More intensive use and lifetime extension can enable net-zero emissions in China's cement cycle

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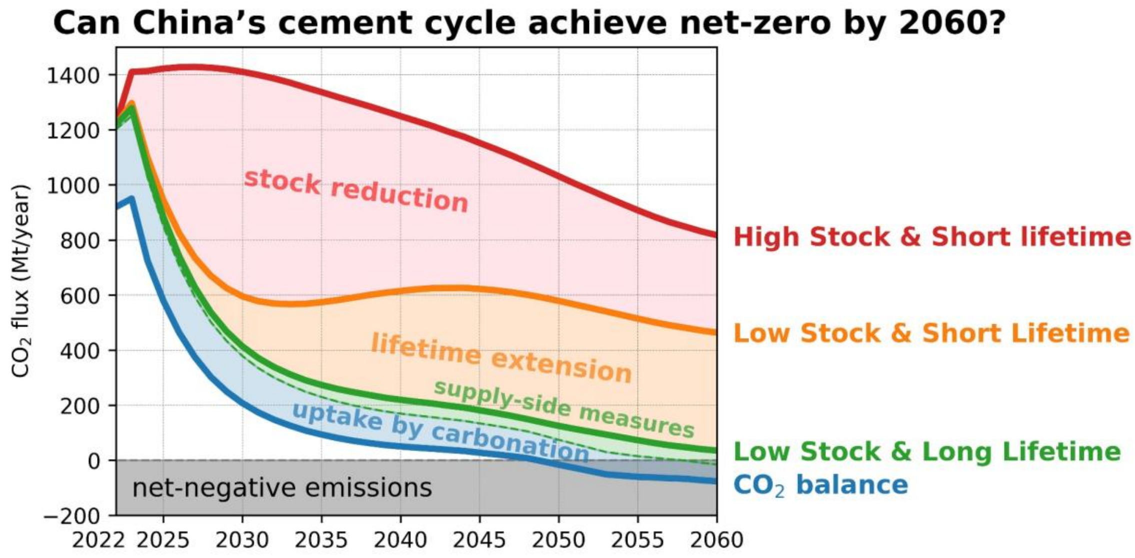
Abstract

Demand-side material efficiency strategies could play a key role in decarbonizing the cement cycle as conventional supply-side measures leave little room for improvement and emerging technologies are still in their infancy and expensive. This study quantitatively evaluates CO_2 reduction opportunities through China's cement cycle by more intensive use and lifetime extension during 2023-2060. More intensive use and lifetime extension can cumulatively save cement consumption by ~58 gigatons (Gt) during 2023-2060, resulting in CO_2 emission reductions of ~33.8 Gt without considering supply-side actions and cement carbonation. If supply-side measures and cement carbonation are considered, China's cement cycle could achieve net-zero CO_2 emissions by 2060 or even mid-century. Besides, it is important to assess social implications, opportunities, and challenges of lower per-capita stocks and longer service-life, when we aim to realize these emission reductions. Also, trade-offs between CO_2 fluxes should be considered in cement decarbonization road mapping because more intensive use and lifetime extension can lower CO_2 uptake by cement carbonation.

Keywords: cement cycle; dynamic material flow analysis; material efficiency; net-zero

Graphic Abstract



1. Introduction

Up to 4 gigatons (Gt) of cement was produced to glue gravels and sands together to form concrete or mortar for satisfying the growing demand for buildings, roads, tunnels, water treatments and delivery systems, sewage lines, and dams around the world (Andrew, 2019). China has emerged as the largest cement producer in the world since its economic reform. Massive production and use of cement, driven by soaring needs for housing and infrastructure development, has positioned the cement sector as a significant source of CO_2 emissions. The sheer volume of cement production released substantial CO_2 emissions, despite a lower emission intensity of around 600 kg CO_2 per tonne of cement compared with metals (Fennell et al., 2021). Annual CO_2 emissions from China's cement sector reached 1.3 Gt in 2020 (Wu et al., 2022). Without fundamental changes, China's cement sector will continue to be a significant source of CO_2 emissions, posing significant risks to climate change goals.

Yet, decoupling CO_2 emissions from cement production is a challenging task, because two-thirds of its CO_2 emissions come from carbonate decomposition during calcination. In addition, large-scale deployment of alternative cement is unlikely to occur due to feedstock constraints and high manufacturing costs (Habert et al., 2020; Monteiro et al., 2017). Consequently, beyond conventional supply-side efforts, demand-side measures based on the philosophy 'using less cement', i.e., material efficiency strategies, could potentially open up the option space for decarbonizing the cement sector in China (Fennell et al., 2022; Miller et al., 2021).

Demand-side material efficiency measures aim to achieve desired levels of service from smaller cement stocks (Hertwich et al., 2019), including more intensive use (Grubler et al., 2018; Pauliuk et al., 2013) and lifetime extension (Cai et al., 2015; Miller, 2020) of in-use product stock, material-efficient design (Cao et al., 2021; Shanks et al., 2019), material substitution (Churkina et al., 2020; Göswein et al., 2022), as well as reusing building components (Eberhardt et al., 2018; Huuhka et al., 2015) and recycling (Wang et al., 2021; Xiao et al., 2012) at the end-of-life. More intensive use of residential and commercial buildings by 20% lower area per person could globally reduce 56.8 Gt CO_2-eq greenhouse gas (GHG) emissions from material production during 2020-2060 (Zhong et al., 2021). Lifetime extension could significantly reduce resource demand to replace demolished buildings and infrastructures by prolonging their service-life (Cai et al., 2015; Miller, 2020). Retrospective analysis showed that a 50% lifetime extension for in-use cement stock could cumulatively lead to a 14% reduction in cement demand and ~0.7 Gt CO_2 emissions from cement production from 1900 to 2015 in the United States (Miller, 2020), whereas extending building lifetime to 50 years could reduce annual CO_2 emissions by 426 Mt per year in China (Cai et al., 2015). Material-efficient design aims to avoid the load-bearing capacity of structural elements not fully utilized, which is common in the construction industry due to designers' cautiousness (Cao et al., 2021). Although current practices, e.g., performance-based structure design and post-tensioning concrete elements (Shanks et al., 2019), could potentially reduce cementitious binder intensity by ~20%, wide-scale deployment of these design-oriented measures will hinge on how fast designers or contractors will take them up, as well as adequate policy interventions (Cao et al., 2021). Material substitution tries to substitute emission-intensive construction materials (e.g., concrete and steel) by bio-based materials with lower embodied emissions, such as engineered timber (Churkina et al., 2020). An optimistic estimate stated that the widespread implementation of timber construction from 2020 to 2050 has the potential to sequester a minimum of 7 Gt CO_2 (Churkina et al., 2020), whereas the realization of this potential will be constrained by the limited supply capacity from available global forests (Pomponi et al., 2020). As for end-of-life options, efficiently reusing concrete components requires prefabricated or modular construction and standardized design on buildings (Huuhka et al., 2015). Besides, technologies to recycle hydrated cement waste into new cement are still in the development phase and need validation (Gastaldi et al., 2015), though crushed concrete debris could be downcycled as coarse aggregate or roadbed to reduce virgin aggregate consumption (Cao et al., 2021). Whilst previous studies (Pauliuk et al., 2021; Zhong et al., 2021) reveal substantial emissions reductions from employing material efficiency measures in the future building sector globally, how CO_2 fluxes interplay with cement stock dynamics under the impact of a lower per-capita stock through more intensive use and lifetime extension is seldom discussed towards the net-zero future.

Besides as an emitter, cement stock could reabsorb substantial CO_2 by carbonation (Xi et al., 2016), a physicochemical process by which unstable calcium oxide embodied in cement materials will react with atmospheric CO_2 over time (Pade & Guimaraes, 2007). An updated analysis shows that up to 21 Gt CO_2 had been absorbed by cement carbonation during 1930-2019, cumulatively offsetting ~55% of process emissions from production (Guo et al., 2021). In addition to retrospective analysis, a global scenario-based projection highlights that cumulative CO_2 uptake from 2015 to 2100 amounts to 81-117 Gt, revealing that the magnitude of this passive sequestration could be greater than the active carbon capture and storage (CCS) prescribed in current technology roadmaps (Cao et al., 2020). Also, for specific countries, cement carbonation could be an important lever to achieve net-zero emissions through the cement and concrete cycle by mid-century (Watari et al., 2022). Whilst the CO_2 uptake by cement carbonation is well recognized in the global carbon cycle (Cao et al., 2020) and carbon budget (Friedlingstein et al., 2022), an explicit understanding of trade-offs between CO_2 emissions and uptake induced by varying stock levels and lifetime scenarios is still lacking, obscuring its role in cement decarbonization roadmaps.

Against this background, we developed an integrated modeling framework that allows us to: (1) analyze historical and future cement flows and stocks; (2) consider the interplay between CO_2 fluxes and cement stock dynamics; and (3) quantify net changes in CO_2 fluxes associated with China's cement cycle. With this integrated modeling framework, we designed wide-ranging scenarios to explore various decarbonization possibilities for China's cement cycle and evaluate the role of cement stock reduction and lifetime extension.

2. Methods and data

The modeling framework consists of three modules: dynamic material flow analysis (DMFA), CO_2 emissions accounting, and cement uptake estimation. First, we collected statistics on China's annual cement production, import, and export to estimate the historical total and per capita in-use cement stock during 1949-2022 by the inflow-driven method. With historical total and per capita in-use cement stock, we employed a stock-driven method to project future cement consumption from 2023 to 2060, considering nine (3×3) demand-side scenarios to reflect varying levels of lifetime extension and stock saturation. We then developed a CO_2 emissions accounting model to quantify annual CO_2 emissions associated with cement production. In parallel with CO_2 emissions accounting, we employed a physicochemical model to estimate CO_2 uptake by cement carbonation spanning the cement cycle. On top of the demand-side scenarios, we considered supply-side measures to explore decarbonization opportunities along the cement cycle. By considering CO_2 emissions and CO_2 uptake, we used net CO_2 emissions to present simulation outcomes.

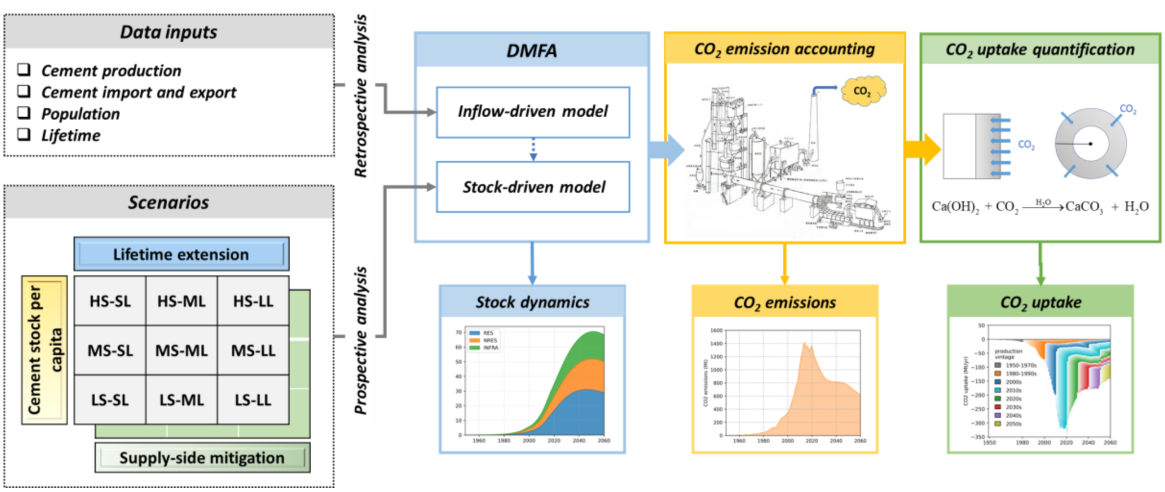


Figure 1 | Integrated modeling framework of the material-energy-emission-uptake nexus in the cement cycle (IMAGINE Cement). Adapted from a previous study (Cao et al., 2021). Note: HS, MS, and

LS represent High Stock, Medium Stock, and Low Stock scenarios. And SL, ML, and LL denote Short Lifetime, Moderate Lifetime extension, Substantial Lifetime extension scenarios respectively.

2.1 Dynamic material flow analysis

DMFA provides a framework to characterize materials entering and leaving a system over a period of time in a mass-balanced manner (Kapur et al., 2008; Liu & Muller, 2013; Muller et al., 2014). Depending on the goal of DMFA, two methods are usually employed in DMFA: inflow-driven and stock-driven (B. Müller, 2006; Bergsdal et al., 2007). In this study, we employed the inflow-driven method to estimate historical total and per capita in-use cement stocks and the stock-driven method to project future cement consumption from 2023 to 2060.

2.1.1 Inflow-driven method

The underlying equation of the inflow-driven method is described as follows.

$$S_t = \sum_{i=1949}^{t} \left(I_i - O_i \right) \tag{1}$$

where S_t denotes the material stock within the system boundary in the year t as well as I and O represent material inputs and outputs, respectively. Cement inflow refers to apparent consumption, that is, domestic production plus imports minus exports. Data on cement production, imports, and exports were taken from the data platform of the National Bureau of Statistics (2023). Cement outflow refers to cement leaving from in-use cement stock, which is calculated as follows.

$$O_t = \sum_{i=1949}^{t} I_i \cdot Dr(i-1949) \tag{2}$$

$$Dr(T) = \int_{T-1}^{T} f(x)dx \tag{3}$$

where $Dr(T)$ represents the demolition rate for the in-use stock after T years it entered use. It could be calculated from the cumulative distribution function of the lifetime distribution $f(x)$, which describes the probability that a unit will be discarded after the time T it enters use (B. Müller, 2006). Given that right-skewed distribution is consistent with the fact that buildings that survive after the demolition peak tend to stay longer than others in their cohort (Miatto et al., 2017), we chose a two-parameter lognormal distribution to characterize the lifetime distribution of in-use cement stock (Eq. (4)).

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{\left(\ln(x) - \mu\right)^2}{2\sigma^2}\right) \tag{4}$$

where μ and σ represent the location and scale parameters respectively.

2.1.2 Stock-driven method

With estimates of historical per-capita cement stock, we projected future cement inflows using a stock-driven method (Cao et al., 2020) that considers key drivers, including per-capita cement stock, population, and lifetime. Annual cement inflows were determined by summing up net additions to cement stocks and cement outflows (Eq. (5)). Future cement stocks were determined by multiplying the population by per-capita cement stocks (Eq. (6)). Due to its abundant resource availability, good workability, long-lasting durability, and versatility, cement is expected to continue to be a dominating construction material moving forward. Therefore, a modified Gompertz function (Liu et al., 2012) was used to simulate the development of per-capita cement stocks, assuming that no abrupt changes will take place moving forward (Eq. (7)).

$$I_t = S_t - S_{t\text{-}1} + O_t \tag{5}$$

$$S_t = P_t \cdot s_t \tag{6}$$

$$s_t = \frac{s_{sat}}{1 + \left(\frac{s_{sat}}{s_{2022}} - 1\right) \cdot \exp(A \cdot (1 - \exp(B \cdot (t - 2022))))} \tag{7}$$

where P_t denotes population, s_t represents cement stock per capita in the year t, a and b denote parameters that determine the growth curve and when s_t reaches 98% of the saturation level s_{sat} at a given time.

2.2 CO_2 emissions accounting

We considered CO_2 emissions associated with the main processing steps in cement production, including raw materials preparation, clinker production, and cement grinding. As emissions-related data were drawn from plant-level statistics, we limited the system boundary of CO_2 emissions accounting to activities that occur within cement plants.

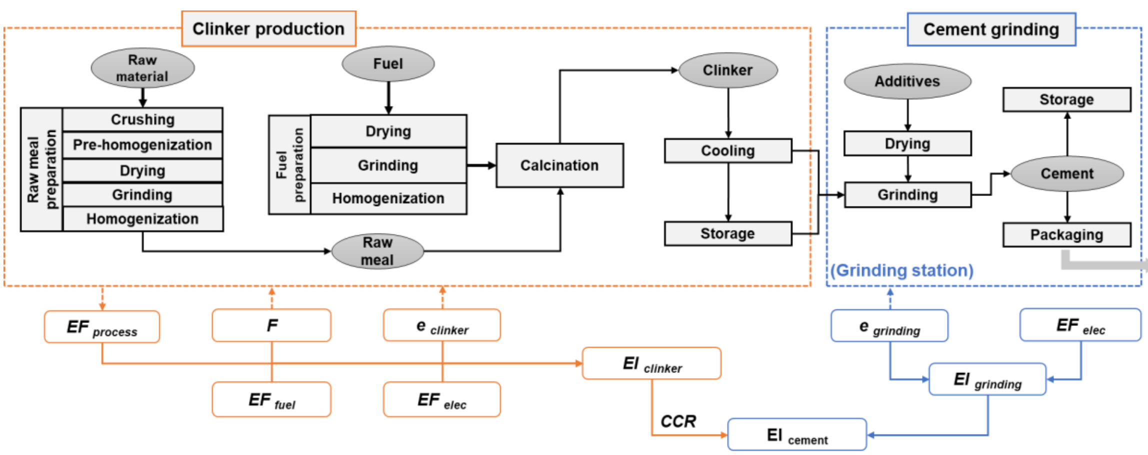


Figure 2 | System boundary of CO_2 emission accounting. (Notes: *EI* represents the emission intensity of a unit process of production. *EF* denotes the emission factors for fuel combustion or electricity generation. *F* and *e* represent thermal and electrical duty for unit process respectively. *CCR* denotes the clinker-to-cement ratio.)

CO_2 emissions associated with cement production stem from three sources: carbonate decomposition, fuel combustion, and electricity use. And the emission intensity, that is the total CO_2 emission released from the production of the unit product, of cement (EI_{cement}) and clinker (EI_{clinker}) could be calculated in Eq. (8) and Eq. (9), respectively.

$$EI_{\text{cement}} = EI_{\text{clinker}} \cdot CCR + EI_{\text{grinding}} \tag{8}$$

$$EI_{\text{clinker}} = EF_{\text{process}} + EI_{\text{fuel}} + EI_{\text{clinker}}^{\text{elec}} \tag{9}$$

where CCR represents the clinker content in unit product cement, i.e., the clinker-to-cement ratio; EF_{process} denotes the emission factor of limestone decomposition during kiln calcination; EI_{fuel} denotes the emission intensity for fuel combustion during calcination; $EI_{\text{clinker}}^{\text{elec}}$ and EI_{grinding} represents the emission intensity from electricity use by clinker production and cement grinding, respectively. And EI_{fuel} could be broken down in Eq. (10) to consider the deployment of alternative fuel.

$$EI_{fuel} = F \cdot \sum_j w_j \cdot EF_{\text{fuel}}^{j} \tag{10}$$

$$EI_{\text{clinker}}^{\text{elec}} = e_{\text{clinker}} \cdot EF_{\text{elec}} \tag{11}$$

$$EI_{grinding} = e_{\text{grinding}} \cdot EF_{\text{elec}} \tag{12}$$

where, F denotes the thermal duty for the unit process of clinker production; w_j denotes the deployment rate of fuel of type j; EF_{fuel}^{j} represents emission factor of fuel of type j; e_{clinker} and e_{grinding} represent electrical duty for the unit process of clinker production and cement grinding, respectively; EF_{elec} denote emission factors for power generation. And the specific values of these parameters are displayed in the Supplementary information. Besides emissions accounting, those cement plants in operation will turnover based on their expected lifetime and the consideration of recent industrial policies (see details in Supplementary Notes B).

2.3 Cement carbonation

A physicochemical model was employed to characterize cement carbonation and estimate CO_2 update across the life cycle of cement (Cao et al., 2020; Guo et al., 2021; Watari et al., 2022; Xi et al., 2016). The cement carbonation model succinctly parameterizes the physicochemical carbonation reactions at different life cycle stages (i.e., production, in-use, demolition, and secondary use) and is populated by region-specific data from field surveys. We considered four CO_2-absorbing materials: concrete, mortar, construction waste, and cement kiln dust (CKD). For this model, we made the following two assumptions. First, cement-based products are characterized by simplified geometries (see Figure S13). Second, the diffusion front is equivalent to the carbonation front, and the area behind the front is regarded as fully carbonated (Guo et al., 2021). With these assumptions, the annual CO_2 uptake by cement and mortar was estimated based on the annual growth in cumulative carbonation fraction of carbonated cement-based products, cement content of the material, clinker-to-cement ratio, CaO content of clinker, the proportion of CaO converted to $CaCO_3$ within the fully carbonated clinker, and molar mass ratio of CO_2 and CaO (Eq. (13)). The cumulative carbonation fraction was determined by the carbonation depth and the thickness of concrete structure components, mortar layer, or diameter of demolished waste particles, based on the simplified geometry assumption (Eq. (14)). And carbonation depth was determined using Fick's diffusion law (Eq. (15)).

$$U_t = S_t^{t_1} \cdot \Delta F_t \cdot f_{\mathrm{cement}} \cdot f_{\mathrm{clinker}} \cdot f_{\mathrm{CaO}} \cdot \gamma \cdot Mr_{\mathrm{CaO}}^{\mathrm{CO_2}} \tag{13}$$

$$F_t = d_t^{t_1} / D \tag{14}$$

$$d_t^{t_1} = k \cdot \sqrt{t_1 - t} \tag{15}$$

Where U_t is the annual uptake by concrete or mortar products; $S_t^{t_1}$ is the remained in-use stock that entered into use phase in year t_1; F_t is the cumulative carbonated fraction and ΔF_t is the annual growth in carbonated fraction; f_{cement} is the cement content in concrete or mortar; f_{clinker} is the clinker content in the cement, i.e., the clinker-to-cement ratio; f_{CaO}

is the CaO content in the clinker or CKD; γ is the fraction of CaO that could be converted to $CaCO_3$; $Mr_{\mathrm{CaO}}^{\mathrm{CO_2}}$ is the molar mass ratio of CO_2 and CaO; k is the carbonation rate coefficient of the material, which is affected by exposure condition, CO_2 concentrations, cement additives, and coating and coverings; and $t_1 - t$ is the cumulative exposed time in years; D is the average thickness of concrete structure components or mortar layer. As for construction waste and CKD, we estimated their CO_2 uptake by an annual carbonation fraction of total mass. The reason is that they are small pieces and particles, and we assume that they will be fully carbonated within one to five years (Guo et al., 2021). All the calculation processes and other details of the carbonation model are displayed in Supporting Information 5.

2.4 Scenarios and narratives

We designed nine demand-side scenarios to reflect the effects of stock saturation and lifetime extension. More specifically, we constructed three stock-related scenarios (i.e., ***Low Stock***, ***Medium Stock***, and ***High Stock***) to represent the implementation of demand-side measures that can decouple cement demand from service provision, including more intensive use and material-efficient design (Cao et al., 2021; Cullen & Cooper, 2022; Hertwich et al., 2019; Pauliuk et al., 2021; Zhong et al., 2021) (Table 1). The three stock-related scenarios reflect the deployment levels of these demand-side measures, ranging from 33.5 t/cap to 57.6 t/cap (details see Supporting Information 2). The Low Stock scenario describes a future in which service levels will maintain at current levels by widespread implementation of efficient measures such as more-intensive use, whereas the aggregate cement intensity will grow by ~18% as service quality will be improved by more cement-based products, leading to a per-capita stock that converges to 33.5 t/cap by 2060. Per-capita stock of Medium Stock scenario will grow and converge to 41.3 t/cap by 2060, as both service levels and quality will be improved moderately. And the High Stock scenario reflects a future in which cement stock per capita in China will grow significantly to 57.6 t/cap by 2060, as its service levels will catch up with that in industrialized countries and the aggregate cement intensity will also increase substantially, due to the widespread implementation of cement-based products.

In addition, we designed three lifetime-related scenarios (i.e., ***Short Lifetime***, ***Moderate Lifetime Extension***, and ***Substantial Lifetime Extension***) to reflect the implementation of lifetime extension. In modeling the effects of lifetime extension, we assumed that the lifetime will gradually increase over time, aiming to avoid abrupt changes in projected cement inflows. The lifetime of cement-based products is determined by physical, social, and economic factors (Huuhka & Lahdensivu, 2014; Liu et al., 2014; O'Connor, 2004; Thomsen & van der Flier, 2011). For the ***Short Lifetime*** scenario, we assumed that the lifetime remains unchanged during 2020-2060. For the ***Moderate Lifetime Extension*** scenario, we assumed that the lifetime is extended to 50 years during 2020-2060. For the ***Substantial Lifetime Extension*** scenario, we assumed that the lifetime is extended to 70 years during 2020-2060, as land use rights in China are usually granted for 70 years(1990).

Table 1 | Scenarios and key assumptions.

Dimension	Scenario	Description
Lifetime	Short Lifetime (SL)	Lifetime remains unchanged during 2020-2060.
	Moderate Lifetime Extension (ML)	Lifetime is extended to 50 years by 2060.
	Substantial Lifetime Extension (LL)	Lifetime is extended to 70 years by 2060.
Stock saturation	High Stock (HS)	Cement stock per capita will grow on historical rates and saturate at 57.6 t/cap by 2060.

Medium Stock (MS)	Cement stock per capita will saturate at 41.3 t/cap by 2060.
Low Stock (LS)	Cement stock per capita will saturate at 33.5 t/cap by 2060.

For population projections, we adopted the medium growth scenario from United Nations Population Prospects 2022, and the high- and low-variants to characterize the upper and lower bounds(2022).

Under each of the nine demand-side scenarios, we considered five supply-side measures to represent decarbonization efforts targeting cement production: (1) thermal efficiency, (2) electrical efficiency, (3) alternative fuels, (4) clinker substitution, and (5) carbon capture and storage (CCS). We collected data from various sources to determine present-day values and values achievable by 2060. More specifically, we retrieved data on thermal and electric efficiency from recent surveys and industrial statistics (2022). We assumed that energy efficiency will improve to the current best levels by 2060 (2018; 2021). The share of alternative fuels will increase to 35% by 2050 and 40% by 2060 (Dinga & Wen, 2022). As recent policies promote high-grade cement with higher clinker content than before (Wu et al., 2022), the clinker-to-cement ratio (CCR) is expected to gradually decrease to 60% by 2060. Besides, we also considered grid decarbonization, which is reflected by decreases in CO_2 emissions per unit of electricity used due to increasing penetration of renewables (Tan et al., 2022). According to technical maturity and economic costs, we considered the most mature post-combustion technology, i.e., absorption with mono-ethanolamine (MEA), as well as oxyfuel (OXY) and calcium looping (CAL) technologies (Gardarsdottir et al., 2019; Voldsund et al., 2019). More specifically, 88-93% of CO_2 from stack flue gas could be captured by these technologies, with varying energy penalties (Voldsund et al., 2019). According to technology readiness

(Hills et al., 2016), mature MEA facilities have been applied to retrofit existing plants, while OXY and CAL are expected to be commercially available for new kilns by 2030 (Hills et al., 2016), respectively. It is expected that around 100 kilns will be equipped with CCS facilities by 2050, based on the current pilot projects and optimistic anticipation (ECRA & CSI, 2017; GCCA, 2021). The deployment pace of CCS was determined by a capacity turnover model (see Supplementary Notes B), in which kilns with a capacity over 5000 tpd and remain lifetime within 20 years are prioritized for CCS deployment to maximize its utility and revenue.

Table 2 | Supply-side mitigation measures.

Measures	Description
Thermal efficiency	Thermal efficiency decreases to 3.0 and 2.9 GJ/t clinker by 2050 and 2060, respectively.
Electrical efficiency	Electrical efficiency for clinker production decreases to 57 and 50 kWh/t clinker by 2050 and 2060, respectively.
	Electrical efficiency for cement grinding decreases to 30 and 28 kWh/t cement by 2050 and 2060, respectively.
Alternative fuels	The share of alternative fuels increases to 35% by 2050 and 40% by 2060, respectively.
Clinker substitution	The clinker-to-cement (CCR) ratio decreases to 60% by 2060.
Carbon capture and storage (CCS)	Around 100 kilns are equipped with CCS by 2050, and five pilot kilns are retrofitted with MEA for demonstration by 2030. CAP and MAL are applicable for new kilns from 2030 and Oxyfuel and CAL are applicable for new kilns from 2040.
Grid decarbonization	CO_2 emissions per unit of electricity used decrease to 0.07 and 0.03 kg CO_2/kWh by 2050 and 2060, respectively.

For each supply-side measure, we assumed a linear trend between now and 2060 for simplification. More details about the methods and data are documented in the Supplementary Information.

3. Results

3.1 Trends of cement stocks

As shown in Figure 3, China's in-use cement stock has increased from 6.2 Gt to 40.5 Gt during 2000-2022. Under Medium Stock scenarios (Figures 3d, 3e, and 3f), the in-use stock will peak at 56.3 Gt by 2040 and then decrease to 51.1 Gt by 2060, if in-use stock per capita will continue to rise based on the historical rate. As economic development and urbanization often lead to lower fertility rates, population declines are expected to arrive in the 2030s (Ye, 2022), leading to a slight decline in in-use stock after the peak. If China's service level will catch up with the levels in industrialized countries, the in-use stock will grow substantially and finally peak at 72.5 Gt by 2050, after that gradually decline to 70.4 Gt in 2060 (High Stock scenarios, Figure 3a, 3b, 3c). In contrast, the in-use stock will only increase by 17 % and peak at 47.5 Gt as early as 2030, with the implementation of material efficiency measures (Low Stock scenarios, Figures 3g, 3h, 3i). Across all scenarios, lifetime extension will significantly change the vintage proportion of the in-use stock. Without lifetime extension, in-use cement stock built before 2020 will gradually decrease to 22.7 Gt in 2040 and finally slide to 8.6 Gt in 2060, whereas in-use stock built after 2020 will amount to as high as 45.2 Gt in 2040 and 61.8 Gt in 2060 (High Stock and Short Lifetime, Figure 3a). If the lifetime is extended to 70 years, in-use stock built before 2020 will survive longer and gradually slide to 28.3 Gt in 2040 and 20.6 Gt in 2060 at a slower rate, and in-use stock built after 2020 could be reduced to as low as 19.2 Gt in 2040 and 21.3 Gt in 2060 (Low Stock and Substantial Lifetime Extension, Figure 3i).

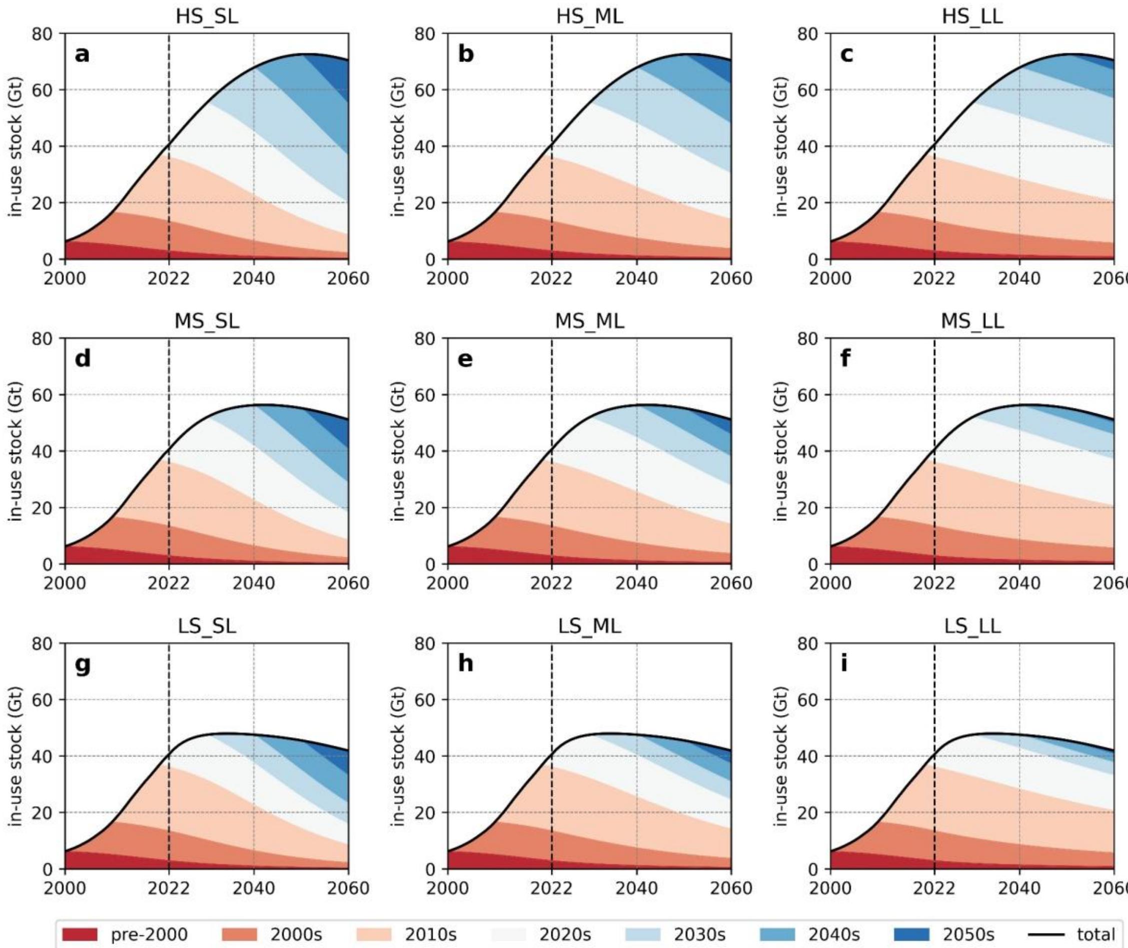


Figure 3 | Projection of China's in-use cement stock of all scenarios during 2000-2060.

3.2 Trends of cement consumption in China

As shown in Figure 4, the gradual saturation of cement stocks leads to declines in cement consumption during 2023-2060. Across all scenarios, China's cement consumption is projected to decrease over the next decades due to the combined effect of a declining population and saturated per-capita cement stocks. This effect could gradually decrease annual cement consumption from 2.1 Gt yr^{-1} in 2022 to 1.7 Gt yr^{-1} in 2030 if per-capita stock grows at the historical rate (Medium Stock and Short lifetime, Figure 4b). In High Stock scenarios, annual consumption will rebound to around 2.2 Gt yr^{-1} in the 2030s after a slight decline in the near term, when much more cement is needed to build up and renovate buildings and infrastructure during 2023-2060 (Figure 4a). Conversely, a quick peaked per-capita stock by material efficiency improvement will constrain the annual consumption, leading to a quick and sharp decline to 1.0 Gt yr^{-1} by 2030, after which annual consumption will fluctuate and eventually slide to 0.8 Gt yr^{-1} in 2060 (Low Stock scenarios, Figure 4c). Lifetime extension can bend the curve of annual cement consumption across all stock-related scenarios. If the lifetime is extended to 50 and 70 years, China's annual cement consumption will substantially decrease to 387-667 Mt yr^{-1} and 38-153 Mt yr^{-1} by 2060, respectively. During 2023-2060, these savings could cumulatively amount to 21.3 Gt in the Low Stock scenario, 24.6 Gt in the Medium Stock scenario, and 28.3 Gt in the High Stock scenario. If combined, a lower per-capita stock and an extended lifetime can bring substantial cement savings, totaling 58 Gt in this period.

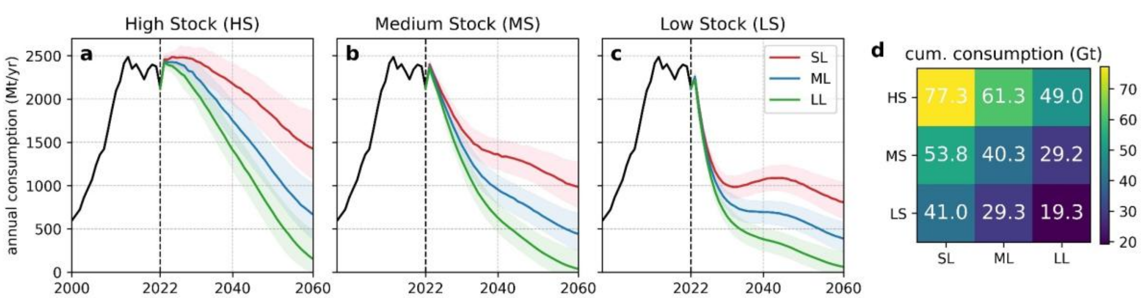


Figure 4 | China's annual cement consumption in the High Stock (a), Medium Stock (b), and Low Stock (c) scenarios in 2000-2060, and the cumulative cement consumption during 2023-2060 of all scenarios (d). Notes: The shaded area represents the simulated results using the high- and low-variant population projections. And SL, ML and LL represent Short Lifetime, Moderate Lifetime Extension, and Substantial Lifetime extension scenarios respectively.

3.3 Decarbonization pathways of China's cement cycle

Future cement consumption sets important boundary conditions for decarbonizing the cement cycle. As shown in Figure 5, trends of annual CO_2 emissions are largely consistent with annual cement consumption across all scenarios. When no supply-side measures are taken, annual CO_2 emissions will gradually decline to 817 Mt yr^{-1}, 564 Mt yr^{-1}, and 464 Mt yr^{-1} in 2060, under the High Stock, Medium Stock, and Low Stock scenarios. In parallel, China will see substantial CO_2 uptake by cement-based products, gradually decreasing from ~282 Mt CO_2 yr^{-1} in 2022 to ~194-329 Mt yr^{-1} in 2060. When CO_2 uptake is considered but no supply-side measures are taken, the CO_2 balance is projected to decline to 488 Mt yr^{-1} (High Stock and Short Lifetime), 326 Mt yr^{-1} (Medium Stock and Short Lifetime), and 269 Mt yr^{-1} (Low Stock and Short Lifetime) by 2060. If the potential of supply-side measures is fully seized, the CO_2 balance is projected to decrease to 228 Mt yr^{-1} (High Stock and Short Lifetime), 125 Mt yr^{-1} (Medium Stock and Short Lifetime), and 95 Mt yr^{-1} (Low Stock and Short Lifetime) by 2060. Among the five supply-side measures, CCS can bring substantial CO_2 savings, ranging from 80 Mt yr^{-1} to 91 Mt yr^{-1} by 2060. The second largest CO_2 saver is clinker substitution, which can deliver CO_2 reductions ranging from 41 to 72 Mt CO_2 yr^{-1} in 2060.

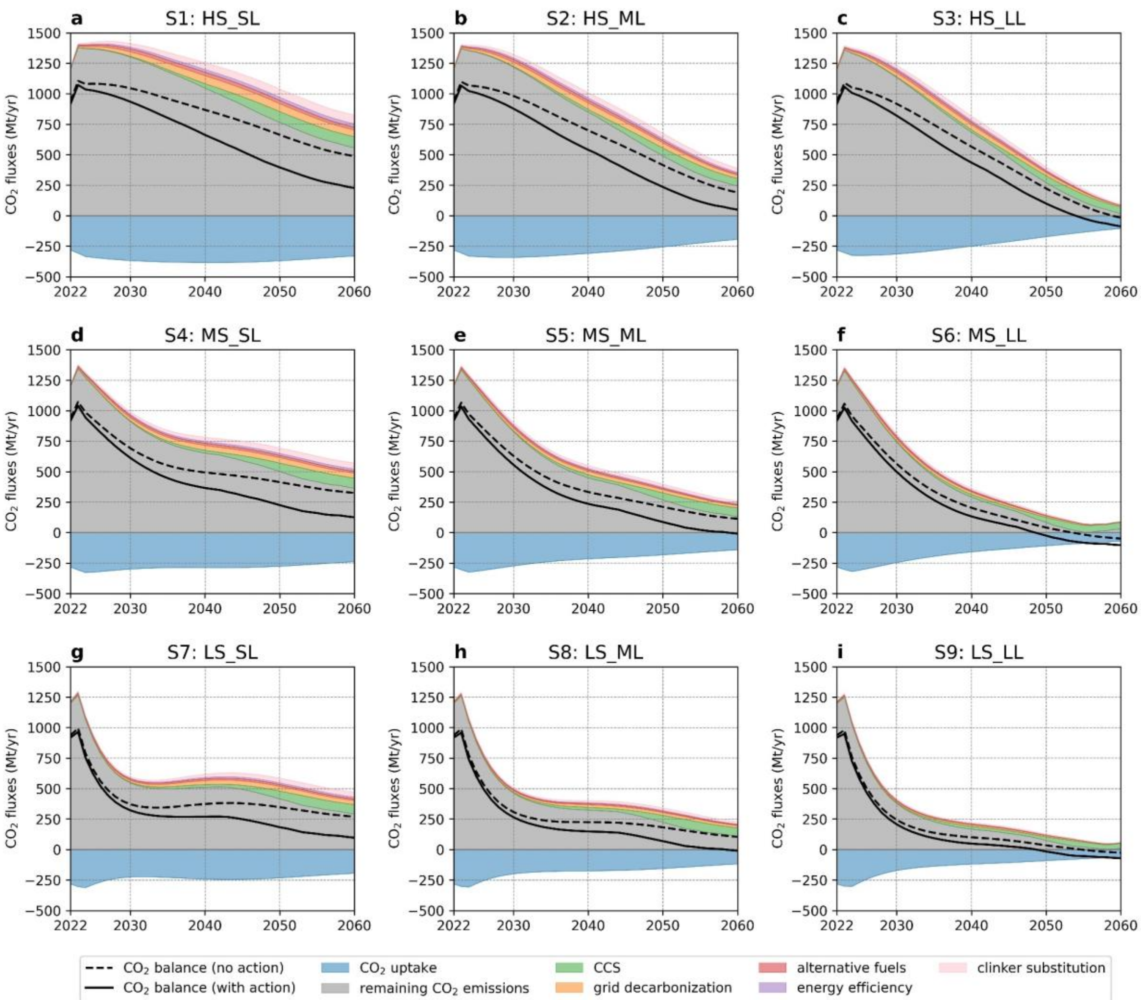


Figure 5 | Annual CO_2 fluxes associated with the cement cycle during 2022-2060.

If the lifetime is extended to 50 years, no-action CO_2 emissions will decline to 384 Mt yr^{-1} (High Stock and Moderate Lifetime Extension), 254 Mt yr^{-1} (Medium Stock and Moderate Lifetime Extension), and 222 Mt yr^{-1} (Low Stock and Moderate Lifetime Extension) by 2060. While lifetime extension can deliver emission cuts, China will see considerable reductions in CO_2 uptake, as less CO_2 uptake will occur due to reduced cement consumption. When CO_2 uptake is considered and supply-side measures are taken, the CO_2 balance is projected to decline to 47 Mt yr^{-1} (High Stock and Moderate Lifetime Extension), -7 Mt yr^{-1} (Medium Stock and Moderate Lifetime Extension), and -11 Mt yr^{-1}

(Low Stock and Moderate Lifetime Extension) by 2060, clearly indicating that these demand-side strategies could enable a net-zero cement cycle by 2060 in China. If the lifetime is further extended to 70 years, the CO_2 balance is projected to reach zero by 2050 in Medium Stock and Substantial Lifetime Extension and Low Stock and Substantial Lifetime Extension scenarios, leading to a negative-emission cement cycle after 2050.

As shown in Figure 6, lower per-capita stocks could cumulatively reduce total CO_2 emissions by 13.7 Gt and 21.1 Gt in 2023-2060. Moderate and substantial lifetime extension will cut total emissions by 6.8-9.3 Gt and 12.7-16.4 Gt, whereas these reductions shrink with stock levels. And combining these two demand-side strategies together could totally decrease the cumulative emissions by 33.8 Gt CO_2. Also, the contribution of CO_2 uptake varies by scenario. Take two extreme scenarios as examples: in the High Stock and Short Lifetime scenario, CO_2 uptake can offset ~31% of the no-action CO_2 emissions, while in the Low Stock and Substantial Lifetime Extension scenario, CO_2 uptake can offset ~45% of the CO_2 emissions without supply-side actions. The varying contributions of CO_2 uptake in decarbonizing the cement cycle indicate that CO_2 balance hinges on two boundary conditions: cement stock and lifetime. Cement stock reduction and lifetime extension can slow down the turnover of cement stocks and reduce the total societal throughout of cement, which in turn deliver emission cuts. However, due to the legacy effects of historically consumed and accumulated cement, CO_2 uptake is comparatively less affected by cement stock reduction and lifetime extension. We therefore highlight that designing decarbonization roadmaps for the cement cycle must consider these two critical boundary conditions.

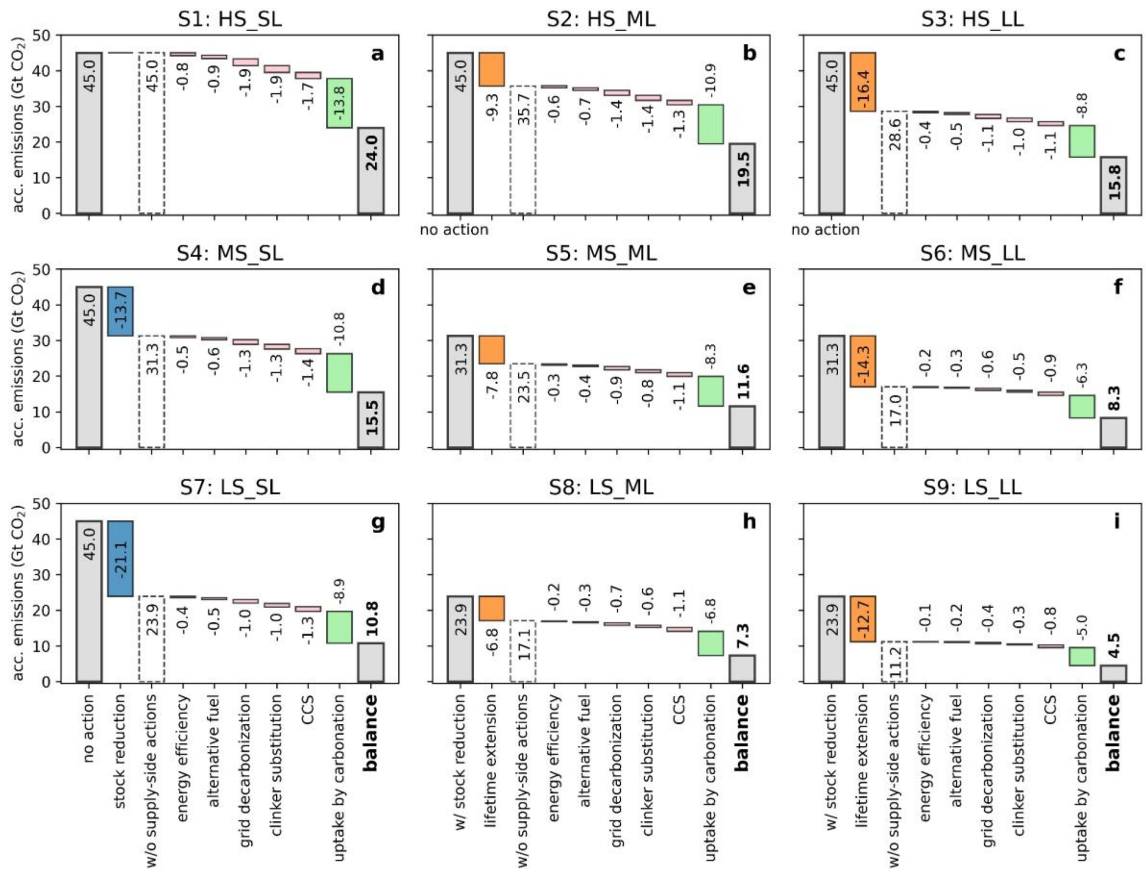


Figure 6 | Cumulative CO_2 emissions and uptake associated with China's cement cycle during 2023-2060. (a)-(i) cumulative CO_2 emissions reductions, uptake, and CO_2 balance of scenarios S1-S9.

4. Discussion

4.1 Robustness of stock saturation assumption

In our scenario analysis, we adopted the ‘stock saturation’ hypothesis, which has been supported by previous studies (Cao et al., 2020; Krausmann et al., 2020; Liu et al., 2012). According to this hypothesis, a convergence of per-capita material stocks is anticipated in the future, following an S-shaped system transition between socio-metabolic regimes (Wiedenhofer et al., 2021). Although empirical evidence of this saturation pattern exists in a few industrialized countries (Cao et al., 2017), we further conducted a forecast using an Autoregressive Integrated Moving Average (ARIMA) model (Fishman et al., 2016) to examine the robustness of the ‘stock saturation’ assumption in this study. The historical acceleration extrapolated constant positive values, suggesting an increasing net addition to stock (NAS) and consequently, a continued growth of the in-use stock (Figure 7). Additionally, Figure 7d reveals that points with zero NAS lie on the edge of the 95% confidence interval of the forecast, which could be interpreted as an indication of ‘stock saturation’ (Wiedenhofer et al., 2021). Presently, the signal of stock saturation is weak as these saturation points appear less likely to occur, but it is expected to strengthen if cement consumption continues to decline in the coming years. Despite the current weak signal, we have chosen to adopt the saturation hypothesis due to its alignment with the developmental trajectories observed in many industrialized countries, as well as China's emphasis on high-quality development today (Xinhua New Agency, 2023). The concept of material stocks saturation implies that China will achieve a ‘decoupling’ of economic development from resource use and transition towards a more service and consumption-based economy in the future, following a phase of rapid growth that has focused on essential infrastructure and capital stock formation (Bleischwitz et al., 2018).

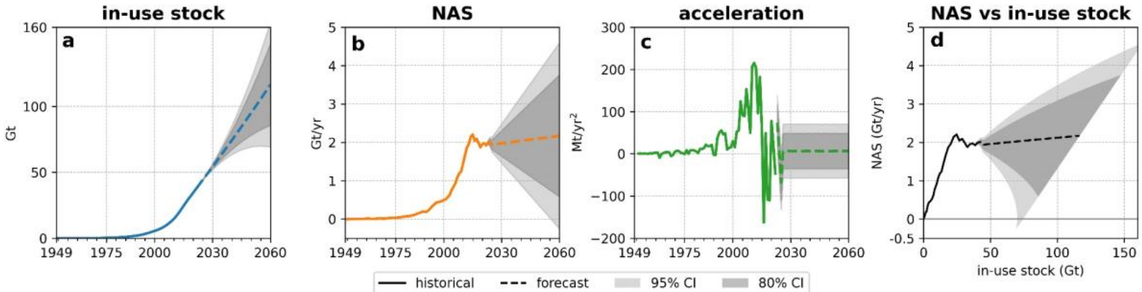


Figure 7 | ARIMA forecast on the level (a), NAS (b), and acceleration (c) based on the historical trend of China's cement stock in 1949-2060, as well as the trajectory of stock to NAS ratio (d). 95% CI and 80% CI refers to 95% and 80% confidence intervals of forecast respectively. NAS is the annual Net Addition to Stock, which is equivalent to inflows minus outflows in a certain year, whereas acceleration is the change in NAS between two consecutive years, or is the second order of difference of in-use stock (Fishman et al., 2016). The ARIMA model results are displayed in Supporting Information.

4.2 Implications of a lower per-capita stock

A lower per capita cement stock, achieved through more intensive use, has the potential to significantly reduce future cement demand and CO_2 emissions. However, it should be noted that this reduction primarily implies a lower per capita service level rather than a decrease in cement intensity of end-use products, which cannot be easily achieved through dematerialization as seen in the past upgrades of smartphones. This raises important social implications, as essential services would need to be provided with significantly lower levels of material stocks. Several measures can be taken in the building sectors to limit per-capita floor area, including smaller dwellings, more shared spaces, increased multi-family housing (Berrill et al., 2022; Creutzig et al., 2021; Hertwich et al., 2019), while a more compact city, characterized by higher urban density, can lead to reduced infrastructure requirements per individual by more efficient transportation networks and mixed land use (Muller et al., 2013). However, it remains uncertain whether these strategies can lead to the levels outlined in Low Energy Demand

(LED) scenarios (Fishman et al., 2021; Grubler et al., 2018). In the United States, there is potential to reduce per-capita residential floor space by 15% from 69.2 m^2/cap to 58.9 m^2/cap by 2060 through a combination of reducing the size of new single-family houses and increasing the proportion of multi-family houses (Berrill & Hertwich, 2021). In comparison, China appears to utilize floor space more efficiently, with its average residential area reaching a lower level of approximately 41 m^2/cap by 2020. Efficiency in the use of floor space also varies between urban and rural areas in China. Affordability issues in high-priced urban areas may limit per capita floor space, while rural areas have the potential for residents to economically build multi-story houses on their own parcels. Additionally, rural-to-urban migration leads to vacant houses for a significant portion of the year, resulting in wasted floor space.

A transition towards lower stock necessitates behavioral and lifestyle changes, along with considerations of architectural design preferences. The underlying challenge lies in achieving a reduced stock without compromising societal development and quality of life. In China, the current per capita cement stock surpasses that of many countries due to its historical reliance on cement-intensive building and infrastructure construction (Figure 8a). We have found a significant association between China's Human Development Index (HDI) and its per capita cement stock from 1990 to 2021 (Figure 8b). Extrapolating the trend reveals that while all stock scenarios would result in a higher HDI than the present, a lower per capita stock may constrain future HDI growth unless China successfully decouples its development from cement stock. Furthermore, well-being concerns should be carefully addressed, as it appears that limiting shelter services based on ‘sufficiency’ considerations may contribute little to overall well-being, whereas other demand-side solutions align with high levels of well-being (Creutzig et al., 2021).

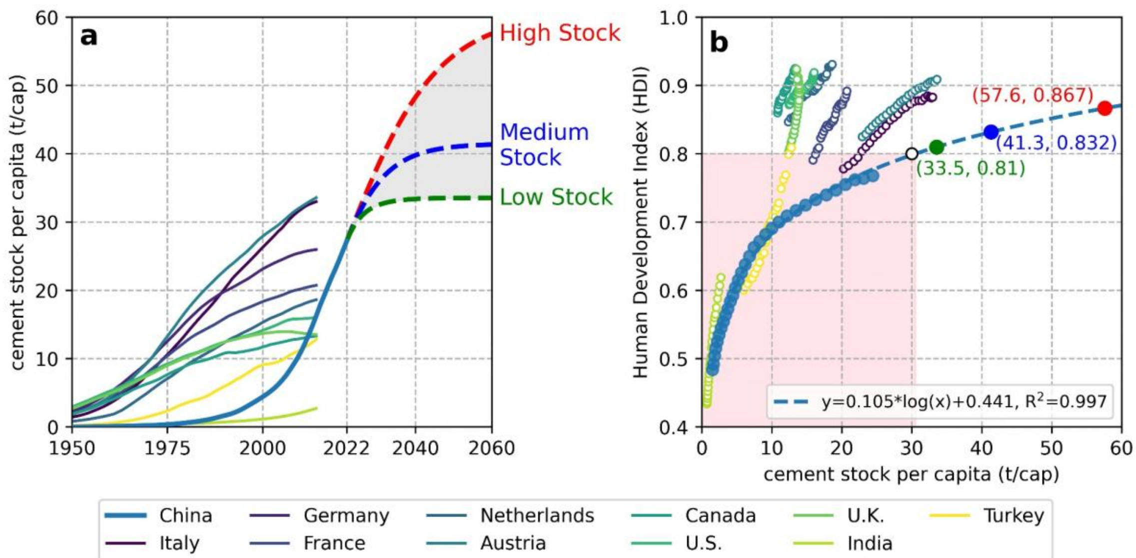


Figure 8 | Comparison of China’s future per-capita cement stock scenarios with other countries (a), and the relationship between per-capita stock and Human Development Index (HDI) (b). The colors of the circles in (b) are the same as those of the lines in (a). The data for high-income countries are obtained from Cao et al. (2017). HDI data are collected from [Home | Human Development Reports (undp.org)].

4.3 Opportunities and challenges of lifetime extension

Both field investigations and macro-level analyses consistently confirm a significantly shorter building lifespan in China compared to the designed service-life of 50 years (Cai et al., 2015; Cao et al., 2019; Liu et al., 2014). Empirical studies have shown that premature demolitions in China are primarily attributed to external factors rather than internal degradation of building materials (Liu et al., 2014; O'Connor, 2004). This phenomenon of “short-lived” buildings in China ultimately reflects a premature “obsolescence” resulting from rapid urbanization over the past two decades (Thomsen & van der Flier, 2011). The discrepancy between rising expectations driven by increasing land values and the actual function and quality of buildings has led to premature demolitions. However, it is worth noting that this pattern may differ in cases where buildings are situated on valueless land, where out-of-service buildings tend to persist without undergoing demolition (Thomsen & van der Flier, 2011).

There have been some improvements observed, as the average building lifespan in China has increased by approximately 0.5 years between 2000 and 2015 (Cao et al., 2019). This extension may be indirectly validated by structural changes in China's building stocks. Over the past two decades, new buildings have become taller and more concrete-intensive than before (Figure 9a-b), suggesting potentially longer service-life due to limitations imposed by China's property rights system. Specifically, high-rise and high-density residential districts, accommodating hundreds to thousands of households in a small piece of land, present daunting challenges for demolition and redevelopment when multiple property rights are involved. In mainland China, most building stocks are within 30 years old, with over 60% constructed during the period from 2000 to 2020. In contrast, the proportion of such buildings is relatively low in Hong Kong Special Administrative Region (SAR) (Figure 9d). Hong Kong experienced a construction boom between the 1960s and 1980s, similar to industrialized countries in the post-war era, and buildings from that period are still in service today (Figure 9c). Additionally, many high-rise buildings in Hong Kong have survived for decades (Figure 9e), potentially supporting the argument that high-rise buildings tend to have longer service-life due to the challenges associated with redevelopment. Therefore, the average building lifespan is expected to increase overall, but the extent of this increase may depend on various practical factors.

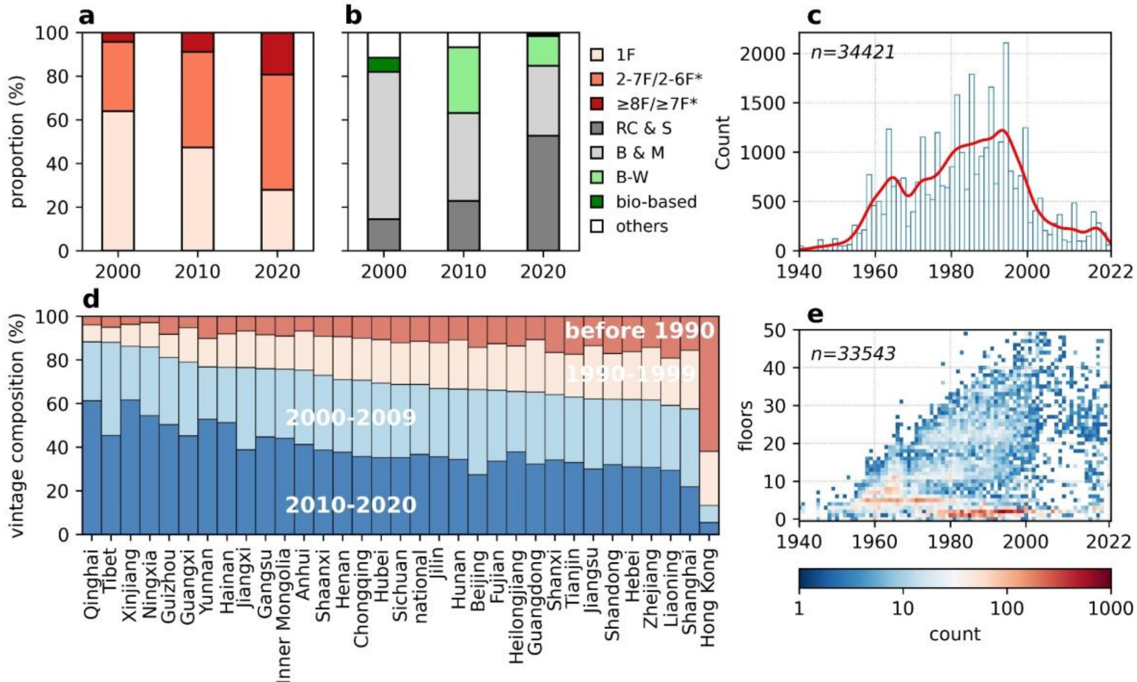


Figure 9 | Current composition of China's building stocks. (a) Residential building stock composition by building floor. (b) Residential building stock composition by building material. (c) Year built of private buildings in Hong Kong Special Administrative Region (SAR). (d) Vintage composition of residential buildings by province as well as HKSAR. (e) Building floors versus year built in HKSAR. Notes: In (a), "2-6F" and "≥7F" are for 2000 and 2010, whereas "2-7F" and "≥8F" are for 2000 and 2010. RC refers to reinforced concrete structure, S refers to steel structures, B and M refers to brick and masonry structures, B-W denotes brick-wood structures, and bio-based mainly refers to structures constructed by bio-based materials. Source: Data for China's provinces are retrieved from (the 7th National Population Census in 2020), whereas the data for Hong Kong were collected from *Database on Private Buildings in Hong Kong* of the Home Affairs Department of HKSAR (2023).

While it is expected that high-rise building stocks will survive for a longer time, addressing the obsolescence of remaining aged low-rise buildings poses challenges in terms of regular maintenance, proper retrofitting, and adaptive reuse, especially when redevelopment appears to be the more economically viable choice given the ongoing urbanization in China. In Hong Kong, the presence of aged buildings also raises social concerns, particularly related to safety issues. The reconstruction of these aged and dilapidated buildings, located on valuable land, is considered a more economically viable solution compared to renovation and reuse. Consequently, there is a growing emphasis on ensuring a successful redevelopment process, which may involve implementing measures such as compulsory sales of the land on which the aged buildings are situated. Furthermore, financial considerations also play a significant role. The inflow of more vulnerable residents into the aged buildings can severely hamper maintenance investments (Thomsen & van der Flier, 2011).

From a technical perspective, the extension of service-life may give rise to side-effects that need to be carefully considered in practice. Durable advanced cement-based materials typically have higher greenhouse gas (GHG) emissions during production compared to those with lower durability (Miller, 2020). When the target service-life is significantly shorter than the physical life of durable concrete mixtures, it becomes less desirable due to higher GHG emissions, leading to a waste in durability performance. Another aspect to consider is the decline in performance as cement stocks age. This decline may result in increased heating and cooling loads due to reduced thermal insulation performance, necessitating additional energy for operation (Grussing, 2014). This technological obsolescence may require future energy retrofitting. Moreover, for road infrastructure, changes in cement-based material properties due to aging, such as surface roughness, can lead to increased fuel consumption and emissions from vehicle use (Reger et al., 2014). These considerations also apply to young high-rise buildings currently in existence, as they will undergo aging and face obsolescence in the future.

4.4 Trade-off in CO_2 uptake

Notwithstanding that stock reduction and lifetime extension could unequivocally deliver emissions cut by decreasing cement production, both will inevitably shrink passive CO_2 sequestration by cement carbonation because of reduced in-use stock, inflows, and demolished outflows (Figure S18). Specifically, CO_2 uptake by in-use concrete structures will be almost halved during 2023-2060 in the Low Stock-Substantial Lifetime Extension scenario (1.3 Gt) compared with that in the High Stock-Short Lifetime scenario (2.3 Gt). Those materials embodied in new construction activities and cement production will decrease significantly in line with the downward trend of cement inflows, especially for rendering mortar, which will be fully carbonated and reabsorb substantial CO_2 within the first few years after entering use. Besides, avoided outflow by lifetime extension will significantly shrink CO_2 uptake by demolished concrete structures, as crushed concrete debris could dramatically increase the surface area exposed to air, leading to a further uptake within the short demolition stage. Only CO_2 uptake by masonry mortar will slightly increase (by ~0.6 Gt) by lifetime extension because it ensures enough time for CO_2 to penetrate through the thick surface rendering layer to reach the masonry mortar layer and induce its carbonation.

Additionally, a sensitivity analysis was conducted to investigate the impacts of parameters' ranges on the future CO_2 uptake (details seem Supporting Information 6). As shown in Figure 10 below, total CO_2 uptake during 2023-2060 will rise with an increase in the CaO contents in clinker and cement kiln dust (CKD) as well as the carbonation rates of concrete mixture. And when the proportion of CaO that could be converted to $CaCO_3$ within the fully carbonated cement and mortar (γ_1 and γ_2) decrease to their lower bounds, total uptake will significantly shrink by 17% and 22%. Further, decreases in corrector coefficients that reflect the impacts of surrounding CO_2 concentrations, coating and covers, and cement additives (β_1, β_2, and β_3) will reduce the total uptake approximately by -5%.

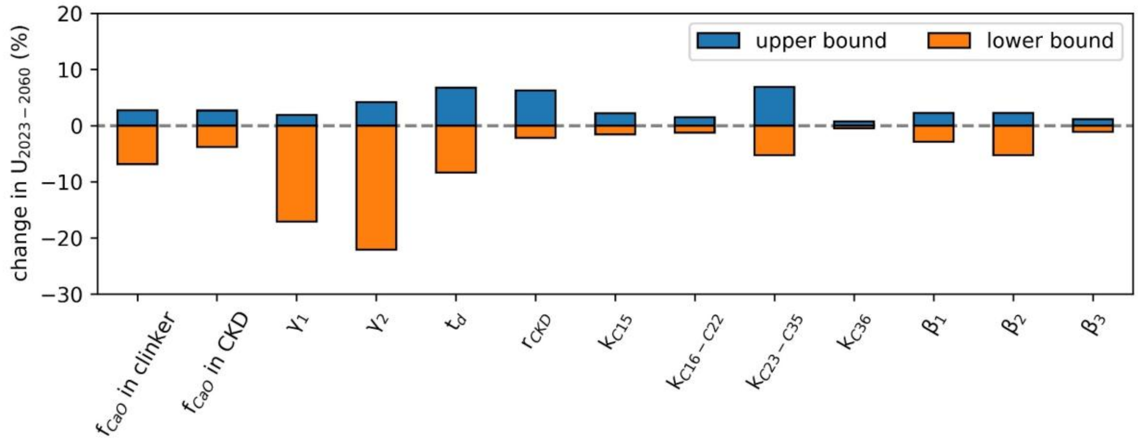


Figure 10 | Impacts of parameter changes on total CO_2 uptake by cement carbonation during 2023-2060.

4.5 Policy recommendations

Effective implementation of demand-side strategies holds significant potential for reducing future demand and greenhouse gas (GHG) emissions through the efficient utilization of material stocks. In this regard, governments play a crucial role in directing the attention towards demand-side measures. Encouraging a more compact layout of buildings, which can be specified in industry guidance or building codes, is a key approach to maximizing the efficient use of building floor area. The current shift in architectural design within the real estate market aligns with this objective, as new apartments are being designed to accommodate more rooms without a substantial increase in total floor area. This trend enables the accommodation of larger families while maintaining housing affordability. Additionally, it is pertinent to initiate a discourse on the concept of “sufficiency” in terms of per-capita building floor area (Cohen, 2020), particularly in light of climate ambitions.

Urban planners also play a vital role in extending the lifespan of buildings and mitigating premature demolitions. They should consider developing new or revising existing building zone requirements that facilitate mixed uses and repurposing of existing structures, thereby extending their longevity (Zhong et al., 2021). Where feasible, urban sprawl with a premise of minimizing adverse impacts on cropland and forest areas, could be prioritized over frequent urban sprawl, which often leads to premature demolition. It is essential to note that ensuring safety is a fundamental requirement for the prolonged utilization of buildings and infrastructure. To achieve this, mainland China should establish a robust legal and regulatory system that includes regular inspections of aged building structures and components. Valuable insights can be gained from Hong Kong’s implementation of the Mandatory Inspection on Building and Mandatory Inspection on Windows regulations.

Furthermore, the cement industry faces challenges in promoting efficient material use due to its profit model, which is inherently linked to the volume of materials sold (Watari et al., 2022). Thus, incentives and subsidies may be necessary to encourage the industry to adopt more sustainable practices. Moreover, the issue of over-capacity in China’s cement sector may be further exacerbated by a decline in cement demand. Underutilized capacity poses a significant risk to newly constructed and costly cement kilns, as annual cement demand is projected to remain below two billion tons based on the scenarios analysis in this study (Lu et al., 2022).

5. Conclusions

This study developed an integrated modeling framework of the material-energy-emission-uptake nexus in the cement cycle (IMAGINE Cement) to quantify the emission mitigation potentials from demand-side measures. And the message of this study is clear: net-zero emissions across China's cement cycle are achievable by 2060 through more intensive use and lifetime extension of in-use stock, in conjunction with a moderate portfolio of supply-side measures. Specifically, combined low demand and an extended lifetime of 70 years could save up to 58 Gt cement demand during 2023-2060, which in turn avoids 33.8 Gt CO_2 production emissions in this period. Also, trade-offs between emission fluxes should be carefully considered in the decarbonization pathways because more intensive use and lifetime extension will compromise the CO_2 uptake by cement carbonation. However, besides these substantial emissions reductions, it is necessary to pay attention on the implications, opportunities, and challenges of lower per-capita stocks and longer service-life of cement stocks, as these changes have a profound impact on social development and quality of life in the future.

Data availability

Part of data used for analysis in this study are available in a repository online in accordance with funder data retention policies (https://doi.org/10.5281/zenodo.8083355).

Acknowledgments

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