TRLs 9-10) to mature (TRL 11).

be produced, such as by substituting the cement raw material from limestone to basalt and producing by a different process (Klappholz 2023; St. John 2023), or substituting calcium carbide slag (X. Wang, Song, and Li 2021).

The CEP incorporated the large-scale use of SCMs as well as the aggressive adoption of some of the yet-to-be-fully commercialized alternative cement technologies. With the support of using new SCMs and innovative SCM technologies, China's clinker-to-cement ratio will decline (without compromising on the quality and performance of cement products) to 0.5 by 2060. Collectively, the production of alternative cement (as discussed above) will increase significantly to 40% by 2030 and 80% by 2060 (Figure 5A).

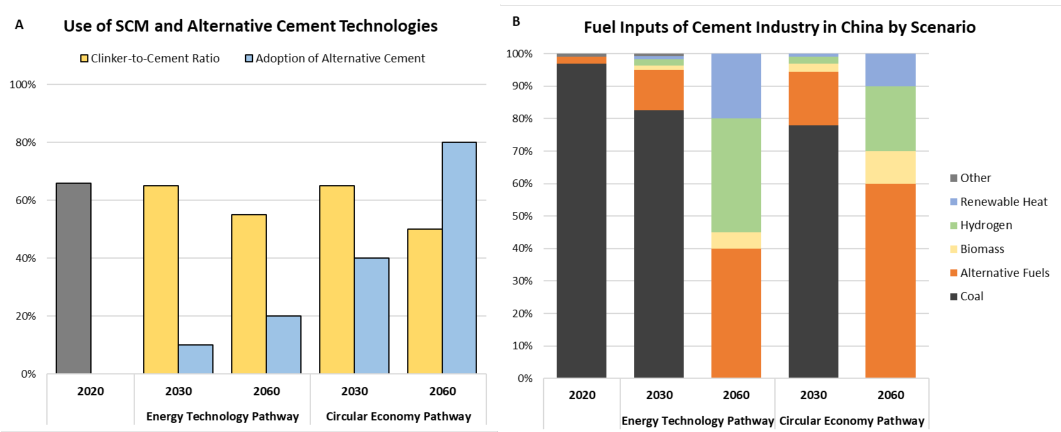

Figure 5. A) Use of SCM and alternative cement technologies by scenario; B) Fuel inputs of cement industry by scenario

Source: this analysis.

Clean energy supply

Compared to the ETP, which relied significantly on green hydrogen and renewable heat[2] accounting for 35% and 20% of total fuel supply by 2060, respectively, the CEP took a less aggressive approach to rely on the promise of clean hydrogen or renewable heating, representing 20% and 10% of total fuel supply by 2060 (Figure 5B). Zero-carbon hydrogen and concentrated solar heating are location-dependent and significantly capital-intensive. Cement production is in every province of China and has a very low-profit margin. Having the capital and access to affordable clean hydrogen and high-temperature renewable heat or the transportation infrastructure developed is a daunting task for the cement industry.

While recognizing some of the alternative fuels, such as industrial, solid, and municipal wastes are not zero-carbon sources, the CEP considered the use of alternative fuels at a higher share (60% of fuel supply by 2060) than in ETP. The cement industry in China is under significant pressure from the central government to "co-process" the wastes in cement kilns as mandated by *China's Circular Economy Development Plan for the 14th Five-Year Plan*, and *the Raw Materials Industry Development Plan for the 14th Five-Year Plan* (NDRC 2021b; China Government Website 2021). Many large cement companies, such as Anhui Conch, Hongshi Group, China National Building Materials Group, Tangshan Jidong, Huaxin Cement, China Resources Cement, and Taiwan Cement, have invested in co-processing production lines (Gu 2022). By 2020, 17% of cement kilns in China have co-processing capabilities (RMI and China Cement Association 2022).

The role of CCS

This analysis especially explored the role of carbon capture and storage (CCS) in achieving net-zero emissions for China's cement industry. Many researchers and industry associations considered the use of CCS to be unavoidable for global and regional cement decarbonization (GCCA 2021; PCA 2021; CEMBUREAU 2020). Several China-focused studies indicated CCS will contribute to 45% of total emission reductions by 2050 (Bai 2021) or the adoption rate will increase to 90% by 2060 (RMI and China Cement Association 2022). However, current CCS applications in the cement industry are very limited (one pilot carbon capture and utilization pilot by Anhui Conch, and one oxy-fuel post-combustion carbon capture demonstration by China United Qingzhou Company) and the scope is focused on carbon capture (Lorea, Sanchez, and Torres-Morales 2022). CCS adoption in China's cement industry faces many challenges, including the engineering complexity of the carbon capture, purification, and liquefication systems, additional energy demand for carbon capture, significant cost

[2] Considered the concentrated solar renewable heating in order to meet the high-temperature process requirement in the cement industry.

increase from additional capital cost, operational and maintenance costs, and transportation cost, as well as lack of infrastructure systems to transport and store captured carbon. The cement industry is not yet included in China's Emissions Trading Systems (ETS) and experts we interviewed for this paper pointed out the lack of economic incentives and business models for CCS. It is important to minimize the use of CCS while achieving net zero.

In CEP, we assumed a 2% CCS adoption rate by 2030 and 30% by 2060 in the cement industry. This is significantly lower, compared to the CCS adoption rates in ETP, which assumed a 2% adoption rate by 2030 but rapidly increases to 70% by 2060. As shown in Figure 6, total captured CO_2 emissions will be about 95 $MtCO_2$/year by 2060 in CEP, while the captured CO_2 emissions will be more than 310 $MtCO_2$/year by 2060 in ETP, or 230% higher.

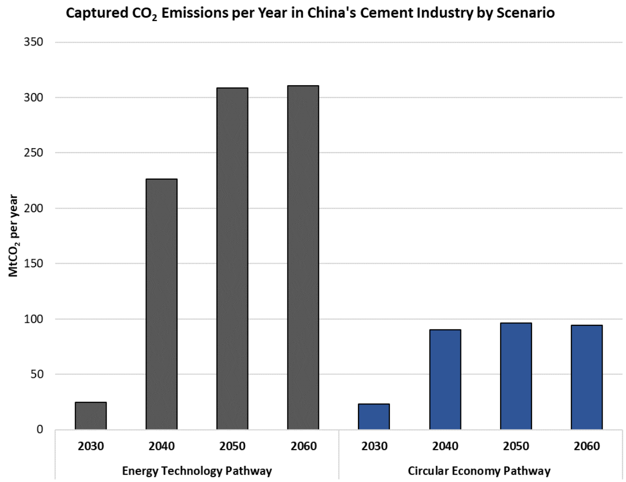

Figure 6. Captured CO_2 emissions per year in China's cement industry by scenario

Source: this analysis.

Net Zero by 2060

We found that both ETP and CEP can reduce CO_2 emissions of China's cement industry to be near zero by 2060, cutting emissions by 95% and 94%, respectively compared to the level in 2020. Both pathways relied on a portfolio of decarbonization strategies but diverged in technology prioritization and implementation – with ETP focusing on supply-side technologies (e.g., green hydrogen and CCS) while CEP emphasizing material-centered demand-side strategies, such as extending building lifetime, increased prefabrication, optimizing cement content in concrete, improved recycling of concrete, use of SCMs (e.g., calcined clay), development and adoption of alternative cements, and alternative fuels.

As shown in Figure 7, optimizing cement utilization and improving material utilization efficiency in product lifecycle phases play a significant role in CEP, representing 42% of cumulative emission reductions by 2030, and 23% of emission reduction from 2030 to 2060. Expanding the use of SCMs and increasing the adoption of low-carbon alternative cements through new materials and innovative technologies can deliver another 14% of abatement potential by 2030 and 13% from 2030 to 2060. Fuel switching is one of the most important strategies in CEP, but rather than relying heavily on green hydrogen and/or concentrated solar, CEP chose to depend on a combination of alternative fuels (industrial, agricultural, and municipal wastes) and other zero-carbon fuels. Most notably, the role of CCS is limited in the CEP, contributing only 5% of total emission reductions by 2030, and 17% from 2030 to 2060. In comparison, ETP shows that CCS accounts for 8% of total emissions by 2030 and 44% of emission reductions from 2030 to 2060.

Policy Implications

Comparing ETP and CEP shows that China's cement industry has more than one singular pathway to near-zero emissions by 2060. There are significant policy implications, for both China and other emerging economies, as their cement production is expected to rise driven by population growth and economic development in the years to come. Policymakers in both China and other emerging economies need to realize that supply-side technologies, such as CCUS, green hydrogen, or concentrated solar, are not the "silver bullet" when it comes to decarbonizing the cement industry. The supply-side technologies are capital-intensive, many of them are location-dependent, which requires further investment in transportation or distribution. These technologies are complex engineering projects that will also require domestic/local technical capacity to design, build, install, operate, and maintain.

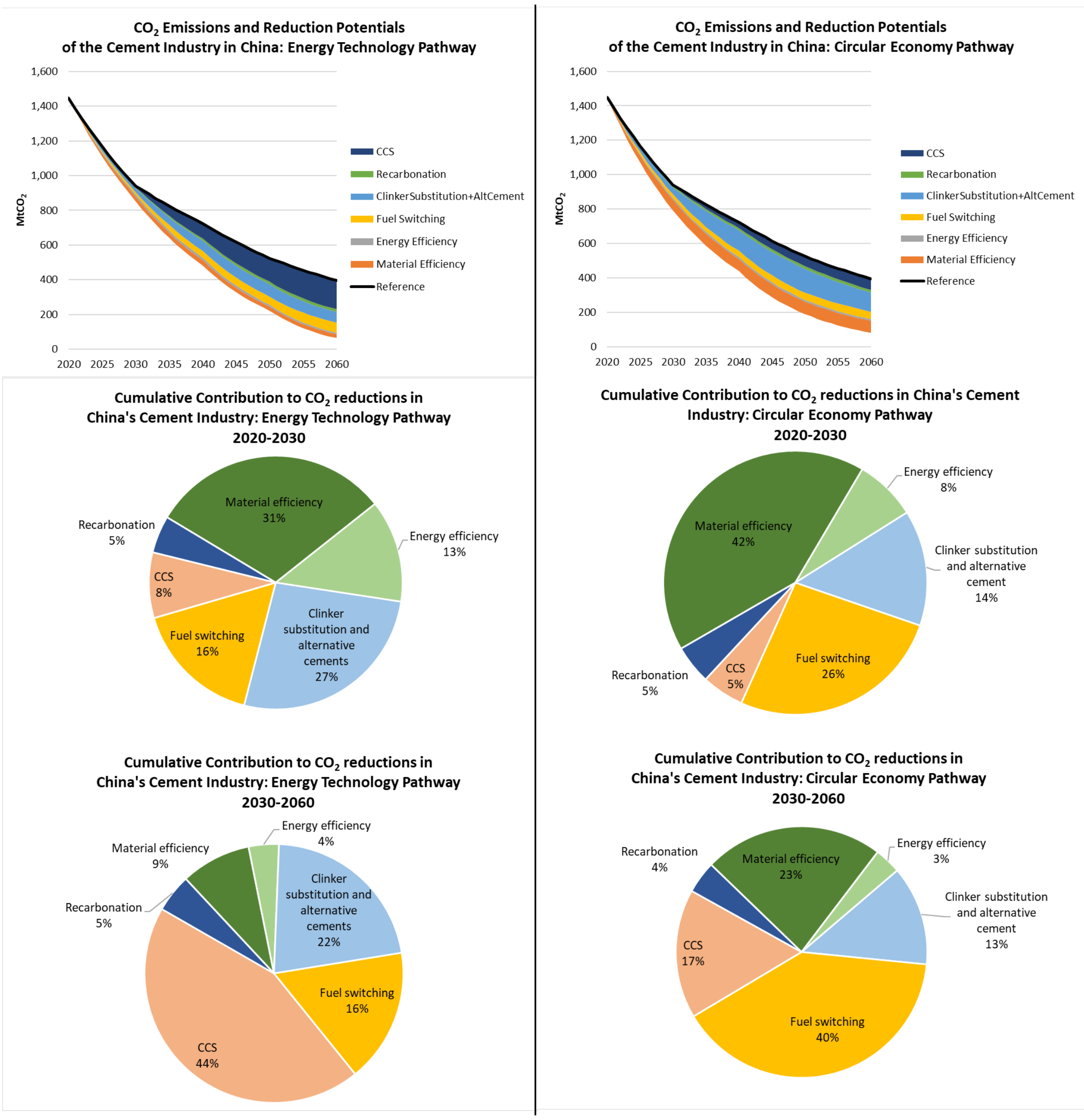

Figure 7. CO_2 emissions reduction potential by decarbonization strategies and timeframe in ETP and CEP

Source: this analysis.

The cement industry can play an important role in advancing circular economy practices and achieving immediate, cost-effective CO_2 savings. As the results of CEP show, policymakers and practitioners in the cement industry need to shift the traditional mindset from only focusing on operational or supply-side technologies to leveraging the product value chain (product design, manufacture, utilization, disassembly, and recycling). The current policy framework has not yet reflected or promoted this paradigm shift, which would be essential to realize the pathway outlined in the CEP.

Table 5 presents the opportunities and barriers to realizing the abatement potential from material-centered and demand-side strategies, and key policy actions that policymakers can implement in the near and mid-to-long term. In addition, to rapidly decarbonize the cement industry, standards, incentives, and regulations on cement-based products need to think beyond national-level, "one size fits all" requirements, and allow cement production to be adaptive to local resources of raw materials and energy sources, as well as local specific applications.

Table 5. Opportunities, barriers, and policy actions to achieve material-level, demand-side potential

Time-frame	Material/Demand-Side Opportunities	Barriers to Achieve Material/Demand-Side Potential	Key Policy Actions

2024-2030 (near term)	• Implementing material efficiency strategies and using SCMs can deliver immediate and cost-effective CO_2 reductions	• Standards and codes restricting the use of certain SCMs • Lack of awareness, know-how, and incentives on optimizing the use of cement-based products	• Revise standards from prescribed to performance-based • Develop and disseminate practice guides on improving material efficiency • Provide incentives for optimizing material use • Establish CO_2 standards for cement-based products (e.g., from concrete to whole buildings) • Develop public and private procurement programs for low-carbon cement products to increase the market demand • Leverage supply chain (e.g., real-estate developers) and transition financing to increase the demand for low-carbon cement products
2030-2060 (mid-to-long term)	• Alternative cements can reduce process-related emissions • Alternative fuels when used and accounted for appropriately can support decarbonization while mitigating waste issues	• Lack of commercialized alternative cement technologies • Lack of access and incentives to use alternative fuels • Insufficient and/or lax standards for using alternative fuels	• Increase RD&D investment in alternative technologies • Validate product performance of alternative cement technologies • Provide cement incentives for using alternative fuels • Enforce strict standards on CO_2 accounting for alternative fuels • Improve waste collection, sorting, and distribution networks • Invest in waste processing and treatment technologies

Note: RD&D stands for research, development, and demonstration

Conclusions

Our analysis showed that the Circular Economy Pathway (CEP) can achieve near-zero emissions by 2060 just as well as a supply-side focused pathway (ETP). However, CEP does not rely significantly on supply-side technologies but leverages the potential of optimizing material uses in all lifecycle stages of the product. CCS only contributes 5% of cumulative emission reductions before 2030 and 17% of cumulative emission reductions from 2030 to 2060 in CEP; while CCS would play an important role in ETP, accounting for 8% and 44% of cumulative emission reductions before 2030, and between 2030 and 2060 respectively. We highlighted the significant and immediate abatement potential by focusing on material and circular economy practices. Policy support on materials and the circular economy will be critical. We recommend revising standards to allow performance-based cement products, providing RD&D support on alternative cements, developing implementation guides to disseminate material efficiency practices, and improving material/waste collection, sorting, and recycling systems. For future research, we would like to conduct cost analysis on specific decarbonization technologies as well as potential investment needs for specific pathways. It would be also beneficial to establish even more targeted scenarios to focus on demand-side interventions.

References

Aktas, Can B., and Melissa M. Bilec. 2012. “Impact of Lifetime on US Residential Building LCA Results.” *The International Journal of Life Cycle Assessment* 17 (3): 337–49. https://doi.org/10.1007/s11367-011-0363-x.

Antunes, Mónica, Rodrigo Lino Santos, João Pereira, Paulo Rocha, Ricardo Bayão Horta, and Rogério Colaço. 2021. “Alternative Clinker Technologies for Reducing Carbon Emissions in Cement Industry: A Critical Review.” *Materials* 15 (1): 209. https://doi.org/10.3390/ma15010209.

Bai, Mei. 2021. “Research on the Path of Achieving Carbon Peak and Carbon Neutrality in China’s Cement Industry.” *Price Theory and Practice* 53 (4): 4–11.

Cao, Zhi, Gang Liu, Huabo Duan, Fengming Xi, Guiwen Liu, and Wei Yang. 2019. “Unravelling the Mystery of Chinese Building Lifetime: A Calibration and Verification Based on Dynamic Material Flow Analysis.” *Applied Energy* 238 (March): 442–52. https://doi.org/10.1016/j.apenergy.2019.01.106.

CBMF. 2022. “Implementation Guidance for the Building Materials Industry ‘14th Five-Year Plan’ Development.” September 15, 2022. http://www.cbminfo.com/BMI/jclhh/_470905/7179743/index.html.

CEMBUREAU. 2020. “2050 Carbon Neutrality Roadmap.” https://cembureau.eu/library/reports/2050-carbon-neutrality-roadmap/.

China Environmental Impact Assessment. 2023. “2022 Cement Industry Green Development Performance Evaluation Report.” July 28, 2023. https://www.china-eia.com/hyhjpgbg/2021/202307/t20230728_1037437.shtml.

China Government Website. 2021. “14th Five-Year Plan Raw Materials Industry Development Plan.” 2021. http://www.gov.cn/zhengce/zhengceku/2021-12/29/content_5665166.htm.

China Government Website . 2022. “Building Materials Industry Carbon Peaking Implementation Plan.” November 2, 2022. https://www.gov.cn/zhengce/zhengceku/2022-11/08/content_5725353.htm.

Digital Cement. 2023a. “2022 Launched 19 New Clinker Production Lines with a Total Capacity of 34.19 Million Tonnes.” January 11, 2023. https://www.dcement.com/article/202301/206885.html.

Digital Cement. 2023b. “China Cement Association: Top 50 Clinker Production Capacity in China in 2023.” May 15, 2023. https://www.dcement.com/article/202305/210323.html.

Downie, Edmund. 2021. "Getting to 30-60: How China's Biggest Coal Power, Cement, and Steel Corporations Are Responding to National Decarbonization Pledges." https://www.energypolicy.columbia.edu/publications/getting-30-60-how-china-s-biggest-coal-power-cement-and-steel-corporations-are-responding-national/.
GCCA. 2021. "Concrete Future - The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete." https://gccassociation.org/concretefuture/.
Gu, Lin. 2022. "Cement Co-Processing: No 'Perfect' Technology in Environmental Protection, Need to Pay Attention to Three Issues." June 2022. https://www.chndaqi.com/column/1604.html.
He, Jie, Jingxuan Cui, Qing Nie, Ying Xiao, and Yaling Ni. 2023. "A Study on the Carbon Neutrality Pathways of China's Cement Industry." China Building Materials Academy. https://www.efchina.org/Reports-zh/report-cip-20230913-zh.
IPCC. 2006. "2006 IPCC Guidelines for National Greenhouse Gas Inventories. Volume 2. Energy. Chapter 2." https://www.ipcc-nggip.iges.or.jp/public/2006gl/.
Khanna, Nina, David Fridley, Nan Zhou, Nihan Karali, Jingjing Zhang, and Wei Feng. 2019. "Energy and CO2 Implications of Decarbonization Strategies for China beyond Efficiency: Modeling 2050 Maximum Renewable Resources and Accelerated Electrification Impacts." *Applied Energy* 242 (May): 12–26. https://doi.org/10.1016/j.apenergy.2019.03.116.
Klappholz, Sol. 2023. "Brimstone's Decarbonised Portland Cement First to Meet Essential Building Industry Standard." World Cement. July 17, 2023. https://www.worldcement.com/the-americas/17072023/brimstones-decarbonised-portland-cement-first-to-meet-essential-building-industry-standard/.
Lewis, Joanna I., David G. Fridley, Lynn K. Price, Hongyou Lu, and John P. Romankiewicz. 2015. "Understanding China's Non–Fossil Energy Targets." *Science* 350 (6264): 1034–36. https://doi.org/10.1126/science.aad1084.
Li, Shen. 2021. "Opportunities and Challenges in Achieving Carbon Peaking and Carbon Neutrality of the Cement Industry." *China Cement*, May 27, 2021. https://www.dcement.com/Item/180572.aspx.
Lorea, C, F Sanchez, and E Torres-Morales. 2022. "Green Cement Technology Tracker." Stockholm. https://www.industrytransition.org/green-cement-technology-tracker/.
Lu, Hongyou, Nina Khanna, Wei Feng, Jing Ke, David Fridley, and Nan Zhou. 2022. "China's Electrification Pathways: Findings from the China Energy Outlook 2022." Lawrence Berkeley National Laboratory. https://eta-publications.lbl.gov/publications/china-s-electrification-pathways.
NBS. 2023. "National Data." 2023. https://data.stats.gov.cn/easyquery.htm?cn=C01.
NDRC. 2021a. "NDRC and Other Ministries Issue Opinions on Stricting Energy Efficiency to Promote Energy Conservation and Carbon Reduction in Key Sectors." 2021. https://www.ndrc.gov.cn/xxgk/zcfb/tz/202110/t20211021_1300583_ext.html.
NDRC. 2021b. "China's Circular Economy Development Plan for the 14th Five-Year Plan." July 2021. https://www.gov.cn/zhengce/zhengceku/2021-07/07/content_5623077.htm.
NDRC. 2023. "Key Industrial Sector Energy Efficiency Benchmark Levels and Standard Levels (2023)." June 6, 2023. https://www.gov.cn/zhengce/zhengceku/202307/content_6890009.htm.
PCA. 2021. "Roadmap to Carbon Neutrality." https://www.cement.org/docs/default-source/membership-2020/pca_roadmap-to-carbon-neutrality_jan-2022.pdf?sfvrsn=9b26febf_2.
RMI, and China Cement Association. 2022. "The Road to Net Zero: Decarbonization in China's Cement Industry." RMI. 2022. https://rmi.org/insight/net-zero-decarbonization-in-chinas-cement-industry/.
Sandberg, Nina Holck, Igor Sartori, Oliver Heidrich, Richard Dawson, Elena Dascalaki, Stella Dimitriou, Tomáš Vimm-r, et al. 2016. "Dynamic Building Stock Modelling: Application to 11 European Countries to Support the Energy Efficiency and Retrofit Ambitions of the EU." *Energy and Buildings*, Towards an energy efficient European housing stock: monitoring, mapping and modelling retrofitting processes, 132 (November): 26–38. https://doi.org/10.1016/j.enbuild.2016.05.100.
Scrivener, Karen, V. M. John, and E Gartner. 2016. "Eco-Efficient Cements: Potential, Economically Viable Solutions for a Low-CO2, Cement Based Materials Industry." UNEP. https://wedocs.unep.org/bitstream/handle/20.500.11822/25281/eco_efficient_cements.pdf.
Scrivener, Karen, Fernando Martirena, Shashank Bishnoi, and Soumen Maity. 2018. "Calcined Clay Limestone Cements (LC3)." *Cement and Concrete Research*, Report of UNEP SBCI WORKING GROUP ON LOW-CO2 ECO-EFFICIENT CEMENT-BASED MATERIALS, 114 (December): 49–56. https://doi.org/10.1016/j.cemconres.2017.08.017.
Shah, Izhar Hussain, Sabbie A. Miller, Daqian Jiang, and Rupert J. Myers. 2022. "Cement Substitution with Secondary Materials Can Reduce Annual Global CO2 Emissions by up to 1.3 Gigatons." *Nature Communications* 13 (1): 5758. https://doi.org/10.1038/s41467-022-33289-7.
Singh, N. B., and B. Middendorf. 2020. "Geopolymers as an Alternative to Portland Cement: An Overview." *Construction and Building Materials* 237 (March): 117455. https://doi.org/10.1016/j.conbuildmat.2019.117455.
St. John, Jeff. 2023. "To Decarbonize Cement, the Industry Needs a Full Transformation." Canary Media. October 24, 2023. https://www.canarymedia.com/articles/clean-industry/to-decarbonize-cement-the-industry-needs-a-full-transformation.
USGS. 2023. "Cement Statistics and Information 2023 Annual Report | U.S. Geological Survey." https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.
Wang, Qian. 2010. "Short-Lived Buildings Create Huge Waste." China Daily. April 6, 2010. https://www.chinadaily.com.cn/china/2010-04/06/content_9687545.htm.
Wang, Xinping, Jiaoli Song, and Guangxin Li. 2021. "Prospect of carbon peak and carbon neutrality of China cement industry." *Cement*, no. 08: 1–9.
Xinhua Net. 2018. "China Bans Capacity Expansion in Cement, Glass Sectors - Xinhua | English.News.Cn." Xinhua News. August 14, 2018. http://www.xinhuanet.com/english/2018-08/14/c_137389439.htm.
Xinhua Net. 2022. "Cement Industry: Emission-Intensive Industry in Building Materials Industry." August 8, 2022. http://www.news.cn/science/2022-08/23/c_1310655157.htm.
Zhou, Nan, Nina Khanna, Jingjing Zhang, Hongyou Lu, Lynn Price, David Fridley, Jing Ke, et al. 2022. "China Energy Outlook 2022." https://international.lbl.gov/china-energy-outlook.

Acknowledgements

This work was supported by Climate Imperative and the ClimateWorks Foundation under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231 with the U.S. Department of Energy.