Incorporating carbon capture and storage in decarbonizing China's cement sector

Tongyuan Wu[a], S. Thomas Ng[b, *], Ji Chen[a]

[a] *Department of Civil Engineering, The University of Hong Kong, Hong Kong, China*
[b] *Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong, China*
* Corresponding author. Email address: thomasng@cityu.edu.hk.

Abstract

China's target of carbon neutrality by 2060 has prompted the hard-to-abate cement sector to seriously consider the deep deployment of carbon capture and storage (CCS) technologies. However, the extent to which CCS should be integrated into the decarbonization pathways of China's cement sector, within a nexus of supply- and demand-side mitigation efforts, is not yet well understood. This study integrates supply- and demand-side transition dynamics to systematically assess the role of CCS in these decarbonization pathways. The results indicate that annual cement demand can be reduced from 1.4 gigatons (Gt) per year to 0.5 Gt per year by 2060 through a series of material efficiency improvements on the demand side. Furthermore, total carbon dioxide emissions from the cement sector could decrease from 0.2-0.8 Gt CO_2 per year to approximately 0.1 Gt CO_2 per year by 2060, with large-scale CCS deployments and other supply-side measures. The required CCS capacity would decrease from 901 to 152 million tons of clinker production per year, depending on the combined efforts from both demand- and supply-side strategies. Additionally, total economic costs are projected to be 9.7-12.8 trillion Chinese yuan (CNY), with mitigation costs ranging from 156 to 228 CNY per ton of CO_2 avoided, which is higher than current carbon prices in China. These findings clearly demonstrate that reliance on CCS can significantly reduce carbon emissions if mitigation potentials are fully capitalized from both the demand- and supply-side efforts.

Highlights

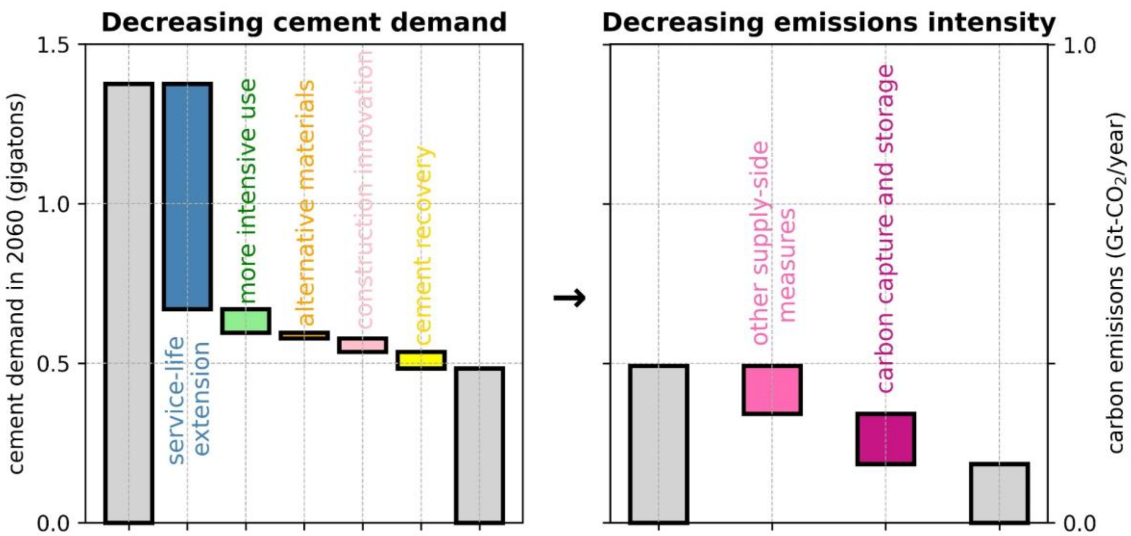
- China's future annual cement demand can be cut by ~0.9 gigatons by 2060, by demand-side efforts.
- CCS deployment can be compensated with other supply-side and demand-side emissions mitigations.
- China's future clinker production capacity is simulated at both national and provincial levels.

Keywords

cement sector; supply-side; demand-side; scenario analysis; net-zero; carbon capture and storage

Word Count: 7342

Graphical abstract



Nomenclature

Abbreviations	
ADEI	Aggregate direct emission intensity
BAU	Business-as-usual scenario
BECCS	Bioenergy with carbon capture and storage
CCS	Carbon capture and storage
DMFA	Dynamic material flow analysis
GHG	Greenhouse gas
IEA	International Energy Agency
LHV	Lower heating value or net calorific value of a type of fuel
LMDI	Logarithmic Mean Divisia Index decomposition
MEA	Mono-ethanol amine carbon capture technology
ME	Material efficiency scenario
NC	The set of new cement kilns
NSP	Cement kilns with new suspension preheater and pre-calciner in China
NZE	Net-zero emissions
OPC	Ordinary Portland cement
TEI	Thermal energy intensity of clinker production
Symbols	
ca	Daily clinker production capacity of a cement kiln
CCR	Clinker-to-cement mass ratio
$D(t)$	Demolition rate of in-use cement stock in year t
EF_{fuel}	CO_2 emission factors of a type of fuel
EI_{cement}	CO_2 emission intensity of cement production
$EI_{clinker}$	CO_2 emission intensity of clinker production
$EI_{process}$	CO_2 emission intensity of limestone decomposition during clinker production
$f(x)$	Probability density function of service lifetime of in-use cement stock
L	Expected operational lifetime of cement plants
mi_t	Cement intensity of products in service in year t
$NP_{i,t}$	The set of new cement plants of province i in year t
pop_t	Population in year $_t$
r_{bio}	CO_2 removal from atmosphere by BECCS
$RP_{i,t}$	The set of retired cement plants of province i in year t
S_t	In-use cement stock in year t
sl_t	Per-capita service level in year t
$TP_{i,t}$	The set of cement plants in operation of province i in year t
W_{ccs}	The Share of CCS deployment in total clinker production capacity

1. Introduction

China produced over 2 gigatons (Gt) of cement in 2020 and emitted around 1.3 Gt of carbon dioxide (CO_2) emissions [1], which makes the net-zero transition daunting. These emissions mainly come from the production of clinker, which is the precursor of cement [2]. Around 850 kilogram (kg) of CO_2 are released from per ton of conventional cement clinker production, with one-third from fuel combustion and two-thirds from limestone decomposition [3]. Fuel emissions can be mitigated by thermal energy efficiency improvements, fuel switching, and co-firing with alternative fuels especially biomass [4], [5], while the process emissions is hard to abate unless alternative clinker produced by de-carbonated materials is ready for pervasive deployment [6], [7]. Thus, carbon capture and storage (CCS) is recognized as an indispensable technology group to reduce the remaining emissions, also owing to the relatively high CO_2 concentration in flue gas from the cement plants [8]. Technology solutions, such as amine scrubbing, calcium looping, and oxyfuel combustion, have been developed and tested in a growing body of demonstration projects [3], [9], [10]. Nevertheless, whilst previous technology roadmaps have examined the mitigation potentials of these strategies to save energy [11], reduce emissions [12], [13], [14], green transition [15], [16], and even achieve net-zero transition [17], [18], [19], to what extent CCS should contribute within a supply-demand nexus is yet to be systematically investigated.

The first issue is the lack of a robust cement demand projection. Production emissions from the material industry depend on the production volume and emission intensity (i.e., the emissions released by unit production) [20]. Thus, the future demand will also play a key role in emission mitigation, and that is why material efficiency matters on the demand-side [21]. Previous roadmaps have relied on socio-economic indicators to predict the future cement demand, such as gross domestic product (GDP) [18], urbanization rate [19], [22], and fixed asset investment [23]. However, there are considerable variations between these projections, with annual demand ranging from as high as 2.5 Gt [24] or as low as 0.6 Gt [25] by 2050, leading to significantly different efforts required to curb production emissions. For instance, the required cement kiln with CCS to achieve net-zero emissions in Japan can be reduced from 70% to 30% if half of maximum potential of demand-side strategies is utilized [26]. Furthermore, these projections often obscure the role of material stocks embodied in our society, rarely considering impacts of material stock saturation [27], [28] and material efficiency improvements [29]. Saturation effect refers to that cement, steel, and other materials consumption may not always expand with economic growth and will saturate at a certain level in future [30]. Material efficiency measures will substantially reduce the building-material-related greenhouse gas (GHG) emissions by mid-century [31], [32], [33]. For instance, extending the lifetime of our built environment by 50% could reduce 14% of cement demand and related production emissions in the United States [34], but these benefits will not be captured in GDP-based projections. By mapping the cement flows in the UK, about half of the emissions could be cut by reducing the cement demand through substituting cement for calcined clay and limestone, reducing the cement content of concrete, post-tensioning floor slabs, using more precast building elements, reducing construction waste, and reducing the overdesign in construction [29]. Also, future stock patterns will dominate the emissions trends of cement [35] and concrete cycle [26]. Likewise, substantial steel [20] and aluminum [27] demand can be avoided by more intensive use, recycling, as well as other material efficiency measures. Therefore, an explicit demand scenario will help policymakers and investors to better prepare for CCS development and avoid the risks of stranded assets in future.

Another limitation is the obscured role of the cement plant turnover process, which will hinder the large-scale deployment of CCS. Plant-level information have been integrated to reveal emission dynamics of carbon dioxide [36], [37], mercury [38], [39], ammonia [40], and other air pollutants [41]. Whilst previous roadmaps have outlined the required CCS capacity and production towards the mid-century to achieve target emissions reduction [15], [17], [19], the extent to which and where the available capacity can be utilized is seldom investigated, resulting in additional costs and potential risks of project failure [42]. For instance, Hill et al. (2016) developed a bottom-up model to optimize CCS application in cement plant in the UK and revealed that failing to synchronize plants shutdown for CCS deployment would increase installation cost by approximately 10% [43]. Although a recent study has planned for low-carbon transition for China’s cement sector at plant-level [44], the impacts of available production capacity under the varying future demand is not considered.

In response, this study develop a framework to integrate both supply- and demand-side dynamics to systematically assess the role of CCS in the decarbonization roadmaps for China’s cement sector towards carbon neutrality by 2060. Specifically, this framework consists of demand projection by dynamic material flow analysis (DMFA), carbon emissions accounting, plant turnover simulation, and economic cost analysis. Four scenarios are developed to quantify the required deployments and mitigation of CCS among the supply- and demand-side efforts. The novelty of this work lies in the following innovations.

- China's future cement demand is explicitly projected in relation to cumulative cement consumption embodied in our society, while exploring the mitigation potentials of material efficiency strategies.
- On the supply-side, the turnover process of production capacity is simulated and integrated into CCS deployments for China's cement sector.
- Future changes in cement production, capacity, and CCS deployments are simulated at the provincial level for the first time.

2. Related work

2.1 Cement production process

Portland cement is the most common type of cement, of which is constituted by 90-95% clinker, 2-3% gypsum and minor additives [2]. As the active part of Portland cement, clinker is produced in a carbon-intensive process, because of high temperature heating traditionally fueled by coal or oil and the direct release of carbon dioxide from limestone decomposition. Figure 1 shows the main processes of the state-of-the-art cement production method with pre-heaters and pre-calciners. Specially, raw materials, composed of limestone, clay and small amounts of 'corrective' materials (e.g., iron ore, bauxite, and sand), are firstly crushed, mixed, and milled into a raw meal, which will be pre-heated to ~850°C by exhaust heat from the kiln in the cyclone pre-heaters, by which calcium carbonate is dissociated into calcium oxide and carbon dioxide. Then, it will be calcined in the rotary kiln at ~1450°C, where reactions between calcium oxide and other elements produce calcium silicates and aluminates. After heating from the kiln, the melted materials should be cooled rapidly to from an assemblage of the silicates alite and belite, tricalcium aluminate and tetra-calcium aluminoferrite, known as clinker [2], which will be further grounded with gypsum and other minor additives to produce cement products.

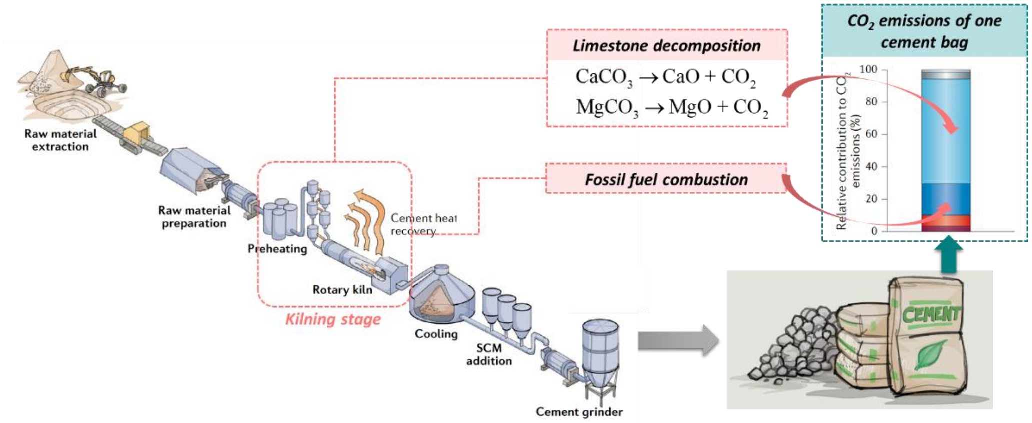


Figure 1 | Cement production processes (adapted from [2]).

2.2 Emissions mitigation options

There are four main types of emissions mitigation options for cement sector: (1) improving energy efficiency (including thermal efficiency and electrical efficiency), (2) switching fossil fuels to low-carbon fuels, (3) clinker substitution to reduce clinker-to-cement ratio, and (4) carbon capture and storage (CCS). These measures will not significantly change current product systems, such as ordinary Portland cement (OPC), whereas low-carbon alternative cement clinker are still in early development stage and may require modifications on current materials standards [6], [7]. In recent years, the advanced dry process kilns with six stages of cyclones pre-heaters can reduce thermal demand to as low as 2.8 GJ/t-clinker [45]. Fuel switching usually refers to the switch from coal to oil or gas, but increasingly biomass is coming to be the focus for a net-zero future [4]. CO_2 emission factors of fuel oil and natural gas can be ~19% and ~ 41% lower than that of bituminous coal, due to their higher energy content and lower carbon content. As for biomass fuels, their carbon emissions can be regarded as zero emissions when accounting, and even can be seen as negative emissions if combined with CCS. Clinker substitution aims to replace part of the clinker in cement using supplementary cementitious materials (SCMs), such as coal fly ash and granulated blast furnace slag. Theoretically, there has a significant mitigation potential in CCR. For instance, a combination of calcined clay with limestone allows the substitution levels of clinker contents up to 50%, that implies CCR can be reduced to 50%, with similar mechanical performance and somehow improved durability [46]. Figure 2 displays the energy efficiency, fuel structure, and clinker-to-cement ratio of global cement sector during 1990-2021. With the new dry process kilns with pre-heater and pre-calciner to extensively replace outdate shaft and wet kilns, overall thermal energy demand has decreased to around 3.46 GJ/t-clinker (Figure 2). However, the global proportion of biomass fuels was only about 7% in 2021, whereas fossil fuels still accounted for over 80% (Figure 2). Besides, the global weighted average clinker-to-cement ratio (CCR) has declined to 0.77 by 2021 and seems to stagnate in recent years.

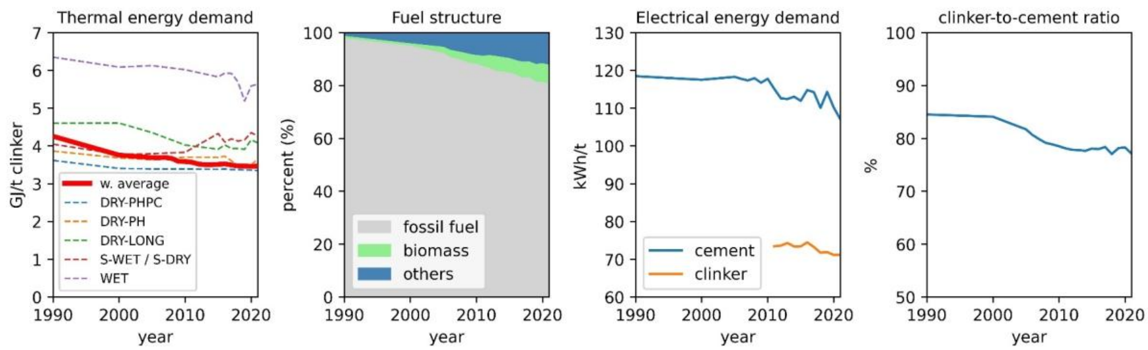


Figure 2 | Energy efficiency, fuel structure, and clinker-to-cement ratio of global cement sector. (Data source: "*Getting the Numbers Right (GNR)*" database 2.0 [47]. Notes: w. average represents the weighted global average. DRY-PHPC refers to dry process cement kilns with pre-heaters and pre-calciner. DRY-PH refers to dry process cement kilns with pre-heaters. DRY-LONG refers to long dry kiln without preheaters. S-WET and S-DRY denote semi-wet and semi-dry process, respectively. WET represents wet or shaft kilns.)

The stagnant efficiency improvement means the cement sector urgently needs to deploy CCS. Thus, a few types of cement CCS have been proposed, simulated, and tested in small-scale pilot projects, e.g., amine scrubbing, oxyfuel [3], calcium looping [48], and direct separation [49]. Voldsund et al. (2019) compared technological performance of five cement CCS technologies, based on process simulations [3]. While targeting 90% capture rate for flue gas, specific primary energy consumption for CO_2 avoided varies from 1.63 MJ/kg CO_2-avoided for the oxyfuel-based capture process to 7.08 MJ/kg CO_2-avoided for the amine scrubbing. Besides, cost-effectiveness is especially important for cement CCS retrofit and new installation. Gardarsdottir et al. (2019) revealed an increase of 49-92% in cost of clinker production equipped with five types of CCS technologies, compared to the cost of clinker without carbon capture. Specifically, the lowest cost is 42 €/t CO_2 avoided of the oxyfuel-based capture process, while the highest cost is 84 €/t CO_2 avoided of the membrane-based assisted liquefaction capture process [9].

2.3 Decarbonization roadmaps

The prerequisite is the determined future production on a year-by-year basis equivalent to the projected cement demand. Then, development rates of low-carbon measures are projected based on state-of-the-art knowledge (e.g., technology maturity and resource availability) to explore future emissions mitigation potentials. For instance, Cao et al. (2020) developed a scenario of five major supply-side mitigation measures for global cement sector [35]. Among these measures, CCS can cumulatively reduce 56.7-94.2 Gt CO_2 emissions during 2015-2100, under the various cement stock and future demand. Cheng et al. (2023)'s projections and scenarios showed that carbon emissions of future cement production in developing countries except China will grow from 0.7 Gt in 2018 to 1.4-3.8 Gt in 2050, which can be cut by ~65% through developing a combination of low-carbon measures [50]. Cavalett et al. (2024) synthesized future deployment rate of a series of mitigation measures from literature and institution reports to develop a 'representative' decarbonization pathway for European cement sector towards mid-century [51]. Notably, they found that only about 50% annual emissions (~64 Mt CO_2 per year) can be mitigated relative to today's emissions, especially with a penetration of only 25% for CCS by 2050.

When specific goals or emissions budgets are determined firstly, annual emissions mitigation and the required deployment rates of mitigation measures can be determined accordingly under certain objectives, such as lowest overall cost. A few global Integrated Assessment Models, e.g., IMAGE and DNE 21+, modeled cement sector separately to optimize the deployment rates of four major measures discussed in the last sub-section [52]. Also, Kermeli et al. (2019) improved the capability of IMAGE model to model cement sector, by considering plant retrofitting as a measure and availability constraints of SCMs [52]. Furthermore, some cement sector-specific studies, sub-divided these major measures into a detailed technology list and optimized their deployment rates in a 'bottom-up' manner, while minimizing total cost, such as [12], [15], [17]. For instance, Dinga & Wen (2022) developed a bottom-up technology transition model for China's cement industry to assess the feasibility of achieving carbon neutrality by 2060, while considering co-benefits of CO_2 mitigation and uncertainty [17]. After deducting monetized co-benefits, a net cumulative cost of 279-345 billion Chinese yuan (CNY) is still required to make a net-zero cement sector possible by 2060.

Furthermore, a more spatial-explicit analysis, such as plant-level analysis, may provide a more concrete data basis to improve feasibility of decarbonization pathways. Hills et al. (2016) developed a bottom-up model for the UK's cement plants, to explore the feasibility of synchronizing CCS installation with shutdowns for major refurbishments at plant level [43]. Besides, regional disparity should be carefully considered in pathway development. Wang et al. (2024) developed an optimal matching between those cement plants prioritized for CCS deployment and suitable CO_2 storage sites in China [53]. However, their spatial layout of cement CCS was only based on current emission inventory, without considering future change in cement demand and production layout across China.

3. Methods

This study develop an integrated framework, which consists of four modules, to systematically assess the role of CCS in the decarbonization pathways of China's cement sector (Figure 3). Specifically, this study starts by forecasting the future cement and clinker production, then simulate the turnover process of the existing cement plants, which implies a low-carbon transition by replacing the retired ones with the new and efficient plants or through a significant retrofit. Then, sector-wide emission accounting is conducted to obtain the required CCS deployment, under the constraint of the net-zero emission cap. Finally, total and unit economic cost of clinker production and emissions mitigation are analyzed for scenarios, especially for CCS deployments. A 2×2 scenario matrix is developed for comprehensive analysis of the mitigation efforts from both the supply- and demand-side. Parameters of each scenario are inputted to the modules and analysis are then conducted. The following sub-sections will introduce the modules one by one in detail, as well as the scenario settings for both the supply- and demand-side.

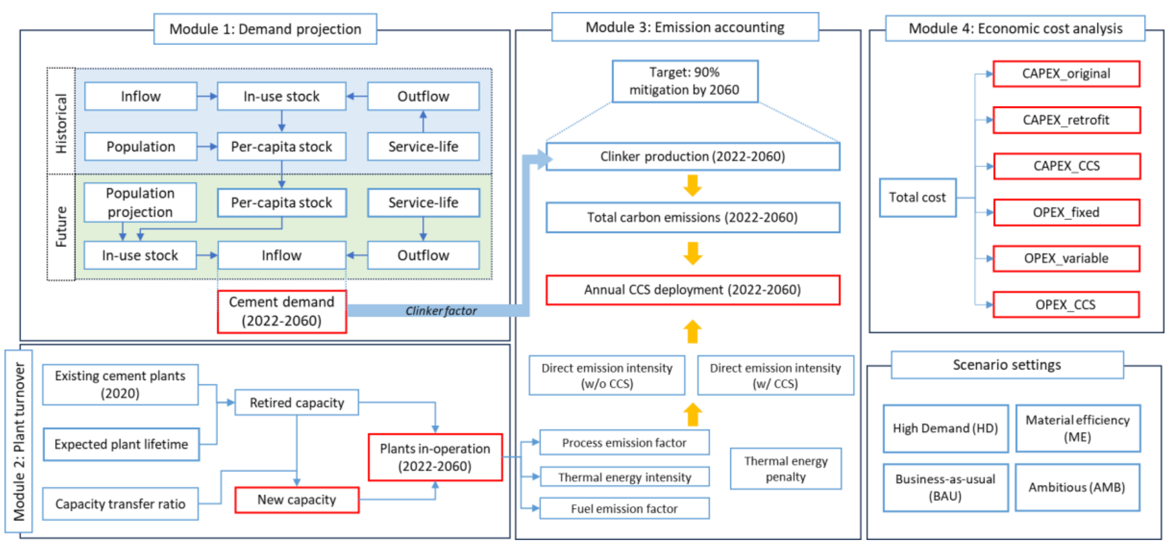


Figure 3 | Research framework.

3.1 Module 1: Demand projection

In this module, this study estimate the historical in-use stock and project future cement demand by inflow-driven and stock-driven approach respectively, based on the framework of dynamic material flow analysis (DMFA) [54], [55]. Annual cement consumption (i.e., inflow) will accumulate within the geographical boundary, while a fraction of them will outflow the stock when reaching the end of their service life, thus stock, inflow, or outflow can be deduced when the other two are known variables, according to the law of mass conservation [56]. Here this study adopts an inflow-driven approach ([28], [57]) to estimate the historical in-use cement stock (1949-2022), based on the annual cement consumption and cohort-based service-life [58]. The annual cement consumption equals to the annual production minus the export and plus the import [28]. As for the future, this study adopts a stock-driven approach to predict the cement consumption towards 2050 [35]. This implies that the total in-use cement stock will first be determined by the population projections and a changing per-capita stock which will saturate at a certain level by 2050. Then annual outflow will be calculated based on the assumed service-life in the scenarios, and the annual inflow (i.e., cement demand) could be derived according to the mass balance principle. Basic equations for calculation are shown in Eq. (1)-(5).

$$S_t = \sum_t \left(I_t - O_t\right), \ (t \le 2022) \tag{1}$$

$$S_t = pop_t \cdot s_t, \ (t > 2022) \tag{2}$$

$$I_t = S_t - S_{t-1} + O_t \ (t > 2022) \tag{3}$$

$$O_t = \sum_{t_1} S_{t-1}^{t_1} \cdot D\left(t - t_1\right) \tag{4}$$

$$D\left(T\right) = \int_{T-1}^{T} f(x)dx \tag{5}$$

where I_t, O_t, and S_t, represent inflow, outflow and in-use stock of cement in year t, respectively. s_t refers to per-capita in-use stock in year t, and pop_t represents population. The superscript t_1 denotes the year the consumption inflows into the stock, $D\left(T\right)$ represents the demolition rate function, which is the integral of a two parameter log-normal service lifetime distribution $f(x)$ over a period of a year [59]. Furthermore, future national cement and clinker demand will be allocated to each province, based on projected population distribution (Eq. (6)). This implies an assumption that all the provinces have a consistent per-capita consumption towards the mid-century.

$$I_{i,t} = I_t \cdot pop_{i,t} \,/ \sum_i pop_{i,t} \tag{6}$$

where $I_{i,t}$ and $P_{i,t}$ denote cement consumption and population of province i in year t.

3.2 Module 2: Plant turnover simulation

This study develops this module to simulate the turnover process of China's cement plants, based on the plant lists in the China Cement Industry Dataset (CCID) [60]. This dataset collected publicly available information about cement plants in operation and compile a list of clinker production lines across China. The list mainly states the company, address, online year, production capacity, and kiln length and diameter of production lines. Geographic information (e.g., latitudes and longitudes) is also obtained by geocoding the exact address using Baidu Maps' API. Figure 4 shows the geographical distribution of cement kilns in China, and the age and size structure of all the kilns.

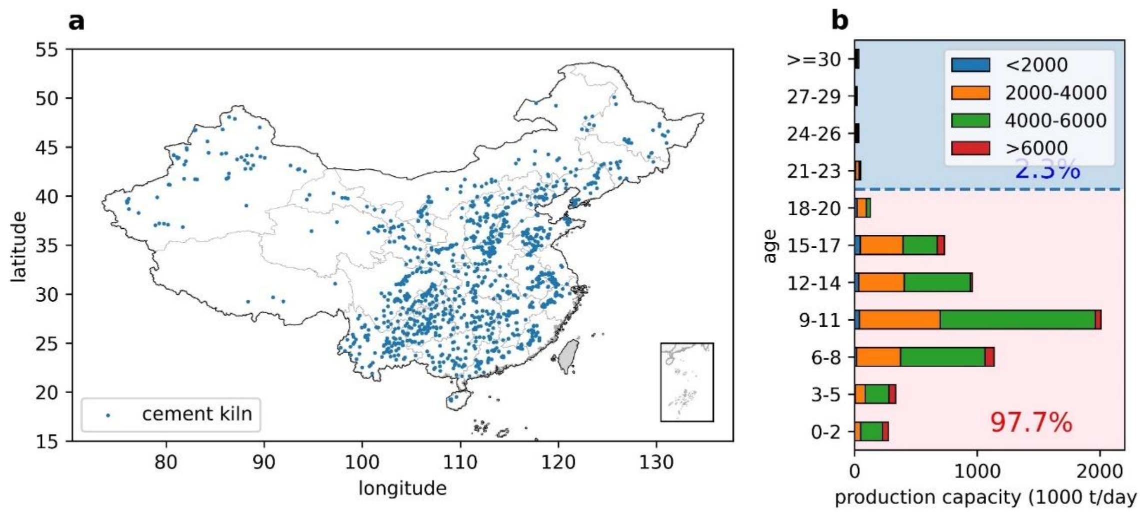


Figure 4 | Existing cement kilns in China (2020). Geographical location of cement kilns (a), and the total production capacity by age and size (b).

In this module, those plants that reach the end of their expected lifetime will retire and transfer their capacity to the new plants. Thus, the year of starting operation and daily clinker production capacity are the key indicators, both of which are retrieved from the CCID. This study assumes that those units with the age longer than the expected lifetime in 2022 will continue in operation but shall retire over the next five years to avoid abrupt changes in the cement kiln stock [61]. The following Equations (7)-(9) delineates the turnover process of cement plants in each province.

$$RP_{i,t} = \left\{ ca^{t_1} \in TP_{t-1} \mid t_1 - t > L \right\} \tag{7}$$

$$NP_{i,t} = \left\{ ca_1^t,\ ca_2^t,\ \ldots,\ ca_n^t \right\} \tag{8}$$

$$TP_{i,t} = \left(TP_{i,t-1} \setminus RP_{i,t}\right) \cup NP_{i,t} \tag{9}$$

Where $TP_{i,t}$, $RP_{i,t}$, and $NP_{i,t}$ represent the set of total cement plants in operation, retired plants, and new plants of province i in year t, respectively. ca^{t_1} denotes the annual clinker production capacity of a kiln, and again superscript t_1 represents the year when it started operation. L represents the expected lifetime of the cement plants, which will vary with scenario settings. The number of new kilns m is determined by the $gap_{i,t}$ between the demand and total available production within and around the province i in year t, and the expected capacity ca_e of new kilns, which is set to two million tons of clinker per year, equivalent to six thousand tons of clinker per day.

$$m_{i,t} = gap_{i,t} / ca_e \tag{10}$$

$$gap_{i,t} = I_{i,t} - \left(P_{i,t} + \sum_j import_{i,t}^j - \sum_j export_{i,t}^j\right) \tag{11}$$

Where $P_{i,t}$ denotes clinker production of province i in year t. $import_{i,t}^j$ represents clinker import from province j to province i in year t, and $export_{i,t}^j$ represents clinker import from province i to province j in year t. In this study, a 31×31 production matrix is used to simulate future provincial production and inter-province trade flows. This matrix will be iterated multiple times, and each iteration will expand the scope for each province to collect adjacent demand. The spatial relationship between province is determined by an adjacency matrix, in which the distance between adjacent provinces is one. In the first iteration, each province on the diagonal will produce clinker to meet its own demand. After that some provinces will have excess capacity or insufficient supply, and they will export or import from adjacent provinces (or accessible provinces) in the next iterations. Thus, $export_{i,t}^j$ and $import_{i,t}^j$ can be determined accordingly after all the iterations of production matrix.

3.3 Module 3: Carbon emissions accounting

In general, the material sector emissions (E) predominantly depend on the mass produced (P) and the emissions released per unit of the material produced, i.e., the emission intensity (EI). Figure 5 shows the system boundary developed in this module to account for carbon emissions from both cement and clinker production and CCS deployments. Specifically, process emissions from limestone decomposition, fuel emissions, and electricity emissions are considered for conventional cement plants without CCS [1], [33], whereas energy penalty for capture facilities and emissions removal by biomass are further included, when CCS is deployed [3].

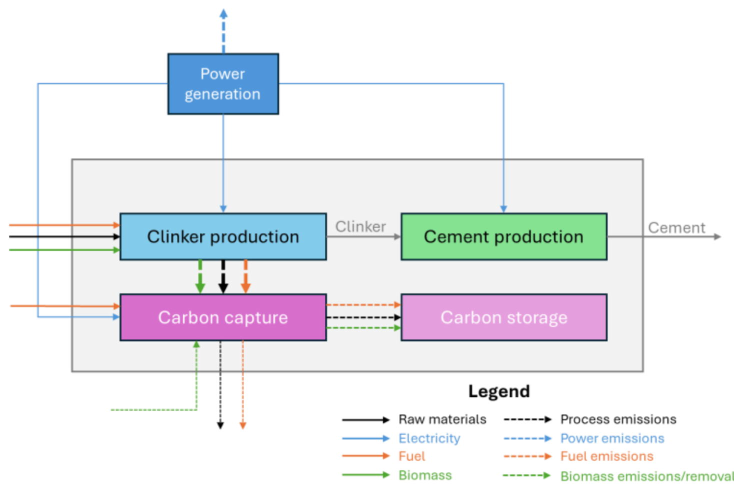


Figure 5 | System boundary of carbon emissions accounting for cement sector.

Equations (12) and (13) are the calculations on direct emission intensity of clinker production without or with CCS respectively.

$$EI_{\text{clinker, w/o CCS}} = EI_{\text{process}} + TEI_{\text{clinker}} \cdot \sum_i w_i \cdot EF_{\text{fuel}}^i \tag{12}$$

Where TEI_{clinker} denotes the thermal energy intensity for clinker production (GJ/t-clinker), EF_{fuel}^i represents the CO_2 emission factor of a specific type i of fuel (kg-CO_2/GJ), and w_i denotes the proportion of a type i of fuel on a thermal basis.

$$EI_{\text{clinker, w/CCS}} = \left(EI_{\text{process}} + TEI_{\text{clinker}} \cdot \sum_i w_i \cdot EF_{\text{fuel}}^i\right) \cdot \left(100\% - c_j\right) + TEI_{\text{CCS}}^j \cdot EF_{\text{fuel}}^i - r_{\text{bio}} \tag{13}$$

Where c_j denotes the capture rate on flue gas of the CCS technology j (%), TEI_{CCS}^j refers to the thermal energy penalty required for carbon capture (GJ/t-CO_2 captured), and r_{bio} represents the CO_2 removal from atmosphere by biomass (kg CO_2/t-clinker) when both the co-firing with biomass and CCS are applied. The fuel of 100% biomass is considered as carbon neutral and set to zero emissions in this study, whereas it is seen as negative emissions when CCS applied.

Therefore, an aggregate emission intensity (EI) can be defined to reflect the sector-wide emission mitigation. It can be calculated based on the emission intensity and share of adopting CCS as follows.

$$EI_{\mathrm{clinker}} = w_{CCS} \cdot EI_{\mathrm{clinker,\ w/CCS}} + \left(1 - w_{CCS}\right) \cdot EI_{\mathrm{clinker,\ w/o\ CCS}} \tag{14}$$

where w_{CCS} represents the share of CCS deployment in the cement sector. The clinker-to-cement mass ratio (CCR), is used to determine the future clinker production per year (Eq. (15)). Then, the total direct CO_2 emissions from clinker production is derived from the production scale and aggregate emission intensity.

$$P_{\mathrm{clinker}} = P_{\mathrm{cement}} \cdot CCR \tag{15}$$

$$E_{\mathrm{clinker}} = P_{\mathrm{clinker}} \cdot EI_{\mathrm{clinker}} \tag{16}$$

Eq. (12)-(16) could be adopted to calculate the total direct CO_2 emissions from clinker production (E_{clinker}). The target emission intensity is firstly derived from the projected clinker production and the emission cap of net-zero scenarios (Eq. (17)). Then, the required CCS deployment share ($w_{\mathrm{CCS}}^{\mathrm{cap}}$) can be calculated reversely according to Eq. (14).

$$EI_{\mathrm{clinker}}^{\mathrm{cap}} = E_{\mathrm{clinker}}^{\mathrm{cap}} \Big/ P_{\mathrm{clinker}} \tag{17}$$

$$w_{\mathrm{CCS}}^{\mathrm{cap}} = \left(EI_{\mathrm{clinker,\ w/o\ CCS}} - EI_{\mathrm{clinker}}^{\mathrm{cap}}\right) \Big/ \left(EI_{\mathrm{clinker,\ w/o\ CCS}} - EI_{\mathrm{clinker,\ w/CCS}}\right) \tag{18}$$

Besides, thermal energy intensity (TEI) for clinker production, fuel type, and process emission factors are also determined in this module. The process CO_2 emission factor is calculated based on the content of calcium oxide and magnesium oxide in clinker. Fuel type is determined based on the scenario narratives. As for TEI, this study firstly fits it with the clinker production capacity by a linear regression model with a logarithmic x on our plant samples [62]. Then, this study determines the TEI for the existing cement plants by this regression model, and obtain a sectoral aggregate TEI (3.297 GJ/t-clinker) which is close to 3.250 GJ/t-clinker from the GNR Emission

Report 2018 [63], though the model only captures 52% of the variations (Figure 6a). Notably, TEI decreases with an increase in production capacity, as large plants always imply a system-wide improvement and an integration of efficient technologies. In recent years, a few kiln systems can reduce TEI to as low as ~2.8 GJ/t-clinker in China [45], and this level will serve as the best available technology (BAT) benchmark in the supply-side scenario analysis.

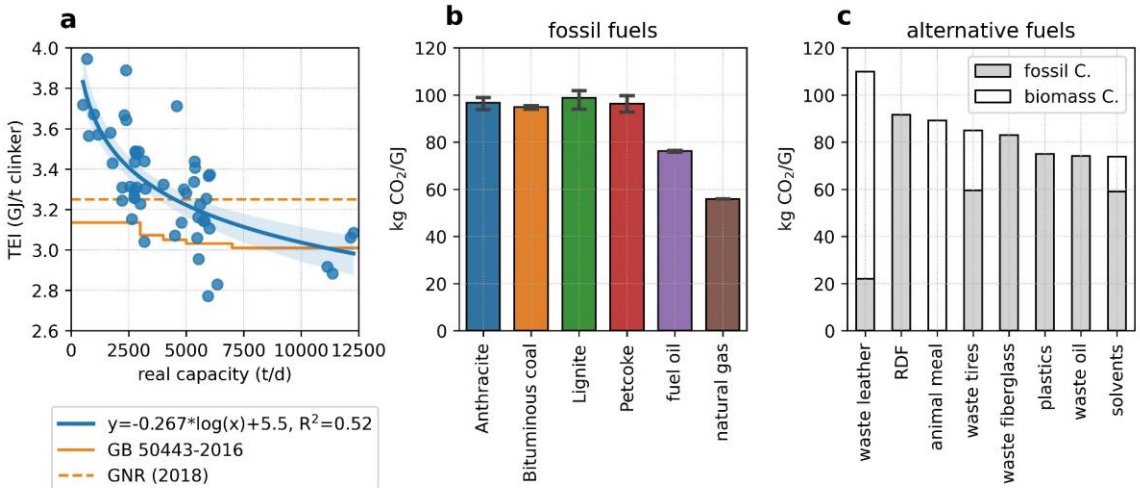


Figure 6 | Thermal energy intensity for clinker production (a), and CO_2 emission factors for fossil fuels (b) and alternative fuels (c). (Notes: This study adopts a regression model [62] to fit the relationship between the TEI and real capacity of our plant samples. Here, the real capacity refers to the daily production during the thermal testing for a cement plant. GNR represents the Getting the Numbers Right platform. GB 50443-2016 represents the current National standard for Energy Conservation Design in Cement Plants [64].)

3.4 Module 4: Economic cost analysis

In this study, the total costs of each scenario and emissions mitigations are calculated from bottom-up. For each cement plant, its total cost can be calculated from capital costs and operating costs as follows.

$$C_t = C_{CAPEX,t} + C_{OPEX,t} \tag{19}$$

$$C_{CAPEX,t} = C_{CAPEX,t}^{ORI} + C_{CAPEX,t}^{RET} + C_{CAPEX,t}^{CCS} \tag{20}$$

$$C_{OPEX,t} = C_{OPEX,t}^{fix} + C_{OPEX,t}^{fix\_CCS} + C_{OPEX,t}^{var} + C_{OPEX,t}^{var\_CCS} \tag{21}$$

Where $C_{CAPEX,t}^{ORI}$, $C_{CAPEX,t}^{RET}$, and $C_{CAPEX,t}^{CCS}$ represents capital cost for original investment for cement plants, retrofitting at the half of operational lifetime, and CCS deployment, respectively. $C_{OPEX,t}^{fix}$ and $C_{OPEX,t}^{fix\_CCS}$ denote fixed operation costs for cement plant and CCS deployment respectively, which include maintenance, insurance and labor costs [9]. $C_{OPEX,t}^{\mathrm{var}}$ and $C_{OPEX,t}^{\mathrm{var\_}CCS}$ represent variable operating costs for cement plant and CCS deployment respectively, which mainly include energy cost (i.e., fuel and electricity) in this study. Besides, capital costs are annualized as follows, assuming that the initial investment can be paid back equally during its operational lifetime [15].

$$C_{CAPEX,t} = uc \cdot ca \cdot \frac{\alpha \cdot \left(1+\alpha\right)^{L}}{\left(1+\alpha\right)^{L} - 1} \tag{22}$$

Where uc is the unit cost, and α is the discount rate of 8% [9].

3.5 Scenario setting

3.5.1 Demand-side scenarios

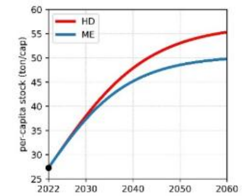
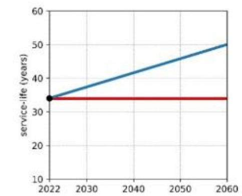
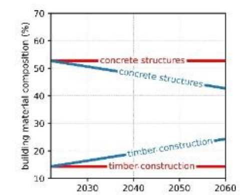
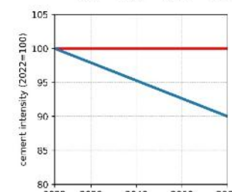
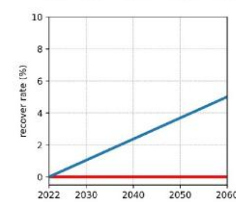
This study adopts the methodology developed in our previous study to develop the demand-side scenarios [33]. Specifically, the per-capita cement stock can be decomposed into the per-capita service level (sl) and the cement intensity per service provided (mi) [65]. For instance, per-capita service level reaches 41 m^2/cap of China's residential buildings by 2020 [66], among which ~53% are reinforced concrete structures with a cement intensity is 0.217 t/m^2 [67]. Thus, the cement stock embodied in this type of built infrastructures is estimated to be 4.8 t/cap in 2020.

$$s_t = sl_t \cdot mi_t \tag{23}$$

This study alters the per-capita service levels and cement intensity, both of which in turn will determine the per-capita cement stock in future. Specifically, this study develops two scenarios, i.e., High Demand (HD) and Material Efficiency (ME) scenarios, to investigate the mitigation potential of material efficiency strategies, such as more intensive use and service-life extension [21], [31], [68]. Table 1 displays the key assumptions for these two scenarios. In the HD scenario, the service level will continue to grow along a trajectory fitted by a logistics function [69], leading to a per-capita cement stock saturated at 55.3 t/cap by 2060, with an unchanged cement intensity. In comparison, the saturated per-capita stock will decrease by 10% in ME scenario, mainly due to equivalent reduction in service level through more intensive use [31]. As for service-life, it will maintain at the current level [58] in HD scenario, whereas it will gradually increase to 50 years in ME scenario, which is the expected lifetime in ordinary building design

[70]. This study also considers the potential mitigations from timber construction. It is assumed that 10% of reinforced concrete residential buildings will be replaced by timber structures by 2060 [31], leading to a reduction of ~1.8 t/cap by 2060. Besides, future technical innovations in construction can also save material consumption. Therefore, cement intensity of ME scenario will decline by 10% by 2060, mainly through lightweight design and lean construction methods, such as prefabricated construction [31]. Given the recent progress in recovering end-of-life (EOL) cement clinker [71], 5% of cement outflow will be recovered and reused by 2060 in the ME scenario.

Table 1 | Scenario narratives on demand-side.

Strategy	High demand (HD)	Material efficiency (ME)	Comparison
More intensive use	Per-capita cement stock will grow and saturate at 55.3 t by 2060.	Per-capita cement stock will continue to grow but at a lower rate and saturated level will decrease by 10%.	
Service-life extension	Service-life of the in-use cement stock will maintain at the current level by 2060.	Service-life of in-use cement stock will gradually increase to 50 years by 2060.	
Alternative materials	Material composition of built environment will remain the same by 2060.	10% of concrete residential buildings substituted by timber structures by 2060.	
Construction innovation	Constant cement intensity by 2060.	10% reduction of cement intensity by 2060, mainly due to lightweight design and prefabricated construction.	
More recovery	No recovery by 2060.	5% of end-of-life cement will be reused by 2060.	

3.5.2 Supply-side mitigation

This study develops two scenarios to quantify the mitigation potential from the supply-side measures. First, a business-as-usual (BAU) scenario is developed to serve as a benchmark before a series of mitigation measures are adopted. All existing plants as well as new plants are expected to operate for 40 years [36], [72]. The existing plants will maintain at the status quo, as no significant retrofit will be conducted in this scenario. Whilst specific technologies and measures can reduce TEI to some extent, it should be noted that by simply adding up the specific reduction potentials of single measures to calculate the total mitigation is not accurate, because some of them have interacting impacts and may reduce the "one kJ" more than once, sometimes possibly leading to going beyond the minimum theoretical energy demand [4]. Thus, this study only considers the TEI reduction from replacement by the new plants and a significant retrofit for the existing plants. In the BAU scenario, the sectoral thermal efficiency of the cement sector will be improved only by replacing existing capacity by the efficient new plants, of which TEI must comply to the current *National standard for Energy-saving Design in Cement Plants* (i.e., GB 50443-2016 [64]). All the plants will continue to adopt coal for the heating energy supply. Besides, the clinker factor, i.e., the mass ratio of clinker in cement, will also remain unchanged by 2060, as recent policies promote high-grade cement with higher clinker content than before [1].

In contrast, an ambitious (AMB) scenario is developed to fully investigate the mitigation potential when leveraging the supply-side measures. The plant lifetime will be reduced to 30 years for those capacity below 3000 t-clinker/day to accelerate the turnover of production equipment. Besides, all the plants will conduct a significant retrofit at half of their expected lifetime. Thermal efficiency will be improved a lot in the AMB scenario, as existing plants will reduce their TEI to fulfill the requirements in GB 50443-2016 [64] after retrofit and new plants will adopt the current best practice to further reduce the TEI to 2.8 GJ/t-clinker. Furthermore, all new plants will fuel the kiln by natural gas and co-fire with 30% of biomass (on a thermal basis) in their pre-calciner, while existing plants will fuel their kiln with oil and co-fire with biomass after retrofitting their production facilities. Also, the clinker factor will be reduced to 50% with the pervasive use of low-clinker cement products in the market, such as LC^3 [46]. A comparison of two supply-side scenarios is displayed in Table 1**Error! Reference source not found.**.

Table 2 | Scenario narratives on supply-side.

Dimension	Business-as-usual (BAU)	Ambitious (AMB)
Thermal efficiency	TEI of new plants only comply with the current National Standard.	TEI of new plants will decrease to 2.8 GJ/t of clinker, whereas that of existing plants will decrease to the level required by the current National standard, after retrofit.
Fuel switching	No alternative fuels. Both the existing and new plants still adopt coal to fulfill all thermal energy requirement.	New plants will be fueled with 70% natural gas and 30% biomass fuel, whereas existing plant will retrofit to fuel the kiln with 70% oil and 30% biomass fuel.
Plant lifetime	40 years.	Kilns with capacity lower than 3000 t/day will operate for only 30 years.
Retrofit	No retrofit.	Retrofit for efficiency improvement at half of the plant lifetime.
Clinker substitution	Clinker-to-cement mass ratio (CCR) will maintain at the current level.	CCR will be reduced to 50% by 2060.

In this study, total carbon emissions from the cement sector will decrease by ~90% by 2060 compared to the current levels, aligning with China's carbon neutrality target and based on the comparable reduction targets for global cement sector in the IEA-NZE scenario [73]. Therefore, the deployment of CCS will act as a crucial lever to bridge the emissions gap, aiming for a net-zero cement sector in China. The annual deployment rate and capacity of CCS can be determined accordingly by Module 2 and 3.

3.6 Data source

For Module 1, statistics on China's cement production, import, and export are collected from the *National Data* platform of National Bureau of Statistics of PRC [74]. Historical service-life of China's cement stock is retrieved from [58]. Historical national and provincial population are also retrieved from *National Data* platform [74], while population projection to 2060 is retrieved from the United Nations (UN) *World Population Prospects 2022* [75]. Notably, variations in population projection, such as up to ~100 million between SSPs [76], may significantly alter future cement stock. However, the investigation on population impacts may be out of the scope of this study, thus the medium scenario of UN's projections [75] is selected as a representative projection for modeling, which is also close to SSP2 "middle-of-the-road" [76]. For Module 2, this study compiled a list of cement plants information, mainly about cement kilns capacity, location, and online year, from the public available government announcements in recent years [60]. For emissions accounting in Module 3, this study conducts a survey of the CO_2 emission factors of fossil fuel and biomass from previous studies and industry report (displayed in

Supplementary Data), whereas emissions factors of future electricity generation are retrieved from another prospective analysis [19]. A few samples of thermal energy intensity of clinker production in China's cement plant are collected through reviewing related studies from China National Knowledge Infrastructure, to fit the relationship between production capacity and thermal efficiency (as shown in Figure 6a). As for economic cost, besides collecting the unit costs of traditional mitigation measures from previous studies or industry reports [4], [12], [44], this study also sourced and transferred cost data of CCS deployments from a detailed analysis of commercial capture plants after successful development and adoption of the capture technologies [9].

4. Results and discussion

4.1 China's future cement demand and clinker production

Figure 7 displays future cement consumption and clinker production in China. As shown in Figure 7a, China's cement consumption will rebound from 2.1 Gt/year to ~2.5 Gt/year by 2030 in HD scenario, after that it gradually decline to 1.4 Gt/year by 2060, mainly due to the downward trend in population after 2030 [77]. In contrast, cement consumption will significantly decrease to 0.5 Gt/year by 2060, through adopting a series of material efficiency strategies. These strategies can cumulatively reduce 26.6 Gt cement consumption, among which 9.8 Gt come from service-life extension, 7.1 Gt from more intensive use, 6.3 Gt from construction innovation, 2.3 Gt from timber construction, and 1.1 Gt from recovering waste cement. As for clinker production, it will gradually decrease to 0.9 Gt/year and 0.3 Gt/year by 2060 in the HD+BAU and ME+BAU scenarios respectively, if the clinker-to-cement mass ratio (CCR) remains unchanged. However, an ambitious CCR of 50% will reduce the annual clinker production to ~0.7 Gt/year and ~0.2 Gt/year in the HD+AMB and ME+AMB scenarios respectively (Figure 7c). This CCR implies a large-scale penetration of low-clinker cement products in China, such as Limestone Calcined Clay Cement (LC^3), which can be blended by only 50% clinker without compromising its mechanical performance [46]. It can cumulatively reduce the total clinker production by more 11% and 9% to 46.0 Gt and 31.0 Gt in the HD+AMB and ME+AMB scenarios, respectively (Figure 7d).

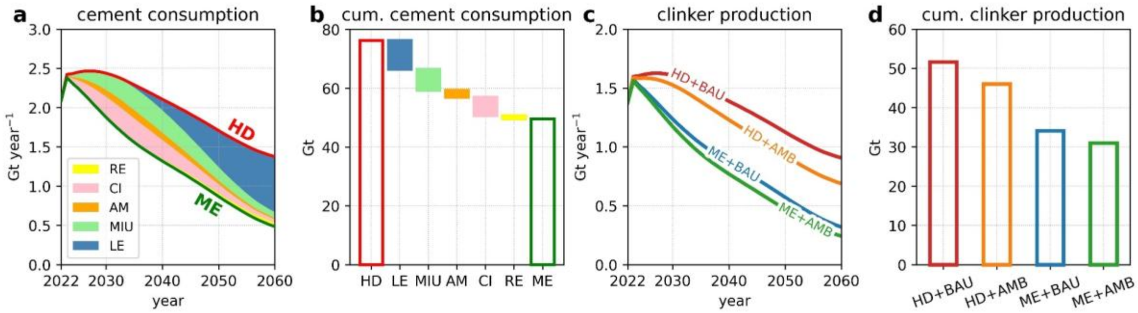


Figure 7 | China's annual cement consumption (a) and clinker production (c) in 2022-2060, and cumulative cement (b) and clinker production (d) during 2023-2060. (LE denotes service-life extension, MIU represents more-intensive use of cement stock. AM represents alternative construction materials. CI denotes for construction innovation. RE denotes cement recovery.)

4.2 Carbon emissions pathways and CCS deployments

Figure 8 depicts fuel and electricity consumption as well as emissions pathways of HD+BAU, HD+AMB, ME+BAU, and ME+AMB scenarios in this study. Apparently, energy consumption for clinker and cement production will decline with the decreasing production scale. In the HD+BAU scenario, fuel consumption peaks at 5.4 exajoule (EJ, 10^{18} joule) per year by 2030 and then declines to 3.1 EJ/year by 2060, primarily from coal, with minor contributions from natural gas consumed for steam generation in MEA carbon capture. An ambitious portfolio of supply-side measures, including thermal efficiency improvement and clinker substitution, can reduce fuel consumption to 2.1 EJ/year by 2060. The ME scenarios show much lower fuel consumption, decreasing to 1.3 EJ/year and 0.9 EJ/year in ME+BAU and ME+AMB scenarios, respectively. Initially, oil will serve as an interim option before the transition to natural gas (64-67%) and biomass fuel (3-7%) by 2060. Similar declining trends are observed in the electricity consumption across four scenarios. Total electricity consumption peaks at 184 TWh/year and then decrease to 36-102 TWh/year by 2060, with ~10 TWh/year consumed for CCS. Consequently, total carbon emissions will decrease to ~130 Mt-CO_2/year by 2060 across the four scenarios, whereas without CCS, total carbon emissions will increase to 0.8, 0.5, 0.3, and 0.2 Gt-CO_2/year in 2060. Additionally, minor carbon dioxide emissions (~44 Mt-CO_2/year) can be balanced through biofuel use with CCS.

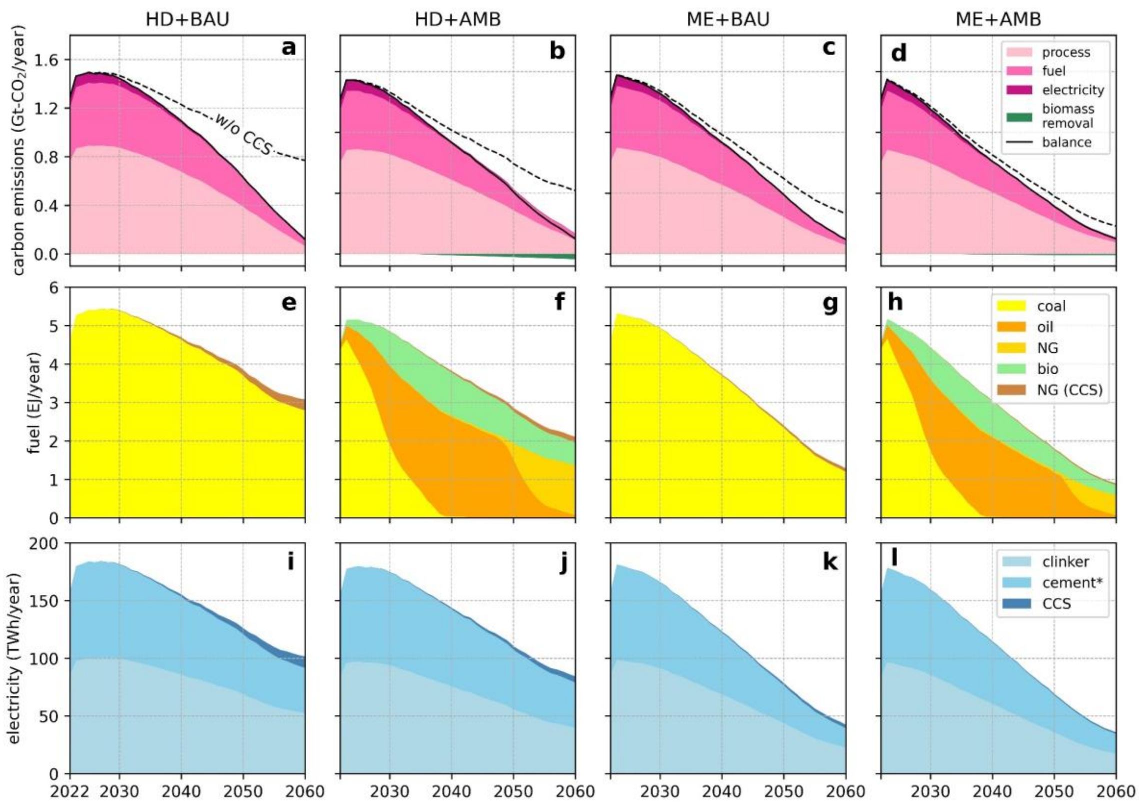


Figure 8 | Carbon emissions, clinker production capacity and CCS deployment, fuel and electricity consumption of cement sector in China in 2022-2060. (Notes: NG denotes for natural gas. bio refers to biomass fuel. Cement* represents electricity consumption for cement grinding.)

Figure 9 illustrates the future capacity turnover and CCS deployment for China's cement sector. China's existing clinker production capacity stands at 5.7 Mt per day or 1.9 Gt per year nationwide (to run for 330 days annually). When all the cement plants are expected to operate for 40 years, the total clinker production capacity is projected to gradually decline to 0.9 Gt-clinker/year by the year 2060 (Figure 9a). New capacity developed after 2022 will depend on future demand, varying from 321 to 935 Mt-clinker/year across four scenarios. Notably, overcapacity remains severe until the 2050s, as a significant portion of the production capacity will be underutilized, even in the ME scenarios. Therefore, the large-scale existing clinker production capacity is incongruent with the reduced future demand, leading to the early retirement and stranding assets associated with the costly clinker production lines [78]. As for CCS deployments, the required capacity to achieve target emissions reduction would increase substantially to 901, 554, 304, and 152 Mt clinker per year by 2060 for HD+BAU, HD+AMB, ME+BAU, and ME+AMB scenarios, respectively. CCS capacity will account for almost clinker production capacity in the HD+BAU scenario, whereas it can be alleviated to 78%, 73%, and 47% in the other three scenarios. The average growth rates of CCS deployment are 23.7, 14.6, 8.0, and

4.0 Mt-clinker/year in these four scenarios, as of which are significantly lower than the historical growth rates of 57 Mt-clinker/year for NSP, which diffused at an unprecedented rate to fulfill the need of socio-economic development in the last two decades [1].

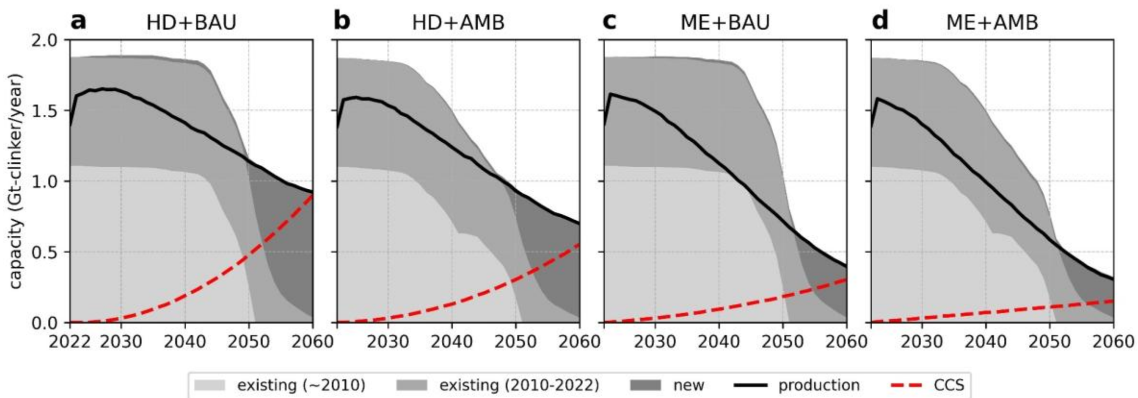


Figure 9 | Clinker production capacity and CCS deployments across four scenarios.

The HD+AMB scenario is used as an example to illustrate the breakdown of production capacity and CCS deployments across provinces in China (Figure 10). The production scale of each province correlates with its respective demand and the size of its own and neighboring production capacities. Younger and larger capacities (over 5000 tons of clinker per day) will be prioritized for CCS deployments. Provinces with significant young capacity and high utilization rates, such as Guangdong and Henan, will deploy CCS from 2030. In contrast, provinces like Hebei will delay deployment until their existing capacities are replaced by new and large plants by 2050. Here the distinct provincial results emphasized that regional disparity should be carefully considered when formulating industry policies aimed at curbing carbon emissions towards carbon neutrality by mid-century.

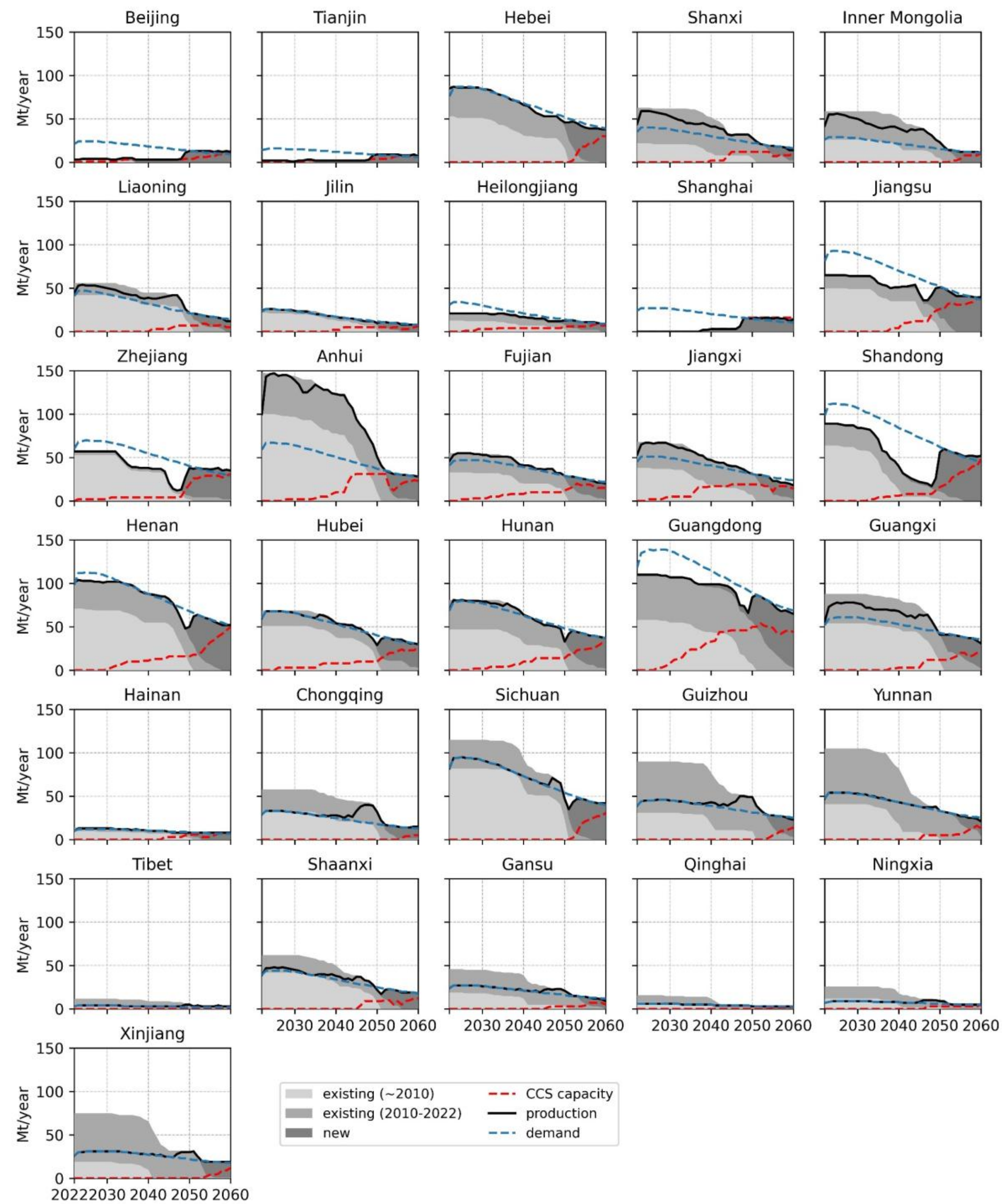


Figure 10 | Clinker production capacity and CCS deployments by province of HD+AMB scenario.

4.3 Economic costs of scenarios

The emissions mitigation costs of HD+BAU, HD+AMB, ME+BAU, and ME+AMB, scenarios are displayed in Figure 11. For HD+BAU scenario, the annual cost will fluctuate around 300 billion CNY, with a significant portion stemming from the operational costs of energy consumption. This cost is projected to gradually increase to ~400 billion CNY from 2050 due to large-scale CCS deployments. In contrast, economic costs will decline significantly to 183-204 billion CNY by 2060 in the ME scenarios, with declining production scale. Cumulatively, total costs will rise from 9.0-11.7 trillion CNY to 9.7-12.8 trillion CNY due to large-scale CCS deployment. The unit cost of clinker production (COC) will also increase from 256, 341, 367, and 515 CNY/t-clinker to 429, 468, 515, and 600 CNY/t-clinker with CCS deployment across the four scenarios. The highest COC in the ME+AMB scenario is primarily due to the significantly decreased clinker production. However, the largest increment in unit cost occurs in the HD+BAU scenario, driven by the extensive scale of CCS installation compared to other scenarios. The unit costs of carbon emission mitigation are 156, 189, 217, and 228 CNY/t-CO_2 for the four scenarios with CCS deployment (Figure 11g). Notably, the mitigation cost for the ME+AMB scenario remains roughly the same with or without CCS deployment. Although all mitigation costs are higher than the current carbon prices in China (51-104 CNY/t-CO_2) [79], these scenarios are expected to be cost-effective as carbon prices gradually rise in the future.

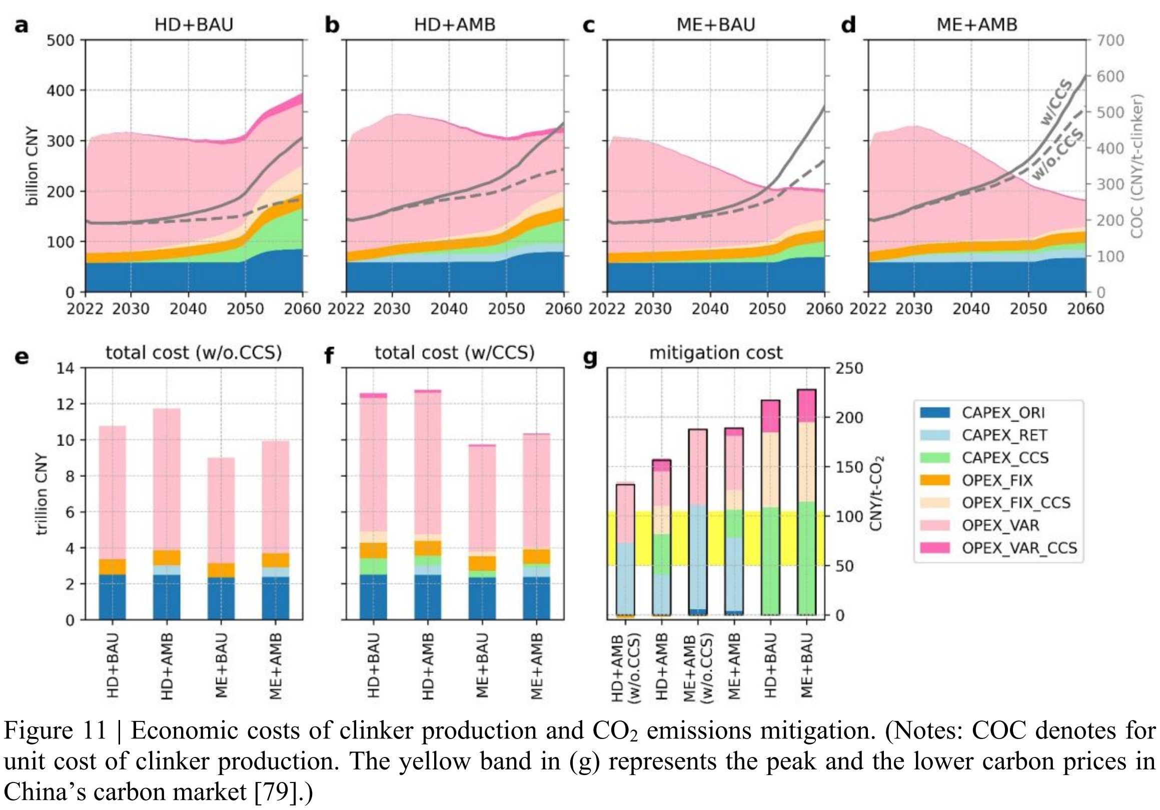


Figure 11 | Economic costs of clinker production and CO_2 emissions mitigation. (Notes: COC denotes for unit cost of clinker production. The yellow band in (g) represents the peak and the lower carbon prices in China's carbon market [79].)

4.4 Discussion

This study establishes a 2×2 scenario matrix to delineate the boundary conditions of future emission trajectories for China's cement sector, and systematically assesses the role of CCS in the decarbonization pathways towards carbon neutrality by 2060. The results show that the reliance on large-scale of CCS deployment seems to be daunting when both the supply- and demand-sides remain the status quo, whereas it can be effectively reduced if the mitigation potentials are tapped on both sides. Another notable benefit of the ME and AMB scenarios is an expanded time window for the preparation of CCS, which is still yet to be ready for large-scale deployment, due to the low technical readiness or vague business model, which will significantly increase the risk of project failure when the capture capacity increases [42]. However, the window is closing, as revealed by the UNEP that current unconditional NDCs will lead to a 2.8°C and 2.6°C increase in temperature by 2100, which are far beyond the goals of the Paris Agreement [80]. The high emissions in the HD-BAU scenario also echo with what the UNEP recently warns. It is urgent to cut off 45% of GHG emissions by 2030 to get on the track to limit global warming to 1.5°C. Before CCS is ready, this substantial emissions reduction for the cement sector can only be realized in the ME+AMB scenario, which is even well lower than the available budget of IEA-NZE. Although CCS deployment can be delayed by 5-10 years in the ME scenarios, the time when it is ready to capture CO_2 fully or near fully from cement plants' flus gas also matters. Historical diffusion of NSP in Chian reveals that it took over 30 years to scale up the unit production capacity from hundreds to over 10 thousand tons of clinker per day (Figure 12a). In contrast, the current largest capture capacity of the demonstration projects is only 50 kt of CO_2 per year [81], which is still far away from the 1 Mt CO_2 per year (for a plant which produces 5,000 t clinker per day). Whilst some end-of-pipe CCS technologies are expected to diffuse as fast as that of desulfurization [82], efficient calcium looping and oxyfuel combustion with low retrofitability require much more knowledge and experience accumulation, when the plant configuration will be significantly changed [3].

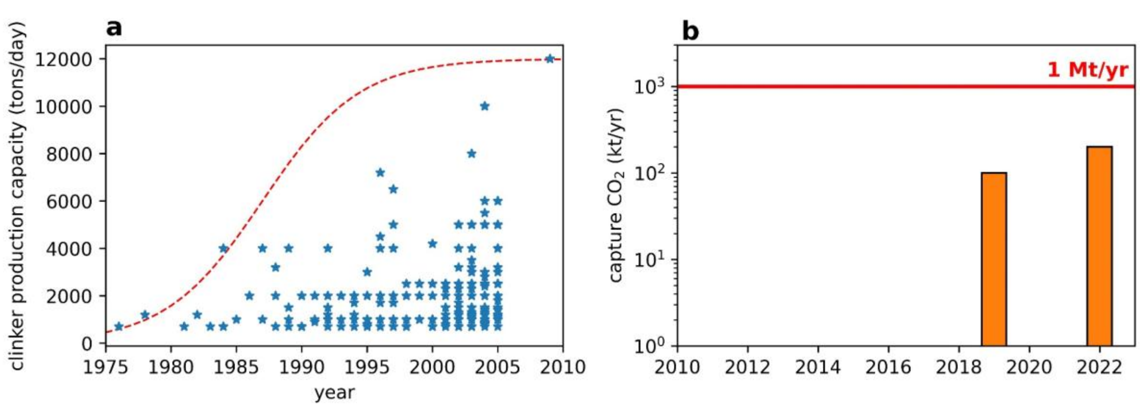


Figure 12 | Diffusion of NSP during 1995 and 2010 (a) and CCS demonstration projects in cement sector (b).

In this study, material efficiency has shown the significant potential to curb future cement demand and in turn the CO_2 emissions from production, but to what extent this potential can be fully tapped depending on how we change the built environment management by effective intervention. Reducing per-capita cement stock without dematerialization implies that our society will provide the desired service levels from unchanged or even smaller stocks. This study takes residential building sector as an example to delineate the opportunities and barriers when aiming at reducing the per-capita stock and extending the service-life. The residential area per capita has seen a significant growth across the provinces in China, with the national average rising from 31 to 42 m^2 during 2010-2020 (Figure 13a). China's housing has become much more spacious than before, and residential area per household is averaged at 111 m^2, with 3.2 rooms and each person has 1.2 rooms [66]. To buck the rising trend of residential floor area, larger household size and more persons per room may be required to increase the use intensity. These measures need better architectural design and social behavior change in the near-term. Besides, regional disparity should be considered during the policy-making process. It seems those developed provinces are more 'material efficient' than the developing provinces, as they have a lower per-capita residential area, which is highly possibly induced by a higher housing price. Service-life extension of residential buildings would also need unprecedented shift in building management, as over 80% of residential buildings were built within 30 years (Figure 13b). Reasonable urban planning, regular maintenance, and renovation can avoid premature demolitions induced by the factors other than physical deterioration of building components within their designed lifespan.

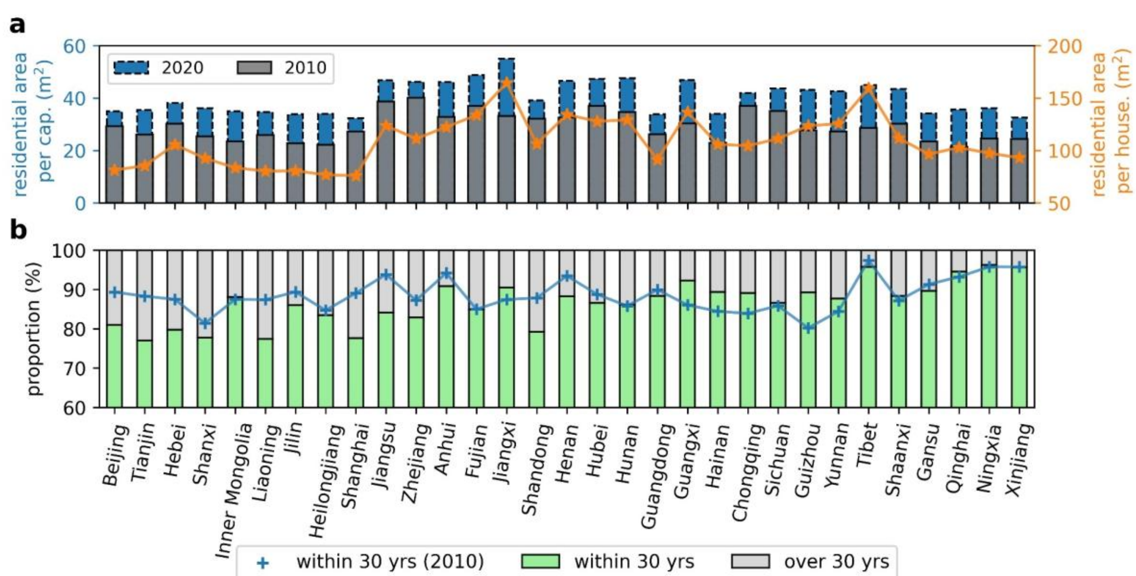


Figure 13 | Residential building area per capita and household (a) and the proportion of residential buildings built within or over 30 years in China's provinces (b). Source: the 7th Population Census [67].

This study can also provide some insights for other developing economies. By employing a range of demand-side material efficiency strategies, it is demonstrated that annual cement demand could be reduced by over 60%, from 1.4 Gt/year to 0.5 Gt/year. This reduction highlights the substantial mitigation potential on the demand side. Therefore, emerging regions, where much infrastructure is still to be built, can leverage these findings to better plan and develop their infrastructure, aiming for lower saturated material stock levels and avoiding emissions lock-in effects [35]. Consequently, demand-side strategies can not only alleviate the pressures and costs of supply-side mitigation but also provide a more balanced and cost-effective pathway to achieving the net-zero by mid-century.

This study has several limitations. For instance, the projected national-level cement and clinker demand is distributed to each province based on future population estimates, which assumes uniform per-capita consumption across all provinces. This assumption may obscure the diverse cement stock saturation status and future demand variations among provinces. In future work, if more detailed provincial-level cement consumption data become available, cement inventory accounting and future forecasts can be conducted for each province from the bottom up. Additionally, CCS deployment does not account for the limitations of carbon storage capacity across provinces, potentially leading to higher transportation costs for storing captured emissions. Future studies could integrate the carbon storage potential of each province into the modeling process to better address regional disparities.

5. Conclusions

This study integrates both supply-side and demand-side strategies to develop decarbonization pathways and assess the role that CCS will play in China's cement sector, towards carbon neutrality by 2060. Four specific scenarios are developed based on two types of settings from both demand- and supply-side perspectives: high demand versus material efficiency, and business-as-usual versus ambitious mitigation. China's future cement demand can be decreased from 1.4 Gt/year to 0.5 Gt/year by 2060, if 10% reduction in per-capita cement stock, service-life extended to 50 years, 10% of concrete residential buildings replaced by timber structures, 10% reduction in cement intensity, and 5% of end-of-life cement recovered to be reused. At the same time, the clinker production can be reduced to 0.2 Gt/year with clinker-to-cement ratio of 50%. Therefore, total carbon emissions can be curbed from 0.2-0.8 to ~0.1 Gt-CO_2/year by 2060, with large-scale CCS deployments and other types of supply-side measures. There would be a required CCS capacity of 152-901 Mt-clinker/year by 2060, to achieve these emissions reductions.

Additionally, total economic costs would be 9.7-12.8 trillion CNY across four scenarios, while the mitigation costs range from 156 to 228 CNY/t-CO_2, which is higher than current carbon prices in China.

Overall, this study delineates substantial emission mitigation potentials from both supply- and demand-side efforts. To fully harness these significant mitigation potentials, it is recommended that the government formulate comprehensive policies and regulations targeting both supply- and demand-side strategies to guide the cement sector's timely transition to net-zero emissions. Based on national and provincial capacity simulations in this study, a considerable amount of capacity is projected to be underutilized in the near- and mid-term. Therefore, it is essential to carefully consider the distinct demand-production-capacity nexus across provinces when planning for CCS and related infrastructure development. This approach will help avoid the risks of stranded assets and maximize the utilization of costly emissions mitigation infrastructure. On the demand side, China should develop policies and regulations to enhance the material efficiency of infrastructure stocks, thereby avoiding the replication of cement stock patterns seen in developed economies [35]. For instance, the government can introduce incentives such as subsidies to promote the renovation of old buildings, thereby extending their service life.

Data availability

Data will be made available based on reasonable request.

Acknowledgements

The authors would like to acknowledge the Environment and Ecology Bureau for financially supporting this study through the Green Tech Fund (project no.: GTF202110158).

References

[1] T. Wu, S. T. Ng, and J. Chen, “Deciphering the CO<sub>2<sub> emissions and emission intensity of cement sector in China through decomposition analysis,” *Journal of Cleaner Production*, vol. 352, p. 131627, Jun. 2022, doi: 10.1016/j.jclepro.2022.131627.

[2] G. Habert *et al.*, “Environmental impacts and decarbonization strategies in the cement and concrete industries,” *Nat Rev Earth Environ*, vol. 1, no. 11, pp. 559–573, Sep. 2020, doi: 10.1038/s43017-020-0093-3.

[3] M. Voldsund *et al.*, “Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation,” *Energies*, vol. 12, no. 3, p. 559, Feb. 2019, doi: 10.3390/en12030559.

[4] European Cement Research Academy and Cement Sustainability Initiative, “Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead; CSI/ECRA-Technology Papers 2017,” Duesseldorf, Geneva, 2017. [Online]. Available: http://www.wbcsdcement.org/technology

[5] D. R. Nhuchhen, S. P. Sit, and D. B. Layzell, “Alternative fuels co-fired with natural gas in the pre-calciner of a cement plant: Energy and material flows,” *Fuel*, vol. 295, 2021, doi: 10.1016/j.fuel.2021.120544.

[6] E. Gartner and T. Sui, “Alternative cement clinkers,” *Cement and Concrete Research*, vol. 114, pp. 27–39, 2018, doi: 10.1016/j.cemconres.2017.02.002.

[7] S. A. Miller and R. J. Myers, “Environmental Impacts of Alternative Cement Binders,” *Environ Sci Technol*, vol. 54, no. 2, pp. 677–686, Jan. 2020, doi: 10.1021/acs.est.9b05550.

[8] T. Hills, D. Leeson, N. Florin, and P. Fennell, “Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting,” *Environ. Sci. Technol.*, vol. 50, no. 1, pp. 368–377, Jan. 2016, doi: 10.1021/acs.est.5b03508.

[9] S. Gardarsdottir *et al.*, “Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis,” *Energies*, vol. 12, no. 3, p. 542, Feb. 2019, doi: 10.3390/en12030542.

[10] M. G. Plaza, S. Martínez, and F. Rubiera, “CO2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations,” *Energies*, vol. 13, no. 21, 2020, doi: 10.3390/en13215692.

[11] J. Ke, N. Zheng, D. Fridley, L. Price, and N. Zhou, “Potential energy savings and CO2 emissions reduction of China’s cement industry,” *Energy Policy*, vol. 45, pp. 739–751, Jun. 2012, doi: 10.1016/j.enpol.2012.03.036.

[12] J. Xu, B.-W. Yi, and Y. Fan, “A bottom-up optimization model for long-term CO2 emissions reduction pathway in the cement industry: A case study of China,” *International Journal of Greenhouse Gas Control*, vol. 44, pp. 199–216, 2016, doi: 10.1016/j.ijggc.2015.11.028.

[13] W. Zhou, D. Jiang, D. Chen, C. Griffy-Brown, Y. Jin, and B. Zhu, “Capturing CO2 from cement plants: A priority for reducing CO2 emissions in China,” *Energy*, vol. 106, pp. 464–474, 2016, doi: 10.1016/j.energy.2016.03.090.

[14] N. Li, D. Ma, and W. Chen, “Quantifying the impacts of decarbonisation in China’s cement sector: A perspective from an integrated assessment approach,” *Applied Energy*, vol. 185, pp. 1840–1848, 2017, doi: 10.1016/j.apenergy.2015.12.112.

[15] C.-Y. Zhang, B. Yu, J.-M. Chen, and Y.-M. Wei, “Green transition pathways for cement industry in China,” *Resources, Conservation and Recycling*, vol. 166, p. 105355, Mar. 2021, doi: 10.1016/j.resconrec.2020.105355.

[16] X. Liu, Z. Yuan, Y. Xu, and S. Jiang, “Greening cement in China: A cost-effective roadmap,” *Applied Energy*, vol. 189, pp. 233–244, 2017, doi: 10.1016/j.apenergy.2016.12.057.

[17] C. D. Dinga and Z. Wen, “China’s green deal: Can China’s cement industry achieve carbon neutral emissions by 2060?,” *Renewable and Sustainable Energy Reviews*, vol. 155, p. 111931, Mar. 2022, doi: 10.1016/j.rser.2021.111931.
[18] M. Ren *et al.*, “Negative emission technology is key to decarbonizing China’s cement industry,” *Applied Energy*, vol. 329, p. 120254, Jan. 2023, doi: 10.1016/j.apenergy.2022.120254.
[19] C. Tan, X. Yu, and Y. Guan, “A technology-driven pathway to net-zero carbon emissions for China’s cement industry,” *Applied Energy*, vol. 325, p. 119804, Nov. 2022, doi: 10.1016/j.apenergy.2022.119804.
[20] N. A. Ryan, S. A. Miller, S. J. Skerlos, and D. R. Cooper, “Reducing CO_2 Emissions from U.S. Steel Consumption by 70% by 2050,” *Environ Sci Technol*, vol. 54, no. 22, pp. 14598–14608, Nov. 2020, doi: 10.1021/acs.est.0c04321.
[21] J. M. Cullen and D. R. Cooper, “Material Flows and Efficiency,” *Annual Review of Materials Research*, vol. 52, no. 1, pp. 525–559, 2022, doi: 10.1146/annurev-matsci-070218-125903.
[22] J. Wei and K. Cen, “Empirical assessing cement CO2 emissions based on China’s economic and social development during 2001–2030,” *Science of The Total Environment*, vol. 653, pp. 200–211, Feb. 2019, doi: 10.1016/j.scitotenv.2018.10.371.
[23] J. Ke, N. Zheng, D. Fridley, L. Price, and N. Zhou, “Potential energy savings and CO2 emissions reduction of China’s cement industry,” *Energy Policy*, vol. 45, pp. 739–751, Jun. 2012, doi: 10.1016/j.enpol.2012.03.036.
[24] X.-Z. Feng, O. Lugovoy, and H. Qin, “Co-controlling CO2 and NOx emission in China’s cement industry: An optimal development pathway study,” *Advances in Climate Change Research*, vol. 9, no. 1, pp. 34–42, Mar. 2018, doi: 10.1016/j.accre.2018.02.004.
[25] Y. Wang, S. Höller, P. Viebahn, and Z. Hao, “Integrated assessment of CO2 reduction technologies in China’s cement industry,” *International Journal of Greenhouse Gas Control*, vol. 20, pp. 27–36, Jan. 2014, doi: 10.1016/j.ijggc.2013.10.004.
[26] T. Watari, Z. Cao, S. Hata, and K. Nansai, “Efficient use of cement and concrete to reduce reliance on supply-side technologies for net-zero emissions,” *Nat Commun*, vol. 13, no. 1, p. 4158, Jul. 2022, doi: 10.1038/s41467-022-31806-2.
[27] G. Liu, C. E. Bangs, and D. B. Müller, “Stock dynamics and emission pathways of the global aluminium cycle,” *Nature Clim Change*, vol. 3, no. 4, pp. 338–342, Apr. 2013, doi: 10.1038/nclimate1698.
[28] Z. Cao, L. Shen, A. N. Løvik, D. B. Müller, and G. Liu, “Elaborating the History of Our Cementing Societies: An in-Use Stock Perspective,” *Environ. Sci. Technol.*, vol. 51, no. 19, pp. 11468–11475, Oct. 2017, doi: 10.1021/acs.est.7b03077.
[29] W. Shanks, C. F. Dunant, M. P. Drewniok, R. C. Lupton, A. Serrenho, and J. M. Allwood, “How much cement can we do without? Lessons from cement material flows in the UK,” *Resources, Conservation and Recycling*, vol. 141, pp. 441–454, 2019, doi: 10.1016/j.resconrec.2018.11.002.
[30] R. Bleischwitz, V. Nechifor, M. Winning, B. Huang, and Y. Geng, “Extrapolation or saturation – Revisiting growth patterns, development stages and decoupling,” *Global Environmental Change*, vol. 48, pp. 86–96, 2018, doi: 10.1016/j.gloenvcha.2017.11.008.
[31] X. Zhong *et al.*, “Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060,” *Nat Commun*, vol. 12, no. 1, p. 6126, Oct. 2021, doi: 10.1038/s41467-021-26212-z.
[32] S. Pauliuk *et al.*, “Global scenarios of resource and emission savings from material efficiency in residential buildings and cars,” *Nat Commun*, vol. 12, no. 1, p. 5097, Aug. 2021, doi: 10.1038/s41467-021-25300-4.
[33] T. Wu, S. T. Ng, J. Chen, and Z. Cao, “More intensive use and lifetime extension can enable net-zero emissions in China’s cement cycle,” *Resources, Conservation and Recycling*, vol. 198, p. 107144, Nov. 2023, doi: 10.1016/j.resconrec.2023.107144.

[34] S. A. Miller, “The role of cement service-life on the efficient use of resources,” *Environmental Research Letters*, vol. 15, no. 2, 2020, doi: 10.1088/1748-9326/ab639d.
[35] Z. Cao *et al.*, “The sponge effect and carbon emission mitigation potentials of the global cement cycle,” *Nat Commun*, vol. 11, no. 1, p. 3777, Jul. 2020, doi: 10.1038/s41467-020-17583-w.
[36] C. Chen *et al.*, “A striking growth of CO_2 emissions from the global cement industry driven by new facilities in emerging countries,” *Environ. Res. Lett.*, vol. 17, no. 4, p. 044007, Apr. 2022, doi: 10.1088/1748-9326/ac48b5.
[37] J. Liu *et al.*, “Carbon and air pollutant emissions from China’s cement industry 1990–2015: trends, evolution of technologies, and drivers,” *Atmos. Chem. Phys.*, vol. 21, no. 3, pp. 1627–1647, Feb. 2021, doi: 10.5194/acp-21-1627-2021.
[38] X. Cai *et al.*, “Establishment of High-Resolution Atmospheric Mercury Emission Inventories for Chinese Cement Plants Based on the Mass Balance Method,” *Environ Sci Technol*, vol. 54, no. 21, pp. 13399–13408, Nov. 2020, doi: 10.1021/acs.est.0c02963.
[39] L. Chen *et al.*, “Rapid Increase in Cement-Related Mercury Emissions and Deposition in China during 2005-2015,” *Environ Sci Technol*, vol. 54, no. 22, pp. 14204–14214, Nov. 2020, doi: 10.1021/acs.est.0c03512.
[40] Y. Chen *et al.*, “Rapid Increase in China’s Industrial Ammonia Emissions: Evidence from Unit-Based Mapping,” *Environ Sci Technol*, vol. 56, no. 6, pp. 3375–3385, Mar. 2022, doi: 10.1021/acs.est.1c08369.
[41] L. Tang *et al.*, “Plant-level real-time monitoring data reveal substantial abatement potential of air pollution and CO2 in China’s cement sector,” *One Earth*, vol. 5, no. 8, pp. 892–906, Aug. 2022, doi: 10.1016/j.oneear.2022.07.003.
[42] N. Wang, K. Akimoto, and G. F. Nemet, “What went wrong? Learning from three decades of carbon capture, utilization and sequestration (CCUS) pilot and demonstration projects,” *Energy Policy*, vol. 158, 2021, doi: 10.1016/j.enpol.2021.112546.
[43] T. Hills, N. Florin, and P. S. Fennell, “Decarbonising the cement sector: A bottom-up model for optimising carbon capture application in the UK,” *Journal of Cleaner Production*, vol. 139, pp. 1351–1361, Dec. 2016, doi: 10.1016/j.jclepro.2016.08.129.
[44] Y. Wang, Z. Wen, M. Xu, J. Chen, and P. He, “Plant-level green transformation strategy in China’s cement industry: Considering energy conservation and emission reduction co-benefits,” *Journal of Cleaner Production*, vol. 467, p. 142945, Aug. 2024, doi: 10.1016/j.jclepro.2024.142945.
[45] J. Ma, F. Liu, T. Guo, C. Tao, and X. Peng, “Development and Application of 5500 t/d Pyro-system with 6-stage Preheater (in Chinese),” *Cement Technology*, no. 4, 2017, doi: 10.19698/j.cnki.1001-6171.2017.04.002.
[46] K. Scrivener, F. Martirena, S. Bishnoi, and S. Maity, “Calcined clay limestone cements (LC3),” *Cement and Concrete Research*, vol. 114, pp. 49–56, 2018, doi: 10.1016/j.cemconres.2017.08.017.
[47] Global Cement and Concrete Assiociation, “The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete,” 2022.
[48] N. Rodriguez, R. Murillo, and J. C. Abanades, “CO2 capture from cement plants using oxyfired precalcination and/or calcium looping,” *Environ Sci Technol*, vol. 46, no. 4, pp. 2460–6, Feb. 2012, doi: 10.1021/es2030593.
[49] J. G. Driver, T. Hills, P. Hodgson, M. Sceats, and P. S. Fennell, “Simulation of direct separation technology for carbon capture and storage in the cement industry,” *Chemical Engineering Journal*, vol. 449, 2022, doi: 10.1016/j.cej.2022.137721.
[50] D. Cheng *et al.*, “Projecting future carbon emissions from cement production in developing countries,” *Nat Commun*, vol. 14, no. 1, p. 8213, Dec. 2023, doi: 10.1038/s41467-023-43660-x.

[51] O. Cavalett, M. D. B. Watanabe, M. Voldsund, S. Roussanaly, and F. Cherubini, “Paving the way for sustainable decarbonization of the European cement industry,” *Nat Sustain*, Mar. 2024, doi: 10.1038/s41893-024-01320-y.
[52] K. Kermeli *et al.*, “The scope for better industry representation in long-term energy models: Modeling the cement industry,” *Applied Energy*, vol. 240, pp. 964–985, 2019, doi: 10.1016/j.apenergy.2019.01.252.
[53] Y. Wang, Z. Wen, M. Xu, and V. Kosajan, “The carbon-energy-water nexus of the carbon capture, utilization, and storage technology deployment schemes: A case study in China’s cement industry,” *Applied Energy*, vol. 362, p. 122991, May 2024, doi: 10.1016/j.apenergy.2024.122991.
[54] D. B. Müller, “Stock dynamics for forecasting material flows—Case study for housing in The Netherlands,” *Ecological Economics*, vol. 59, no. 1, pp. 142–156, Aug. 2006, doi: 10.1016/j.ecolecon.2005.09.025.
[55] H. Bergsdal, H. Brattebø, R. A. Bohne, and D. B. Müller, “Dynamic material flow analysis for Norway’s dwelling stock,” *Building Research & Information*, vol. 35, no. 5, pp. 557–570, Oct. 2007, doi: 10.1080/09613210701287588.
[56] A. Kapur, G. Keoleian, A. Kendall, and S. E. Kesler, “Dynamic Modeling of In-Use Cement Stocks in the United States,” *J of Industrial Ecology*, vol. 12, no. 4, pp. 539–556, Aug. 2008, doi: 10.1111/j.1530-9290.2008.00055.x.
[57] Z. Cao *et al.*, “Estimating the in-use cement stock in China: 1920–2013,” *Resources, Conservation and Recycling*, vol. 122, pp. 21–31, Jul. 2017, doi: 10.1016/j.resconrec.2017.01.021.
[58] Z. Cao, G. Liu, H. Duan, F. Xi, G. Liu, and W. Yang, “Unravelling the mystery of Chinese building lifetime: A calibration and verification based on dynamic material flow analysis,” *Applied Energy*, vol. 238, pp. 442–452, Mar. 2019, doi: 10.1016/j.apenergy.2019.01.106.
[59] A. Miatto, H. Schandl, and H. Tanikawa, “How important are realistic building lifespan assumptions for material stock and demolition waste accounts?,” *Resources, Conservation and Recycling*, vol. 122, pp. 143–154, Jul. 2017, doi: 10.1016/j.resconrec.2017.01.015.
[60] T. Wu, “China Cement Industry Dataset (CCID).” Zenodo, 2023. [Online]. Available: https://doi.org/10.5281/zenodo.8083481
[61] Y. Lu, F. Cohen, S. M. Smith, and A. Pfeiffer, “Plant conversions and abatement technologies cannot prevent stranding of power plant assets in 2 °C scenarios,” *Nat Commun*, vol. 13, no. 1, p. 806, Feb. 2022, doi: 10.1038/s41467-022-28458-7.
[62] J. Oda, K. Akimoto, T. Tomoda, M. Nagashima, K. Wada, and F. Sano, “International comparisons of energy efficiency in power, steel, and cement industries,” *Energy Policy*, vol. 44, pp. 118–129, 2012, doi: 10.1016/j.enpol.2012.01.024.
[63] International Energy Agency, “Thermal specific energy consumption per tonne of clinker in selected countries and regions, 2018.” [Online]. Available: https://www.iea.org/data-and-statistics/charts/thermal-specific-energy-consumption-per-tonne-of-clinker-in-selected-countries-and-regions-2018
[64] Ministry of Housing and Urban-Rural Development of the People’s Republic of China, “National Standard for Energy-saving Design in Cement Plants (GB50443-2016),” 2016.
[65] D. B. Muller *et al.*, “Carbon emissions of infrastructure development,” *Environ Sci Technol*, vol. 47, no. 20, pp. 11739–46, Oct. 2013, doi: 10.1021/es402618m.
[66] Office of the Leading Group of the Seventh National Population Census of the State Council, *China Population Census Yearbook 2020*. China Statistics Press, 2022.
[67] D. Yang, J. Guo, L. Sun, F. Shi, J. Liu, and H. Tanikawa, “Urban buildings material intensity in China from 1949 to 2015,” *Resources, Conservation and Recycling*, vol. 159, p. 104824, Aug. 2020, doi: 10.1016/j.resconrec.2020.104824.

[68] E. G. Hertwich *et al.*, “Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review,” *Environmental Research Letters*, vol. 14, no. 4, 2019, doi: 10.1088/1748-9326/ab0fe3.
[69] S. Pauliuk, R. L. Milford, D. B. Müller, and J. M. Allwood, “The Steel Scrap Age,” *Environ. Sci. Technol.*, vol. 47, no. 7, pp. 3448–3454, Apr. 2013, doi: 10.1021/es303149z.
[70] Ministry of Housing and Urban-Rural Development of the People’s Republic of China, “Uniform Standards for Civil Building Design (GB 50352-2019),” 2019.
[71] C. F. Dunant, S. Joseph, R. Prajapati, and J. M. Allwood, “Electric recycling of Portland cement at scale,” *Nature*, May 2024, doi: 10.1038/s41586-024-07338-8.
[72] D. Tong *et al.*, “Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target,” *Nature*, vol. 572, no. 7769, pp. 373–377, Aug. 2019, doi: 10.1038/s41586-019-1364-3.
[73] International Energy Agency, *Net Zero by 2050-A Roadmap for the Global Energy Sector (4th revision)*. 2021.
[74] National Bureau of Statistics of China, “National Data.” Accessed: Mar. 04, 2024. [Online]. Available: https://data.stats.gov.cn/english/
[75] Department of Economic and Social Affairs of United Nations, “World Population Prospects 2022.” Accessed: Jan. 01, 2022. [Online]. Available: https://population.un.org/wpp/
[76] International Institute for Applied Systems Analysis, “SSP Scenario Explorer 3.1.0 Release.” Accessed: Jul. 26, 2024. [Online]. Available: https://data.ece.iiasa.ac.at/ssp/#/workspaces
[77] Y. Ye, “When will China’s population peak? It depends who you ask.” [Online]. Available: https://www.nature.com/articles/d41586-022-02304-8
[78] A. Pfeiffer, C. Hepburn, A. Vogt-Schilb, and B. Caldecott, “Committed emissions from existing and planned power plants and asset stranding required to meet the Paris Agreement,” *Environmental Research Letters*, vol. 13, no. 5, 2018, doi: 10.1088/1748-9326/aabc5f.
[79] China Business Network Research Institute, “China Carbon Market Annual Report (2022&2023).” 2024. Accessed: Jul. 22, 2024. [Online]. Available: https://www.cbnri.org/news/5446589.html
[80] United Nations Environment Programme, “Emissions Gap Report 2022 The Closing Window - Climate crisis calls for rapid transformation of societies,” Nairobi, 2022. [Online]. Available: https://www.unep.org/emissions-gap-report-2022
[81] Global CCS Insitute, “Global Status of CCS 2022,” 2023. [Online]. Available: https://status22.globalccsinstitute.com/
[82] S. van Ewijk and W. McDowall, “Diffusion of flue gas desulfurization reveals barriers and opportunities for carbon capture and storage,” *Nat Commun*, vol. 11, no. 1, p. 4298, Aug. 2020, doi: 10.1038/s41467-020-18107-2.