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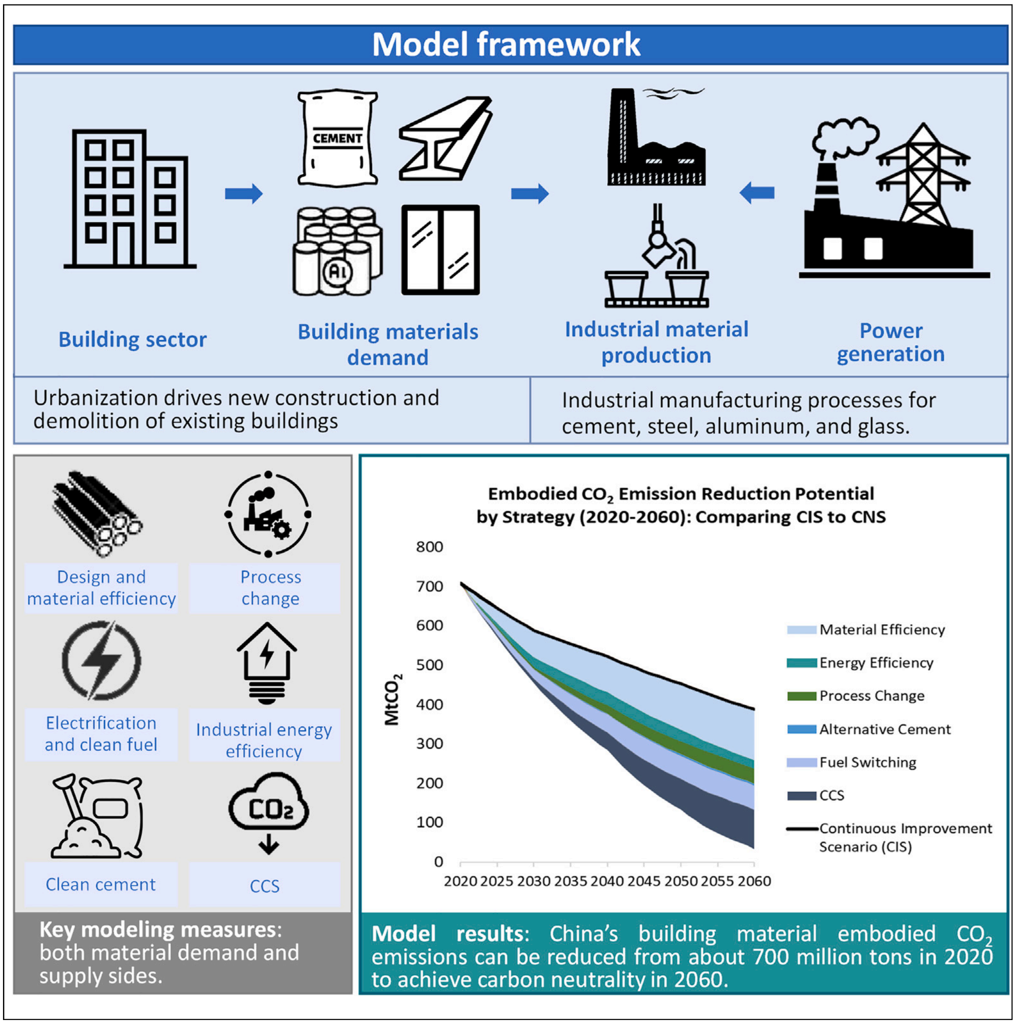

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Highlights

An integrated model on embodied emissions of building materials in China

Quantified the contribution of demand and supply-side decarbonization strategies

Improve material efficiency in value chain has the largest abatement potential

Policy recommendations to accelerate material efficiency practices in China

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Reducing China's building material embodied emissions: Opportunities and challenges to achieve carbon neutrality in building materials

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SUMMARY

Embodied emissions from the production of building materials account for 17% of China's carbon dioxide (CO_2) emissions and are important to focus on as China aims to achieve its carbon neutrality goals. However, there is a lack of systematic assessments on embodied emissions reduction potential of building materials that consider both the heterogeneous industrial characteristics as well as the Chinese buildings sector context. Here, we developed an integrated model that combines future demand of building materials in China with the strategies to reduce CO_2 emissions associated with their production, using, and recycling. We found that measures to improve material efficiency in the value-chain has the largest CO_2 mitigation potential before 2030 in both Low Carbon and Carbon Neutrality Scenarios, and continues to be significant through 2060. Policies to accelerate material efficiency practices, such as incorporating embodied emissions in building codes and conducting robust research, development, and demonstration (RD&D) in carbon removal are critical.

INTRODUCTION

As buildings become more energy-efficient and emit less carbon dioxide (CO_2) during their operation, it is increasingly urgent to focus more on the embodied energy and emissions of buildings, which includes material production, material transportation, building construction, building maintenance, and demolition. Currently, the embodied CO_2 emissions of buildings contribute to 11% of total worldwide CO_2 emissions, and will account for about half of the total carbon footprint of new construction between now and 2050.[1] Reducing embodied emissions is critical—not only for industrialized nations but also for other urbanizing countries—to achieve the Paris Agreement goals of limiting the global average temperature increase to 2°C and pursuing efforts to limit it to under 1.5°C.

China is the world's largest construction market, emitting about a quarter of the global building embodied CO_2 emissions.[2] China's building construction types are dominated by reinforced-concrete structures, which account for more than 60% and 80% of total residential and non-residential buildings in the country, respectively.[3] In 2015, the Chinese buildings sector alone consumed about 148 million tonnes (Mt) of steel and 574 Mt of cement, accounting for about 18% and 24% of China's total steel and cement production. The production of building materials was responsible for more than 80% of the embodied emissions of China's buildings sector, contributing to 17% of China's total CO_2 emissions and emitting 1,400 Mt of CO_2 in 2015.[2]

Previous studies evaluated the potential of decarbonization strategies to reduce building embodied emissions and have attempted to develop corresponding emission pathways. The strategies can be divided into two categories: (1) reducing material demand, including reducing building demand,[4,5] expending building lifespan,[6–8] and selecting low-carbon and lightweight building structure[4–6]; (2) cleaner material production, including improving energy efficiency,[5,7,9,10] fuel switching,[11] circular economy, and carbon capture and storage (CCS).[12] Some recent studies[5,13–15] attempted to link building material demand and production, and quantified the mitigation potential of building material embodied emissions at regional and global level. However, these studies also have not yet sufficiently considered the heterogeneous industrial characteristics, such as production process (primary vs. secondary production), facility sizes (small vs. large kilns), technologies (e.g., vertical kilns vs. shaft kilns), energy inputs of each production routes and technology (i.e., fuel shares), and so on. In addition, previous studies have limited scope in terms of material coverage (e.g., only cement and concrete[15]) or breadth of decarbonization strategies (only considered energy efficiency improvement[5]). In addition, previous studies[5,15–17] also did not have a targeted country focus on China, which represents about 25% of the global building embodied CO_2 emissions.

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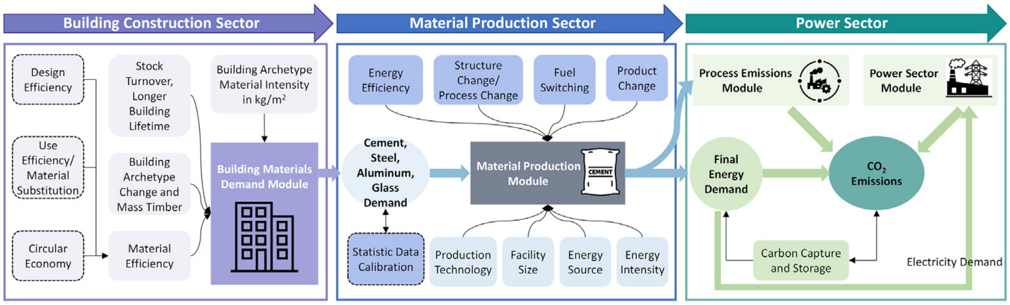

Figure 1. Modeling structure of embodied energy and emissions in building materials illustrates the modeling approach, which takes into consideration both demand-side and supply-side measures, as well as a decarbonizing power sector and the energy impacts of carbon capture and storage measures

In this study, we developed an integrated model based on bottom-up buildings sector data and stock-turnover demand in China. The scope of this study includes urban residential, rural residential, and public and commercial buildings given their different building material intensities, but does not include city infrastructure (e.g., roads and pavements), industrial warehouses and facilities, ports, or other types of construction. The model considered various industrial manufacturing processes and abatement measures for key building materials, including cement, steel, aluminum, and flat glass. Additionally, the study also considered the value chain stages of these materials, including production, design, usage, reuse, and recycling, where both commercialized and emerging technologies and practices will be adopted. The study modeled reusing and recycling of building materials, but did not specifically model life cycle stages of raw material mining, transporting of raw materials and products, and other end-of-life stages, such as demolition, waste transportation, waste processing, and disposal.

Scenario settings to model building materials' embodied emissions

In this study, we focused on building materials used in China's urban residential, rural residential, and public and commercial buildings, and did not consider building material demand for other infrastructure systems, industrial facilities, or warehouses.

In the residential sector, China's building structure types are vastly different from those in countries such as the United States, Canada, and Australia where wood structures are mostly common, but they are similar to those in countries such as India and in European and Association of Southeast Asian Nations (ASEAN) countries, where reinforced-concrete structures are also widely used. In the public and commercial sector, China's building structure types are unique, as there are few wooden structures and a relatively low share of steel structures (about 17%), while the large majority (>80%) of public and commercial buildings are built with concrete-steel framing. In comparison, steel structures represent about 45% and 25% of the total commercial building stock in the United States and Europe, respectively.[3] In this study, we expect that China will gradually favor more steel structure buildings, due to their structural advantages and successful adoption in industrialized countries. We do not expect that China will significantly increase its share of wooden buildings, due to concerns over limited resources and China's demand for high-rise buildings.

Figure 1 shows the modeling framework that integrates building material demand and building material production. The first module, the Building Materials Demand Module, deals with building material demand calculations. It includes a stock turnover model to calculate new construction building floor space and the share of new construction built with different archetypes. The building floor space calculated for each archetype was multiplied by the material intensity to determine the total material demand. Material efficiency measures were considered in the low carbon scenario (LCS) and carbon neutrality scenario (CNS) to reduce material demand and incur savings.

Using the material demand results from the first module as an input, the second module, the Material Production Module, calculates the energy demand and CO_2 emissions impact of producing building materials. We modelled cement, steel, aluminum, and flat glass industries from the bottom up, considering the production technology, sizes of production facilities, primary and secondary production, energy inputs, and energy intensity levels within each industry. Sub-scenarios were developed to capture the effects of energy efficiency, process change, fuel switching (including electrification and alternative fuels), and alternative cement products. The Material Production Module calculates the final energy demand of the modeled industries. Some industries, such as cement, have process emissions that come from the chemical reactions of the manufacturing process. The process emissions are calculated in the process emission module.

Lastly, CCS technologies are considered for the cement and steel industries, taking the CCS system energy requirements into account. In addition, the Power Sector Module calculates power sector CO_2 emissions and the primary energy demand.

We developed three scenarios in this study, using 2015–2020 as the base period. The continuous improvement scenario (CIS) assumes that the building materials sector will adopt the maximum feasible shares of today's commercially available technologies in energy efficiency and renewable energy by 2060. The LCS goes beyond CIS, by adopting material efficiency improvement measures, as well as adopting emerging technologies in renewable technologies and CCS. The CNS is the most ambitious scenario, which aggressively implements technologies in all categories and is also supported by a faster-decarbonizing power sector. To focus on the strategies that directly impact embodied emissions of key building materials, all three scenarios assumed China's power sector will be fully decarbonized by 2050.

To explore LCS and CNS in more detail, we developed six sub-scenarios to further quantify the energy and emission impacts of different decarbonization strategies, which include adopting material efficiency measures; improving energy efficiency to the practical limits;

Table 1. Scenarios to reduce building materials embodied emissions

Scenario	Description
Continuous Improvement Scenario (CIS)	Building material demand: • The lifetime of the buildings built after the year 2000 increases from the current average building lifetime of 30 years[8,18] to 50 years. • Concrete-steel remains as the dominant building construction archetype in China. Building material production: • Only energy efficiency and renewable energy technologies are considered. • Energy intensity improvement is consistent with today's technological upgrades and policy requirements. • There is maximum adoption of commercially available technologies. Electricity generation: • The power sector becomes fully decarbonized by 2050.
Low Carbon Scenario (LCS)	Building material demand: • Lifetime of 40% of the new buildings increases from the current average level of 30 years[8,18] to 70 years[19–21] by 2060. • China gradually increases the share of steel buildings and decreases the contribution from concrete-steel building structures. Building material production: • Both energy efficiency and renewable energy technologies are considered, along with moderate adoption of material efficiency strategies, process change, fuel switching, alternative cement chemistry, and CCS. • Energy intensity improvement improves significantly, reaching the advanced levels internationally. • Moderately adopting both commercial and emerging technologies. Electricity generation: • The power sector becomes fully decarbonized by 2050.
Carbon Neutrality Scenario (CNS)	Building material demand: • Lifetime of 70% of the new buildings increases from the current level of 30 years[8,18] to 70 years[19–21] by 2060. • China significantly increases the share of steel buildings and decreases the contribution from concrete-steel building structures. Building material production: • Both energy efficiency and renewable energy technologies are considered, along with aggressively adoption of material efficiency strategies, process change, fuel switching, alternative cement chemistry, and CCS. • Energy intensity improvement improves significantly, reaching the advanced levels internationally. • Aggressively adopting both commercial and emerging technologies. Electricity generation: • The power sector becomes fully decarbonized by 2050.

conducting process change within the manufacturing processes; switching to hydrogen, concentrated solar thermal, and other low or zero-carbon fuels; producing less-carbon intensive cement products; and considering the energy requirements and the emissions impacts from CCS in both the cement and steel industry. Table 1 summarizes the study's technological considerations and assumptions. Key assumptions and parameters are developed based on a combination of sources and analysis, including peer-reviewed articles, academic reports from universities and think tanks, China's Five-Year Plans and policy documents (for near and medium goals, and as an indication for long-term projection), China's *Minimum Energy Performance Standards* on industrial products, expert interviews, and international best practices. Detailed information on the assumptions are provided in the STAR Methods (see Tables 4, 5, 6, 7, and 8) and presented by scenario, decarbonization strategy, and time frame (2020–2030 and 2030–2060).

Material efficiency includes a set of strategies to deliver goods and services with less materials. Studies reported that material efficiency strategies are playing an increasingly important role in reducing emissions in industry.[17,22,23] Material efficiency potential can be achieved through designing buildings so that fewer materials are needed without compromising the performance[24,25]; improved practices to turn bulk building materials into products, e.g., prefabricated concrete components[25]; designing policy and mechanisms to extend product lifetime[21,26]; replacing carbon-intensive materials with less carbon-intensive materials, when appropriate[27,28]; reducing construction wastes[24,29]; reusing building components directly without melting[30,31]; and improving the collection, sorting, and recycling of building materials.

Energy efficiency is a key strategy that industries can employ to reduce embodied emissions today. For example, China's cement industry has improved its energy efficiency significantly through the adoption of rotary suspension kilns, precalciners, and waste heat generation technologies over the past 15 years[32] However, the industry still has room for continued improvement and maintenance of energy efficiency levels, especially for smaller kilns, by adopting measures such as energy management and process control systems,[33] combustion system improvements, upgrades of dry kilns to multi-stage preheater kilns, improved refractories, and improved raw material mills and cement grinding.[34] Under CNS, the weighted average energy intensity of China's cement industry is expected to improve and reach between Level 1 (the most efficient level) and Level 2 by 2030, as prescribed in the current version of the *Chinese Minimum Energy Performance Standard of Cement (GB16780-2021).*[35] Energy intensity of cement production in the LCS improves slower, about 2% higher than LCS by 2030, and 4% higher by 2060.

Process change can also be an effective strategy. For example, the Chinese cement industry conducts "supply-side reforms" by consolidating and phasing out smaller production lines by 2050 in LCS but significantly accelerates the process and phase out all smaller cement production kilns by 2030 in CNS. In the iron and steel industry, process change considers the transitions from primary (iron ore and coal-based) steelmaking to be more scrap based and green hydrogen based. China's Ministry of Industry and Information Technology set a goal of increasing the share of EAF steelmaking from the current 10%–15% by 2025.[36] In this study, the share of EAF reaches to 40% by 2050 in LCS but further increases to 50% by 2050 in CNS. By 2060, EAF shares continues to increase, reaching 50% in LCS and 60% in CNS. A comparison of the assumptions used in this analysis with other studies is presented STAR Methods (Table 6).

Fuel Switching is important for building materials industries that have been heavily dependent on fossil fuels. Potential increased adoption of solid wastes,[37–39] green hydrogen,[40] biomass,[41] and renewable heat (heat produced from renewable sources, such as solar thermal and geothermal),[42] as well as increased use of electricity,[43] are being considered in the building materials industry.

Reducing process emissions relies on multiple strategies. About half of cement industry CO_2 emissions are from the chemical reaction process, i.e., from the limestone calcination process to produce clinker. Different strategies are available to reduce CO_2 emissions from the process, by improving the clinker-to-cement ratio, using more supplementary cementitious materials (SCMs), and using alternative materials to replace limestone.[44–46] However, China's clinker-to-cement ratio has been low in recent years (it dropped to below 0.6 in 2017) due to a combination of low-quality materials used and the use of SCMs such as fly ash and blast furnace slags.[47] This study expects China's clinker-to-cement ratio to stabilize at around 0.6 through 2060 in both LCS and CNS.

Alternative Cements, such as belite clinker,[48] has been emerging to reduce the reliance on limestone, thus reducing process-related CO_2 emissions in the cement industry.[24,45,49] Given China's massive scale of cement production and the availability and access to alternative raw materials, the LCS considers the use of alternative cement products with limited penetration of the Chinese cement market (25% by 2060) and the share increases slightly to 35% by 2060 in CNS. This study also considered the potential thermal energy savings, as well as the potential electrical energy impacts from producing alternative cements.

CCS is considered for both cement and steel industry in both LCS and CNS. We considered the improvement of capturing yields of CCS systems,[44,50–52] as well as the energy requirements[53–56] to operate the carbon-capturing systems.

RESULTS

Pathways to achieve carbon neutrality in the embodied emissions of building materials

In the CIS (the base case), the total energy demand of China's building materials production declines, due to (1) the slowdown of new construction and the associated reduction in demand of steel and cement, and (2) the continued technological energy efficiency improvement in all studied material-producing industries. Therefore, as shown in Figure 2A, the final energy demand of building materials declines from 154 million tons of coal equivalent (Mtce) in 2020 to 97 Mtce in 2060; a reduction of 44%.

Driving by moderate implementation of material efficiency measures in design, use, and recycle stages of materials and energy efficiency improvement, the energy consumption of producing building materials under LCS declines, by 3% in 2030 and 10% by 2060 as compared to CIS (Figure 2A).

The CNS further reduces the final energy demand to produce building materials by 10% in 2030 and 29% by 2060, compared to CIS (Figure 2A). Material efficiency strategies and practices play the most significant role in further reducing final energy demand in both the near term (before 2030) and long term (2030–2060), accounting for about 59% of total energy reductions by 2060 (Figure 2B). Energy efficiency and process change together continue to deliver an important share of energy savings, about 33% and 39% by 2030 and 2060, respectively. Switching to other zero or low-carbon fuels and small-scale production of alternative cement has very limited contributions to final energy savings.

CCS, while important for reducing CO_2 emissions in the cement industry, may lead to additional energy requirements to capture CO_2 and to regenerate the absorbents.[24,44,55,56] Additional energy demand to compress, transport, and store CO_2 is not considered in this study. The scale of additional energy requirements for CO_2 capture is estimated to be less than the energy savings potential from other measures, reducing the total energy-saving potential by about 39% by 2060. The additional energy demand needed for CCS could be met partially through onsite lower-temperature heat, by improving waste heat management and utilization.

In all three scenarios, embodied CO_2 emissions (both energy-related and process-related emissions) of material demand decrease through 2060. In CIS, total CO_2 emissions decrease from 826 million metric tons of CO_2 ($MtCO_2$) in 2015 to 386 $MtCO_2$ in 2060, or a 53% reduction (Figure 3A). This is due to a combination of factors including reduced levels of new construction in China, improved levels of energy efficiency in key industries, and a fully decarbonized grid by 2050.

The CNS shows that embodied CO_2 emissions in China's building materials sector can be reduced to nearly zero, but to do so China will have to aggressively adopt material efficiency strategies, energy efficiency, and fuel switching measures in the near-term, and continue the pace through 2060 while adopting CCS in the cement industry (Figure 3B). CNS demonstrates that material efficiency strategies contribute the greatest CO_2 emissions reduction, or 51% of the total reduction by 2030 and 36% by 2060. Energy efficiency as well as process changes can collectively deliver 15% of total emission reduction potential from now to 2060, while using low or zero-carbon fuels can reduce another 17% of total emissions by 2060. Implementation of CCS may be necessary for cement industry to achieve carbon neutrality before 2060, but in the near-term its contribution is relatively small, at around 9% by 2030.

Given the characteristics of China's building types, cement and steel are the most important building materials to target in order to reduce embodied emissions in China's building sector. The study shows that both materials account for 94% of total CO_2 emission reductions by 2030 and 97% by 2060.

Strategies to improve material efficiency in the value-chain of the building materials

The study highlights the significant potential of adopting and deploying material efficiency technologies and practices. Specifically, the modeling results show that having better construction quality and maintenance to extend the building lifetime can effectively reduce new

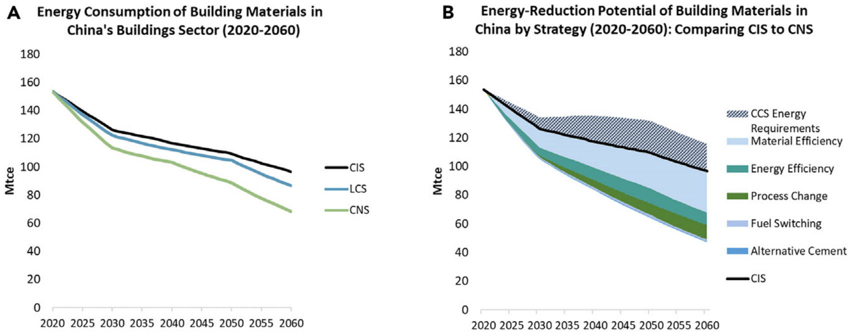

Figure 2. Final energy reduction potential of China's building materials, by strategy

(A) Shows the energy-saving potential in both LCS and CNS compared to CIS, by implementing both demand-side and supply-side measures, showing a reduction in total energy demand by 3% by 2030 and 10% by 2060 under LCS, and 10% by 2030 and 29% by 2060 under CNS.

(B) Illustrates the energy impact of each of the key strategies, showing material efficiency has the largest energy-saving potential in both the near term (before 2030) and long term (2030–2060), accounting for 59% of total energy-savings by 2060. Adopting energy efficiency and process change measures can also deliver about one-third of total energy savings by 2060 in CNS. Large-scale adoption of CCS technologies would require additional energy to operate CCS systems, reducing the total energy savings by 39% by 2060. CIS: continuous improvement scenario; LCS: low-carbon scenario; CNS: carbon neutrality scenario.

construction and the associated demand for energy-intensive building materials. Improving the lifetime of 70% of new buildings, increasing from 30 years to 70 years in CNS has the potential to building material demand by 18% by 2060.

Improved building structure design and construction techniques (such as prefabrication and post-tensioning) also can reduce 5% of cement demand and 6% of steel requirements by 2060. Optimizing cement content, i.e., applying the appropriate amount of cement to meet required performance levels, without overusing cement can save 4% of cement demand, if the practice is adopted at 45% by 2060.

The circular economy principles and practices can contribute to material savings. Improving semi-manufacturing and product manufacturing yields in steel and aluminum industries can deliver another 2–7% of material savings by 2060. Steel component reuse (without melting) can reduce 6% of steel demand by 2060 assuming the practice is scaled-up to an adoption rate of 40%. Reducing construction wastes and recycling concrete currently have limited material-saving potential due to technological, economic, and regulatory barriers.

Material substitution, i.e., using sustainable structure types (e.g., mass timber) can further reduce demand for cement and steel, by 4% and 5%, respectively. However, due to China's limited resources in wood and local resource availability, we expect the adoption rate of mass timber building structures in China to be low, at 9% by 2060.

Table 2 provides key material efficiency strategies, adoption rates, estimated material-saving potential, as well as the applicability of these measures.

DISCUSSIONS

We found that it is possible to significantly reduce embodied emissions associated with building materials to be near zero by 2060 in China. However, such reduction is only possible with unprecedented scale-up of material efficiency practices,[63] strengthened the improvement of energy efficiency, adoption of zero-carbon fuels, accelerated commercialization of emerging innovations, and targeted deployment of CCS in the cement industry. Specifically, we showed that material efficiency strategies are essential to significantly reduce embodied emissions, contributing to 51% of total CO_2 reductions before 2030 and 36% of total CO_2-saving potential by 2060.

Even though the technology pathway is clear, significant barriers exist—such as lack of codes and standards to regulate building material energy and embodied emissions, lack of information sharing on material energy and CO_2 emission intensity between the demand side and material production side, and lack of methods to procure environmental products through the building construction process.

To overcome these barriers, building material energy and embodied emission standards need to be established in China. Building operation energy standards always employ prescriptive measures and sometimes whole building energy performance targets. Similar requirements need to be established on using building materials and evaluating the whole building's embodied energy and carbon performance. An Environmental Product Declaration (EPD) needs to be established in the building construction processes to allow green materials to be available through the whole building construction supply chain. Disclosure of building material energy and CO_2 emission data on the industry side is necessary to enable the selection of low-carbon materials on the demand side. Local government can develop green procurement program pilots to drive the demand for low-carbon building materials.

Circular economy programs need to be established to increase the use of scrap materials in these industries, such as improving collection and sorting systems for scrap metals. Incentive programs should be considered to accelerate the use of alternative fuels and electrification in industry. Energy efficiency programs that emphasize on continuous improvement, such as energy management (ISO 50001), benchmarking and energy assessments, are cost-effective and commercially available today. Research, development, and demonstration support of emerging technologies such as green hydrogen, renewable heat, and CCS industry applications are critical to ensure the feasibility and commercial availability of these technologies for large-scale adoption by 2030. Robust life cycle assessments on energy and resource

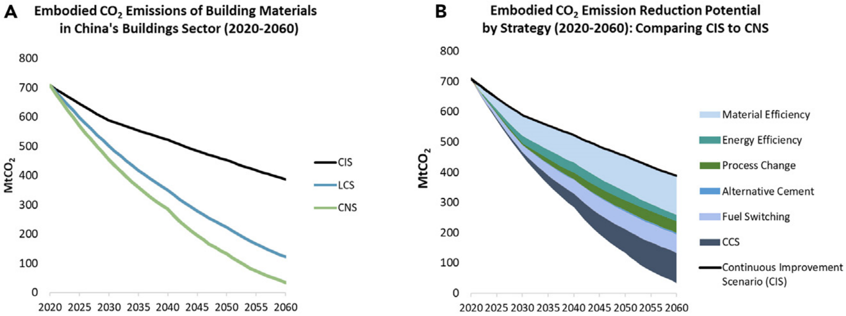

Figure 3. Embodied CO_2 emissions reduction potential by strategy and material

(A) Shows that embodied CO_2 emissions of key building materials used in China's buildings sector can achieve near-zero in CNS and be significantly reduced in LCS.

(B) Shows that in CNS, material efficiency contributes to the most significant CO_2 emissions reductions in the near term (51% of total CO_2 reductions by 2030) and continues to play a major role through 2060 (36% of total CO_2 reductions by 2060). Energy efficiency improvement, process change (e.g., phasing out small and inefficient facilities and increasing recycling), and switching to zero-carbon fuels (e.g., green H_2 and renewable heat) contribute 11%, 4%, and 17%, respectively, by 2060. CCS adoption and scaling-up may be necessary in order to achieve carbon neutrality by 2060; however, its contribution is relatively small before 2030.

requirements should be conducted to understand the energy and infrastructure demands of CCS systems. Financial mechanisms of CCS applications need to be explored and developed.

To support China's green building materials transition, detailed policy strategies, target areas, specific policy levers, timelines, as well as enabling institutions in China to implement these policies are provided in Table S1.

Conclusions

Our study found that it is technically feasible to reduce 29% of energy use and achieve near-zero emissions in China's building materials sector by 2060 by relying on the combined efforts of energy efficiency improvement, material efficiency strategies, switching to low- or zero-carbon fuels, and large-scale adoption of CCS, especially in the cement sector. This type of "portfolio approach" to decarbonize the basic materials industry has been emphasized by governments (for example US Department of Energy's Industrial Decarbonization Roadmap[64]), industrial associations,[65,66] academia and think-tanks.[24,67–70]

We showed that material efficiency strategies such as extending building lifetimes, increasing the use of prefabrication, improving product and building design, replacing steel and cement with mass timber, and effectively reusing and recycling building materials contribute the most to embodied emissions reductions before 2030 (51% of total CO_2 reduction potential) and by 2060 (36% of total CO_2 reductions). Our study quantified the potential of material efficiency and circular economy strategies in China's building materials sector, which is the largest in the world. Our findings on the significant and near-term impacts of these strategies are consistent with literature that focused on others regions or geographic boundaries.[7,9,15–17,24,25] A similar finding, at the global level, has been stressed in the Working Group III's report in the latest IPCC Sixth Assessment Report.[63]

It is important to take a holistic approach to integrate building material demand and production to reduce building material energy use and CO_2 emissions. The results of this research find that a significant amount of energy savings can be achieved through the efficient design, use, and reuse and recycling of building materials. Compared with the industrial material production-side energy savings, the demand-side material savings tend to be less technology-intensive and more cost-effective. Several material production-side energy and CO_2 emission reduction measures are considered in this analysis, including energy efficiency in material production processes, alternative cement, manufacturing process changes, and fuel switching. CCS is also considered, especially given the significant process-related emissions from the cement industry.

Unlike the CO_2 emissions from operational energy, building material embodied CO_2 emissions will be very challenging to achieve carbon-neutrality without effective large-scale adoption of CCS. However, as of today, only one CCS project is developed in China's building materials industry due to significant barriers, such as additional energy requirements to capture, compress, transport, and store CO_2 emissions, lack of research and development (R&D) in CCS infrastructure, lack of economic incentives and financial mechanisms to install CCS systems, and the need to monitor and evaluate realized CO_2 reductions.

Innovative policy design and tangible policy support to deploy and upscale cost-effective measures, such as material efficiency and energy efficiency measures need to happen immediately. At the same time, policy support on research, development, testing, pilot, and demonstration of technologies in the areas of fuel switching, alternative cement, and CCS is critical for achieving deep decarbonization in building materials industries.

Limitations of study

Future work is needed to conduct techno-economic analyses of various material efficiency strategies to evaluate actual, real-world energy and CO_2 emissions reduction impacts. Barrier analysis on technology adoption and techno-economic analysis on the cost of implementation

Table 2. Material efficiency strategies, potential, and applicability

Value Chain Stages	Measures	Savings Potential (%)	Adoption Rate 2015 (%)	Adoption Rate 2060 in CNS (%)	Material-Saving Potential by 2060 in CNS (%) relative to CIS	Building Materials	Applicability
Design	Improved building design[24,25]	10	0	45	5	Cement	New buildings
Use	Extending building lifetime from the current level of 30 years[8,18] to 70 years by 2060[19,20,26]	25	0	70	18	Cement	All applications
	Increased use of precast components and post-tensioning of floor slabs[25]	10	5	75	6	Cement	Low- to mid-rises in new buildings in urban res and commercial
	Optimizing cement content in concrete[25,57]	8	0	45	4	Cement	All applications
	Use of timber[27,28]	40	0	9	4	Cement	Low- to mid-rises in new buildings
	Additive manufacturing[58]	15	0	5	1	Cement	New residential single-family homes (e.g., rural residential homes)
Recycle	Reducing construction wastes[24,29]	2	0	5	0.1	Cement	All applications
	Recycle concrete into recycled concrete aggregate[24,59]	2	0	5	0.1	Cement	Roads and urban paved area
Design	Improved design and construction (buildings)[60]	13	5	45	6	Steel	Buildings
Use	Extending building lifetime from the current level of 30 years[8,18] to 70 years by 2060[19,20,26]	25	0	5	18	Steel	Buildings
	Use of timber[27,28]	50	0	9	5	Steel	Buildings
Produce	Improving semi-manufacturing yields[17,50,61]	7	0	70	5	Steel	All applications
	Improving product manufacturing yields[17,50,61]	13	0	45	6	Steel	Product steel
Recycle	Direct component reuse (without melting)[30]	15	0	40	6	Steel	Buildings and industrial steel use
Produce	Improving semi-manufacturing yields[17,50,62]	10	0	70	7	Aluminum	All applications
	Improving product manufacturing yields[17,50,62]	5	0	45	2	Aluminum	All applications
Use	Extending building lifetime from the current level of 30 years[8,18] to 70 years by 2060[19,20,26]	25	0	70	18	Aluminum	Buildings and industrial aluminum use

(*Continued on next page*)

Table 2. *Continued*

Value Chain Stages	Measures	Savings Potential (%)	Adoption Rate 2015 (%)	Adoption Rate 2060 in CNS (%)	Material-Saving Potential by 2060 in CNS (%) relative to CIS	Building Materials	Applicability
Recycle	Direct component reuse (without melting)[31]	2	0	40	1	Aluminum	Buildings and industrial aluminum use
Use	Extending building lifetime from the current level of 30 years[8,18] to 70 years by 2060[19,20,26]	25	0	70	18	Flat glass	Buildings

should be conducted to refine assumptions on future technology adoption and design targeted policy to accelerate the transition. Analysis of the life cycle energy and resource impact of carbon removal measures is needed. The current model may be expanded to incorporate dynamic material flow analysis to better quantify and evaluate the stocks and flows all life cycle stages, especially extraction of raw materials and end-of-life stages. In addition to targeting material energy use and emissions, other areas also can be targeted to reduce building embodied energy consumption, such as construction machinery and transporting building materials. Building material energy reduction research needs to be integrated with the focus on transporting building materials and reducing on-site construction machinery energy demand. The link between building embodied energy and CO_2 emissions with operational energy and CO_2 emissions is also worthy of investigation, to understand the synergic effects of building life cycle energy savings. In addition, similar modeling work that considers both the supply and demand side measures to reduce embodied emissions of building materials can be utilized in other emerging countries, which are expected to demand significant building materials as they urbanize and improve living standards. It is important to conduct the analysis, identify opportunity areas, and design policies to support other emerging countries to mitigate embodied emissions of building materials.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- METHOD DETAILS
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- QUANTIFICATION AND STATISTICAL ANALYSIS
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  - Construction material demand
  - Material production model

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.109028.

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AUTHOR CONTRIBUTIONS

Conceptualization, H.L., W.F., and N.Z.; literature analysis, H.L., W.F., and K.Y.; writing—original draft preparation, H.L. and W.F.; writing—review and editing, H.L., K.Y., W.F., N.Z., L.P., D.F., and S.D.; supervision, N.Z. and L.P.; project administration, W.F. and N.Z.; funding acquisition, N.Z. All authors have read and agreed to the published version of the manuscript.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
Long-Range Energy Alternatives Planning (LEAP)	Stockholm Environment Institute	https://leap.sei.org/
Next Energy Modeling system for Optimization	Stockholm Environment Institute	https://www.sei.org/projects-and-tools/tools/nemo-the-next-energy-modeling-system-for-optimization
Other		
Material production data	National Bureau of Statistics Online database[47]	https://data.stats.gov.cn/easyquery.htm?cn=C01
Building archetypes data	IEA and UNEP[71] Zhu et al. (2020)[2]	https://wedocs.unep.org/20.500.11822/27140 https://doi.org/10.1016/j.jclepro.2020.122438
Material intensity data	Xing et al. (2021)[3] You et al. (2023)[4]	https://doi.org/10.1088/1748-9326/abe008 https://doi.org/10.1016/j.resconrec.2022.106679
Building lifetime data	China: Cao et al. (2019),[10] Wang (2010),[11] Wang et al. (2018)[12] US: Aktas and Bilec (2012)[13] EU: Sandberg et al. (2016)[14]	https://doi.org/10.1016/j.apenergy.2019.01.106 https://www.chinadaily.com.cn/china/2010-04/06/content_9687545.htm https://doi.org/10.1016/j.jclepro.2018.08.314 http://doi.org/10.1007/s11367-011-0363-x https://doi.org/10.1016/j.enbuild.2016.05.100
Energy intensity data	NDRC,[72] NDRC[73]	https://www.ndrc.gov.cn/xxgk/zcfb/tz/202110/t20211021_1300583_ext.html. https://www.gov.cn/zhengce/zhengceku/202307/content_6890009.htm

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Wei Feng (weifeng@lbl.gov).

Materials availability

This study did not generate new unique reagents.

Data and code availability

- All data reported in this paper will be shared by the lead contact upon reasonable request.
- This paper does not report the original code.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon reasonable request.

METHOD DETAILS

Modeling framework and method

The analysis of building sector material demand and energy consumption was modeled using Berkeley Laboratory's China 2050 Demand Resource Energy Analysis Model (DREAM). The model was implemented by applying LEAP (Long-Range Energy Alternatives Planning) software and the Next Energy Modeling system for Optimization (NEMO).[74]

As shown in Figure 1 of the manuscript, the building material energy and CO_2 modeling can be characterized as three sub-models: (1) a building material demand model, (2) a material production model, and (3) a power sector model. Here we focus on the methods used to estimate building material demand and energy demand for material production. The power sector model considers different power generation technologies, including coal, natural gas, biomass, nuclear, wind, hydro, solar, wind, and geothermal. The model can be adjusted in a number of technical parameters, such as generation mix, efficiency levels, and demand-side management. The parameters of power sector refer to the studies of Zhou et al. (2019)[75] and Khanna et al. (2016).[76]

QUANTIFICATION AND STATISTICAL ANALYSIS

Building floor turnover and annual new construction rate

The building material demand model uses urbanization rate and per capita residential and public and commercial building floor space as input variables to calculate the total floor space. The existing building follows its average life time to retire, and the new construction is built in each year to make sure the remaining existing building stock, plus the new construction, meet the total building floor space stock. The building stock turnover model is governed by Equation 1 in year *i:*

$$\text{Total Stock}_i = \text{New construction}_i + \text{Existing stock}_i - \text{Demolition}_i \qquad \text{(Equation 1)}$$

The Continuous Improvement Scenario (CIS) assumes that the lifetime of the buildings built after the year 2000 increases from the current average lifetime of 30 years[8,18] to 50 years. The Low Carbon Scenario (LCS) assumes that the lifetime of 40% of new buildings increases from 30 years to 70 years by 2060. The most ambitious scenario, the Carbon Neutrality Scenario (CNS) assumes that the lifetime of 70% of new buildings increases from 30 years to 70 years by 2060, due to improvement in construction quality, improved maintenance, better city and urban planning, and reduced commercial incentives for building demolition.[21] The building lifetime of 70 years is based on average building lifetime in the United States (which is about 60–70 years)[20] and in EU countries (which is 70–125 years).[19] The LCS and CNS have slower building retirement than CIS, and thus, less new construction will be needed. Table 1 provides new construction floor space in the CIS scenario.

Table 1. New construction building floor space in CIS

CIS (unit: billion m^2)	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Public and commercial	0.77	0.72	0.73	0.57	0.41	0.41	0.46	0.49	0.53	0.52
Rural residential	0.07	0.07	0.06	0.11	0.16	0.14	0.16	0.18	0.20	0.19
Urban residential	1.36	1.25	1.13	1.17	1.26	1.19	1.22	1.16	0.95	0.97

Construction material demand

To calculate the building construction material demand driven by a new construction rate, five building archetypes commonly in China's urban and rural construction were defined. These five archetypes, based on different structuring engineering design, were steel, concrete-steel, brick-concrete, timber, and mass-timber. Each archetype defines a material intensity number for each construction material in kilograms (kg) of building material per square meter (m^2) of construction floor space. Table 2 below provides the baseline material intensity number this study used for modeling. The material intensities are commonly found in existing case studies and literature for Chinese buildings.[2,24]

Table 2. Material intensity by building archetypes

Material Intensity (kg/m^2)	Mass Timber	Timber	Brick	Concrete-Steel	Steel
Steel	0	5	20.8	70	150
Cement	30	60	180	280	140
Brick	10	25	251.6	10	0
Aluminum	1.9	1	0.56	1.9	8.6
Glass	7	3.2	3.2	7	20.9
Timber	486.8	29.9	0	5	2

Each archetype has a different penetration in the urban residential, rural residential, and public and commercial building sectors. Generally, new construction in China is primarily built with concrete-steel structure types for multistory and high-rise buildings in urban areas. In recent years, the steel structure type has been favored, and its market share is growing. Brick-concrete and wood structures are less common in urban areas, but more commonly found in rural new construction. Mass timber is considered in the deep mitigation scenario as a low-carbon archetype to replace concrete-steel and steel structures in urban areas. However, due to a Chinese fire code constraint, mass timber can only be used for buildings with fewer than six floors. We only assumed a 9% mass timber penetration in 2060 in CNS.

Table 3 below summarizes different archetype market penetration rates in CIS. The 2015 values were obtained through existing literature and surveying Chinese building design institutes. The 2060 penetration assumes China will build more steel structure buildings, as most developed countries do, and decrease the share of concrete and steel structures.[71]

Table 3. Archetypes penetration in urban residential buildings

CIS	2015	2020	2025	2030	2035	2040	2045	2050	2055	2060
Mass Timber	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Brick	15%	15%	15%	15%	15%	15%	15%	15%	15%	15%
Concrete-steel	84%	80%	76%	72%	67%	63%	59%	55%	55%	55%
Steel	1%	5%	9%	13%	18%	22%	26%	30%	30%	30%

Material production model

This study analyzed four building materials: cement, crude steel, aluminum, and flat glass. For each type of building material, three scenarios were developed.

(1) Continuous Improvement Scenario (CIS): assumes China's buildings and building materials sectors will fully adopt the maximum feasible shares of today's commercially available, cost-effective energy efficiency and renewable energy supply by 2060.
(2) Low Carbon Scenario (LCS): assumes China's buildings and building materials sectors will adopt and deploy deep decarbonization measures, structural shifts, material efficiency practices, and CCS *moderately* by 2060.
(3) Carbon Neutrality Scenario (CNS): assumes China's buildings and building materials sectors will adopt and deploy deep decarbonization measures, structural shifts, material efficiency practices, and CCS *as much as technically feasible* by 2060.

LCS and CNS also include a set of sub-scenarios, including energy efficiency improvement, structural change, fuel switching (including electrification), alternative cements, and carbon capture and storage (CCS) (see Tables 4, 5, 6, and 7). By considering all these measures in each of the building material industries, we calculated specific energy intensity for cement, steel, aluminum, and flat glass production.

Specifically, Equation 2 shows the calculation for the cement industry:

$$EI_{cement} = \sum_k \left(\sum_m (FS_i \times EI_i) \right) \quad \text{(Equation 2)}$$

Where:
EI_{cement} = weighted average of energy Intensity of cement.
EI_i = energy intensity of fuel i.
FS = fuel share (e.g., coal, coke, natural gas, electricity, hydrogen, renewable heat, solid wastes)
k = cement production technology (rotary and vertical)
m = kiln size
i = type of energy source.

Similarly, Equations 3, 4, and 5 were used for the steel, aluminum, and flat glass industries:

$$EI_{steel} = \sum_j \sum_i (FS_i \times EI_i) \quad \text{(Equation 3)}$$

Where:
EI_{steel} = weighted average of energy Intensity of crude steel.
EI_i = energy intensity of fuel i.
FS = fuel share (e.g., coal, coke, natural gas, electricity, hydrogen, renewable heat, solid wastes)
j = steel production technology (Blast Furnace-Basic Oxygen Furnace [BF-BOF]; Scrap-EAF; DRI-EAF)
i = type of energy source

$$EI_{aluminum} = \sum_n \sum_i (FS_i \times EI_i) \quad \text{(Equation 4)}$$

Where:
$EI_{aluminum}$ = weighted average of energy Intensity of aluminum.
EI_i = energy intensity of fuel i.
FS = fuel share (e.g., coal, coke, natural gas, electricity, hydrogen, renewable heat, solid wastes)

n = aluminum production technology (primary and secondary aluminum production)
i = type of energy source

$$EI_{flat\ glass} = FS_i \times EI_i \qquad \text{(Equation 5)}$$

Where:

$EI_{flat\ glass}$ = weighted average of energy Intensity of flat glass.
EI_i = energy intensity of fuel i.
FS = fuel share (e.g., coal, coke, natural gas, electricity, hydrogen, renewable heat, solid wastes)
i = type of energy source.

For each material-producing industry, the following mitigation technologies and measures were considered: energy efficiency improvements, structural change, fuel switching, product change, and carbon capture and storage. Detailed assumptions on these technologies and measures for cement, steel, aluminum, and flat glass under three scenarios are provided in Tables 4, 5, 7, and 8 below.

In addition, for this study, we compared our assumptions of EAF shares in China by 2050 and 2060 with several studies, as shown in the Table 6. Our assumption for 2050 is quite comparable with other studies, and while most studies did not provide assumptions for 2060, our study added the analysis through 2060.

For cement production, the Chinese government has published some decarbonization plans, such as *the Carbon Peaking Plan for Building Materials Sector*[77] *and the Industry Sector Carbon Peaking Action Plan*.[78] The policies mainly include follow main orientations: 1) Phasing out low-efficiency kilns including vertical kilns and small-size kilns (<2,000 tonnes per day [tpd]). 2) Improving energy efficiency of kiln by adopting advanced technique and technique retrofit. The *Industry Sector Carbon Peaking Action Plan* requires energy intensity unit cement to decrease 3% by 2025 (i.e., decrease 1% per year).3) Adopting alternative energy sources,[77] such as biomass, waste and hydrogen. Meanwhile, improve electrification rate in industry production, such as electricity boilers and industry heat pumps.[78] Considering the high cost of hydrogen and higher emission factor of electricity under current Chinese conditions, He et al. (2023) suggested selecting biomass and waste as alternative energy sources in the short and mid-term and selecting hydrogen and green electricity as alternative energy sources in mid and long term.[79] 4) Using alternative raw materials and considering alternative cement chemistry. The *Carbon Peaking Plan for Building Materials Sector*[77] call for a reduction in the use of carbonates, an increase in the proportion of calcium-containing resources[48] (e.g., such as carbide slag, phosphorylase, fluorogypsum, manganese slag, and bauxite residues), and promoting low-carbon cements, such as belite cements and calcium sulphoaluminates. Considering techno-economics, Zhang et al. (2021) suggest a 30% of market penetration of alternative cement by 2050.[80] Furthermore, based on relevant policies and literature, we set three technology scenarios in Table 4.

For steel production, Chinese current policies and studies emphasize the following decarbonization orientations: 1) Promoting industrial process changes, i.e., from carbon-intensive blast furnace (BF) and basic oxygen furnace (BOF) to less intensive scrap-based electric arc furnace (EAF) process. Currently, the proportion of EAF in China is around 10% and significantly lower than developed countries, such as close to 70% in U.S and 40% in EU. The Chinese government set a target to increase the production share of EAF to be increased to 20% by 2030.[78] Although promoting EAF currently faces challenges of high production cost, lack of scrap resources at present, and insufficient technical capacity, some scholars have pointed out the challenge will be mitigated along with circular economy policies and the clean-up of power systems.[81,82] 2) Improving energy efficiency: China has set the baseline and benchmark level of steel production and required more than 30% of steel production need to meet the benchmark level by 2025.[72] Take the blast furnace (BF) as an example, the energy intensity of BF will reduce by 5% by 2025 (i.e., 1.25% per year). 3) Using alternative energy sources: The Chinese government is supporting iron and steel industry to gradually replacing the use of coal and coke in the iron and steel industry.[78] In especially, under the background of high proportion of renewable power toward carbon neutrality, the key role of hydrogen-based ironmaking has been highlighted. Currently, China is exploring to piloting some projects for large-scale hydrogen production and hydrogen utilization in industry production, and attempts to established a completed industry chain covering green power generation, hydrogen production, storage, transportation and utilization.[82] IEA estimated that 44% of global steel production will come from electrolytic hydrogen-based technologies by 2050 under the Net Zero Scenario.[83] Considering techno-economics, Ren et al. (2021) pointed out hydrogen-based steel production in China will increase to 23–25% by 2050,[84] which is similar with our CNS scenario setting (column 2 in Table 5). Furthermore, based on relevant policies and literature, we set three technology scenarios in Table 5. Several studies[51,61,68–70,85,86] pointed out the share of scrap-based EAF in China would reach 40%–60% by the mid of the century (see a summary of various assumptions used in the studies in Table 6).

For aluminum production, China has largest aluminum production in the world. Chinese aluminum production in China accounted for more than half of global aluminum production.[87] Currently, China government has developed circle economic and strictly limited electrolytic aluminum production capacity.[77] 1) Promoting industrial process change: IEA forecasted the secondary aluminum will account for 56% of global aluminum by 2050. China set a target of 11.5 Mt secondary aluminum production per year by 2025.[88] Meanwhile, considering construction sector is major consumer sector of aluminum (28%) and China's buildings demand is kept a decreasing trend, we set a higher proportion of second aluminum than IEA's global value (see in Column2 in Table 7). 2) Improving energy efficiency: China has set the baseline (13,350 kWh/t) and benchmark (13,000 kWh/t) level of electrolytic aluminum.[73] In other words, the energy intensity of aluminum production will decrease by 0.66% per year. Therefore, we set a decreasing of 0.4%, 0.8% and 1.2% in CIS, LCS and CNS, respectively. 3) Alternative energy sources. Energy of primary aluminum production is primarily electricity and is not expected to change in future. With the decarbonization progress in the power system, the emission intensity of primary aluminum will continue to decline. For secondary aluminum, its energy consumption mainly comes from the melting process which predominantly relies on fossil fuels in China. Considering the potential of industrial electrification and development of electrotechnologies,[89] we set 90% of electricity share for secondary aluminum in CNS scenario. Furthermore, based on relevant policies and literature, we set three technology scenarios in Table 7.

Although flat glass accounts for 42% of global total glass production, its recycling rate only arrived 11% in global wide.[90] 1) Improved recycling: flat glass currently cannot be recycled back into flat glass, but can be downcycled into fiberglass or asphalt mixtures. Currently, recycling flat glass has an official target in China but is still in the beginning stage. Considering the development of circle economic in China, we set a 10% and 16% of recycling target by 2060 in LCS and CNS scenarios, respectively. 2) Improving energy efficiency: due to its high emissions, Chinese government has strictly limited flat glass production capacity and required called for the replacement of outdated capacity with new advanced capacity.[91] Meanwhile, China has set the baseline and benchmark level of flat glass and required more than 30% of flat glass production need to meet the benchmark level by 2025.[72] Specifically, the energy intensity unit flat glass is targeted to decrease 2% per year. 3) Alternative energy sources, such as biomass and hydrogen are also encouraged by the central government.[77] In addition, the glass industry needs to improve its energy structure, by incorporating high shares of clean electricity.[77] Based on relevant policies and literature, we set three technology scenarios in Table 8.

Table 4. Modeling assumptions for cement demand in China's buildings sector

Cement Sector	Process Change	Efficiency Improvements	Fuel Switching	Material Efficiency	Alternative Cements	Carbon Capture and Storage (CCS)
CIS	Phasing out all vertical kilns by 2020	Weighted average energy efficiency reaches to *Level 2* of the current Minimum Energy Performance Standard of Cement (2020 MEPS standard) in China by 2030. Efficiency continues to improve slightly through 2060.	Continue reducing coal use in the cement industry to 73% of the final fuel use by 2060 in large rotary kilns (>4,000 tonnes per day [tpd]). Small and gradual increase MSW to 20% by 2060 in large rotary kilns Small and gradual increase biomass to 7% by 2060 in large rotary kilns	The lifetime of the buildings built after the year 2000 increases from the current average building lifetime of 30 years–50 years	Alternative cement strategies are not considered.	CCS applications are not considered.
LCS	Phasing out all vertical kilns by 2020 Phasing out all small rotary kilns (<4,000 tonnes per day [tpd]) by 2040	Weighted average energy efficiency reaches to the *average of Level 1 and Level 2* of the current Minimum Energy Performance Standard of Cement (2020 MEPS standard) in China by 2040. Efficiency stays at the same level through 2060.	The use of coal in cement industry is reduced to 40% of final fuel use by 2060 in large rotary kilns (>4,000 tpd). Significantly increase industrial wastes and other wastes to 45% by 2060 in large rotary kilns. Significantly increase biomass to 5% by 2060 in large rotary kilns Use of hydrogen starts in 2040 and increases to 5% by 2060 in large rotary kilns. Use of renewable heat begins in 2040 and increases to 7% by 2060.	Lifetime of 40% of the new buildings increases from the current level of 30 years–70 years by 2060. Moderate adoption of other material efficiency measures (see Table 2 in the manuscript).	Considered adoption of alternative cement (e.g., belite clinker), reaching 20% of market penetration by 2060.	Adoption rate of CCS increases to 10% by 2030 and increases to 55% by 2060. Capturing yields at 65% by 2030 and increases to 80% by 2060.

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Cement Sector	Process Change	Efficiency Improvements	Fuel Switching	Material Efficiency	Alternative Cements	Carbon Capture and Storage (CCS)
CNS	Phasing out all vertical kilns by 2020 Phasing out all small rotary kilns (<4,000 tonnes per day [tpd]) by 2030	Weighted average energy efficiency reaches to the *average of Level 1 and Level 2* of the current Minimum Energy Performance Standard of Cement (2020 MEPS standard) in China by 2030. Efficiency continues to improve 0.4% per year through 2060.	Significantly reduce coal use in cement industry to 3% of final fuel use by 2060 in large rotary kilns (>4,000 tpd). Significantly increase industrial wastes and other wastes to 65% by 2060 in large rotary kilns. Significantly increase biomass to 15% by 2060 in large rotary kilns. Use of hydrogen starts in 2040 and increases to 10% by 2060. Use of renewable heat begins in 2040 and increases to 7% by 2060.	Lifetime of 40% of the new buildings increases from the current level of 30 years–70 years by 2060. Moderate adoption of other material efficiency measures (see Table 2 in the manuscript).	Considered adoption of alternative cement, reaching 25% of market penetration by 2060.	Adoption rate of CCS increases to 10% by 2030 and increases to 100% by 2060. Capturing yields at 65% by 2030 and increases to 85% by 2060.

Note: tpd = tonnes per day.

Table 5. Modeling assumptions for steel demand in China's buildings sector

Steel Sector	Process Change	Efficiency Improvements	Fuel Switching	Material Efficiency	Carbon Capture and Storage (CCS)
CIS	Scrap-based EAF steel reaches to 43% by 2060. DRI based steel reaches to 7% by 2060.	Weighted average energy intensity improves 1.3% per year through 2060.	No fuel switching in BF-BOF. Electricity accounts for 100% of total energy use in Scrap-based EAF. Coke use accounts for 75% of energy inputs in DRI by 2050.	The lifetime of the buildings built after the year 2000 increases from the current average building lifetime of 30 years–50 years.	CCS applications are not considered.
LCS	Scrap-based EAF steel reaches to 50% by 2060. Hydrogen-DRI based steel reached to 15% by 2060.	BO-BOF energy intensity improves 0.8% per year on average through 2060. Scrap-EAF energy intensity improves 1.3% per year on average through 2060. DRI energy intensity improves 0.1% per year on average through 2060. Steel rolling energy intensity improves 0.5% per year on average through 2060.	Decreased use of coke and coal to 50% of the final energy inputs in BF-BOF by 2060. Increased use of MSW-plastic wastes to 10% by 2060 in BF-BOF. Electricity accounts for 100% of the total energy use in Scrap-based EAF. Green hydrogen use accounts for 10% of energy inputs in BF-BOF by 2060. Green hydrogen use accounts for 40% of energy inputs in DRI by 2050.	Lifetime of 40% of the new buildings increases from the current level of 30 years–70 years by 2060. Moderate adoption of other material efficiency measures (see Table 2 in the manuscript).	CCS applications were considered for the BF-BOF process. Adoption rate reaches to 2% by 2030 and increases to 30% by 2060. Capturing yields at 65% by 2030 and increases to 80% by 2060.

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Steel Sector	Process Change	Efficiency Improvements	Fuel Switching	Material Efficiency	Carbon Capture and Storage (CCS)
CNS	Scrap-based EAF steel reaches to 60% by 2060.	BF-BOF energy intensity improves 0.9% per year on average through 2060, reaching the practical minimum energy intensity level.	Decreased use of coke and coal to 40% of the final energy inputs in BF-BOF by 2060.	Lifetime of 70% of the new buildings increases from the current level of 30 years–70 years by 2060.	CCS applications were considered for the BF-BOF process. Adoption rate reaches to 2% by 2030 and increases to 40% by 2060.
	Hydrogen-DRI based steel reached to 25% by 2060.	Scrap-based EAF energy intensity improves 1.5% per year on average through 2060, reaching practical minimum energy intensity level.	Increased use of MSW-plastic wastes to 35% by 2060 in BF-BOF.		Capturing yields at 65% by 2030 and increases to 85% by 2060.
		DRI energy intensity improves 0.3% per year on average through 2060.	Electricity accounts for 100% of the total energy use in Scrap-based EAF.	Aggressive adoption of other material efficiency measures (see Table 2 in the manuscript).	
		Steel rolling energy intensity improves 0.9% per year on average through 2060, reaching the practical minimum intensity level by 2060.	Hydrogen use accounts for 15% of energy inputs in BF-BOF by 2060. Hydrogen use accounts for 75% of energy inputs in DRI by 2050.		

Table 6. Comparison of EAF shares in China by different studies

Reference	Projected EAF Shares in China	
	2050	2060
Zhang et al. (2018)[85]	45%	N/A
IEA (2020) Sustainable Development Scenario[51]	45%	N/A
Yu et al. (2021)[70]	56%	N/A
Bataille et al. (2021)[68]	45%	N/A
Chen et al. (2021)[69]	60%	N/A
Expert interview with China Metallurgical Planning Institute	50-60%	N/A
Mission Possible Partnership (2022) Carbon Cost Scenario[61]	39%	N/A
Hasanbeigi et al. (2023)[86]		
Advanced Scenario	40%	N/A
Net-Zero Scenario	60%	N/A
This study		
Low Carbon Scenario (LCS)	40%	50%
Carbon Neutrality Scenario (CNS)	50%	60%

Table 7. Modeling assumptions for aluminum demand in China's buildings sector

Alumina	Process Change	Efficiency Improvements	Fuel Switching	Material Efficiency	Carbon Capture and Storage (CCS)
CIS	Phasing out sintering process in alumina-making by 2060. Bayer process accounts for 95% of all alumina production by 2060.	Bayer process energy intensity improves 0.9% per year on average through 2060	The share of natural gas increases from 13% in 2020 to 18% in 2060. The share of electricity increases from 30% in 2020 to 43% in 2060.	Material efficiency strategies were not considered.	CCS applications were not considered.
LCS	The production share from non-Bayer processes in alumina-making is reduced to 2% by 2050. Bayer process accounts for 98% of all alumina production by 2050.	Bayer process energy intensity improves 1% per year on average through 2060	Increase the use of electricity to 70% by 2060 in the Bayer process. Increase the use of hydrogen to 5% by 2060 in the Bayer process. Increase the use of renewable heat to 5% by 2060 in the Bayer process.		
CNS	Phasing out sintering process in alumina-making by 2050. Bayer process accounts for 100% of all alumina production by 2050 and continues through 2060.	Bayer process energy intensity improves 1.1% per year on average through 2060, reaching to the practical minimum energy intensity level.	Increase the use of electricity to 75% by 2060 in the Bayer process. Increase the use of hydrogen to 18% by 2060 in the Bayer process. Increase the use of renewable heat to 7% by 2060 in the Bayer process.		

Aluminum	Process Change	Efficiency Improvements	Fuel Switching	Material Efficiency	Carbon Capture and Storage (CCS)
CIS	Secondary aluminum making accounts for 60% by 2060.	Primary aluminum energy intensity improves 0.4% per year on average through 2060, reaches today's state-of-art level by 2060. Secondary aluminum energy intensity improves by 1.1% per year on average from 2020 to 2060.	Coke, fuel oil, and natural gas account for 72% of energy inputs by 2060 in secondary aluminum production.	The lifetime of the buildings built after the year 2000 increases from the current average building lifetime of 30 years–50 years	CCS applications were not considered.
LCS	Secondary aluminum making accounts for 70% by 2060.	Primary aluminum energy intensity improves by 0.8% per year on average through 2060. Secondary aluminum energy intensity improves by 2.2% per year on average from 2020 to 2060.	78% of energy inputs for secondary aluminum production is from non-fossil by 2050. Fossil fuels are phased out by 2060.	Lifetime of 40% of the new buildings increases from the current level of 30 years–70 years by 2060. Moderate adoption of other material efficiency measures (see Table 2 in the manuscript).	

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Aluminum	Process Change	Efficiency Improvements	Fuel Switching	Material Efficiency	Carbon Capture and Storage (CCS)
CNS	Secondary aluminum making accounts for 85% by 2060.	Primary aluminum energy intensity improves by 1.2% per year on average through 2060, reaching practical minimum energy intensity by 2050.	100% of energy inputs for secondary aluminum production is from non-fossil by 2050. Hydrogen accounts for 5% of energy inputs by 2060. Renewable heat accounts for 5% by 2060. Electricity accounts for 90% by 2060.	Lifetime of 70% of the new buildings increases from the current level of 30 years–70 years by 2060.	
		Secondary aluminum energy intensity improves by 2.3% per year on average from 2020 to 2060.		Aggressive adoption of other material efficiency measures (see Table 2 in the manuscript).	

Table 8. Modeling assumptions for flat glass demand in China's buildings sector

Flat Glass	Process Change	Efficiency Improvements	Fuel Switching	Material Efficiency	Carbon Capture and Storage (CCS)
CIS	Due to various types of glass used, it can't be mixed together nor with container glass, so it currently can't be recycled back into flat glass, but can be downcycled into fiberglass or asphalt mixtures.	Flat glass energy intensity improves to the current best practice level under China's Minimum Energy Performance Standard for flat glass by 2060. Average energy intensity decreases 2% per year on average from 2020 to 2060.	Natural gas accounts for 55% of total fuel inputs by 2060. Fuel oil and other oil products account for 45% of the total fuel input by 2060.	The lifetime of the buildings built after the year 2000 increases from the current average building lifetime of 30 years–50 years	CCS applications were not considered.
LCS	Flat glass recycling rate begins to increase to 2% by 2030 and to 10% by 2060.	Flat glass energy intensity improves to the current best practice level under China's Minimum Energy Performance Standard for flat glass by 2050. Average energy intensity decreases 2.1% per year on average from 2020 to 2060.	Hydrogen use increases to 10% by 2060. Biogas use increases to 5% by 2060. Renewable heat increases to 5% by 2060. The share of natural gas is reduced to 15% by 2060. Increased use of electricity through 2060.	Lifetime of 40% of the new buildings increases from the current level of 30 years–70 years by 2060.	CCS applications were not considered.
CNS	Flat glass recycling rate begins to increase to 3% by 2030 and to 16% by 2060.	Flat glass energy intensity improves to the current best practice level under China's Minimum Energy Performance Standard for flat glass by 2040 and continues to improve 0.4% per year through 2060. Average energy intensity decreases 2.4% per year through 2060.	Hydrogen use increases to 25% by 2060. Biogas use increases to 12% by 2060. Renewable heat increases to 13% by 2060. Natural gas is phased out by 2060. Increased use of electricity through 2060.	Lifetime of 70% of the new buildings increases from the current level of 30 years–70 years by 2060.	CCS applications were not considered.