

Original Research

Construction activities drive half of China's ambient PM_{2.5} health burden

Zhanxiang Wang^{a,b}, Huizhong Shen^{a,b,*}, Ruixin Zhang^{a,b}, Ruibin Xu^{a,b}, Peng Guo^{a,b}, Zhiyu Zheng^{a,b}, Jinling He^{a,b}, Siqi Wu^c, Yilin Chen^c, Dong Xie^{a,b}, Jinjian Zhang^{a,b}, Lianming Zheng^{a,b}, Hang Su^d, Dabo Guan^e

^a Shenzhen Key Laboratory of Precision Measurement and Early Warning Technology for Urban Environmental Health Risks, School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China

^b Guangdong Provincial Observation and Research Station for Coastal Atmosphere and Climate of the Greater Bay Area, Southern University of Science and Technology, Shenzhen, 518055, China

^c School of Urban Planning and Design, Peking University Shenzhen Graduate School, Shenzhen, 518071, China

^d Key Laboratory of Atmospheric Environment and Extreme Meteorology, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China

^e Department of Earth System Sciences, Tsinghua University, Beijing, 100080, China

ARTICLE INFO

Article history:

Received 8 September 2025

Received in revised form

28 January 2026

Accepted 28 January 2026

Keywords:

Construction

Air pollution

Premature deaths

Sustainable development

ABSTRACT

Construction activities generate substantial air pollutants and greenhouse gas emissions, contributing heavily to ambient PM_{2.5} exposure and associated mortality worldwide. In China, rapid urbanization has driven a massive expansion of the construction sector, with emissions arising from building material production, onsite operations, upstream supply chains, and operational energy use in buildings. Although end-of-pipe controls have markedly lowered pollutant emissions since 2013, further reductions are increasingly costly, and air quality and climate policies remain poorly integrated. The full lifecycle health burden imposed by construction-related air pollution, its temporal evolution, and the scope for health co-benefits from decarbonization—particularly across urban and rural divides—have been incompletely characterized. Here we integrate a detailed construction emission inventory, input–output analysis, inverse atmospheric modelling, and health impact assessment to quantify these impacts in China from 2000 to 2019. We show that construction-related emissions, including upstream power and industrial sources, caused 1.10 million (95% CI: 0.83–1.37 million) premature deaths in 2019, accounting for 50% (95% CI: 38–62%) of national ambient PM_{2.5}-attributed mortality. Health burdens evolved through three phases: rapid increase with 130% CO₂ growth during intense urbanization (2000–2008), decoupling via pollution controls that averted 0.36 million deaths despite rising CO₂ (2008–2015), and synergistic declines from energy-mix optimization and technology upgrades (2015–2019). Urban mortality stems predominantly from upstream industrial emissions, whereas rural mortality is driven by residential heating; decarbonizing power and heavy industry offers the largest urban co-benefits, while rural clean-electricity heating requires concurrent power-sector greening to prevent CO₂ penalties. These results position the construction sector as a pivotal target for integrated policies that jointly advance air quality, public health, and climate objectives.

© 2026 The Authors. Published by Elsevier B.V. on behalf of Chinese Society for Environmental Sciences, Harbin Institute of Technology, Chinese Research Academy of Environmental Sciences. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

* Corresponding author. Shenzhen Key Laboratory of Precision Measurement and Early Warning Technology for Urban Environmental Health Risks, School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China.

E-mail address: shenzh@sustech.edu.cn (H. Shen).

1. Introduction

China's rapid urbanization, driven by industrialization and economic growth, has precipitated a construction boom characterized by skyscrapers, extensive residential complexes, and comprehensive infrastructure networks [1,2]. Activities underpinning the construction sector, such as the production of building

materials and the consumption of operational energy, accounted for approximately 20% of the nation's total energy use in 2001, and this percentage had risen sharply to 46% by 2020 [3,4]. This growth has significantly increased emissions of air pollutants and greenhouse gases, such as fine particles (PM_{2.5}), nitrogen oxides (NO_x), sulfur dioxide (SO₂), Ammonia (NH₃), and carbon dioxide (CO₂), with adverse impacts on human health and the climate [5,6].

From a lifecycle perspective, construction-related emissions arise from several key stages. First, diesel-fired machinery used in onsite construction and demolition emits NO_x and PM_{2.5} during operations [7]. Second, upstream processes, including power generation, material production, and transportation, generate substantial emissions, specifically in sectors such as clinker, cement, steel, and other non-metallic minerals. These processes release CO₂, SO₂, NO_x, and primary particulate matter (PM) through both fossil-fuel combustion and industrial processes [8–10]. Moreover, during the operational phase of buildings and infrastructure, electricity and heating demand indirectly drive emissions from the power and district-heating sectors [11,12], with rural heating being a major contributor to PM, particularly organic carbon (OC) and black carbon (BC) [13,14]. While construction-related CO₂ emissions have been reported to account for 34–45% of China's total CO₂ emissions [3,15], comprehensive quantification of associated air pollutant emissions remains limited. This gap hinders understanding of the associated health burden, particularly given the construction sector's substantial role in shaping both climate impacts and public health outcomes.

As urban expansion and rural revitalization progress, addressing ambient air pollution and achieving low-carbon development in China's construction sector becomes increasingly challenging. Since 2013, China has made significant strides in controlling air pollution through targeted measures targeting construction-related emission sources, such as power generation [16,17], iron and steel production [10,18], cement manufacture [9,19], and residential energy use [14,20]. As a result, emissions of key pollutants, such as PM_{2.5}, SO₂, and NO_x, from these sources have declined [9,17,18]. However, as many of the most cost-effective measures have already been implemented, further reductions in emissions are becoming increasingly challenging and expensive [10,16,21]. The current policy framework in China's construction sector remains fragmented, with separate approaches to climate change and air pollution [6,22–24]. Moreover, the framework tends to focus on CO₂ mitigation in isolation, neglecting the health impacts of construction-related air pollutant emissions and urban–rural disparities.

In parallel, China has implemented low-carbon development strategies in the construction sector to achieve the nation's dual carbon goals [25], namely, peaking carbon emissions by 2030 and attaining carbon neutrality by 2060 [26]. These strategies include adopting low-carbon materials, transitioning to clean energy, and improving energy efficiency [25,27]. While these measures can effectively reduce carbon emissions, they also present new opportunities to further reduce air pollutant emissions [28–30]. However, most existing studies have focused solely on energy savings or carbon mitigation; few quantify the additional health benefits that can be unlocked when low-carbon actions are aligned with air-quality goals. Additionally, few studies have systematically compared urban and rural construction patterns. This gap in our understanding of the health co-benefits hinders the development of integrated policies for both pollution reduction and carbon mitigation in China [31,32].

To address this gap, we use an integrated modeling framework combining emission estimation, input–output (IO) analysis, inverse atmospheric modeling, and health risk assessment to quantify the health impacts of construction-related air pollution in

China (Supplementary Fig. S1). This framework provides a detailed understanding of the spatiotemporal characteristics of construction-related health burdens while evaluating the co-benefits in terms of premature deaths avoided and CO₂ mitigation. The goal is to provide insights into urban–rural disparities in health burdens linked to construction-related emissions and to quantify the synergies between CO₂ reductions and health benefits. This approach aims to support the development of integrated policies that address both climate change and public health, maximizing the societal and environmental outcomes of mitigation efforts.

2. Methods

2.1. Development of the construction-related emission inventory database

There has been increasing academic scrutiny of emissions from the construction sector and their environmental impacts. Current assessment methods can be broadly categorized into three approaches: (1) life cycle assessment (LCA), which quantifies embodied carbon emissions based on buildings and infrastructure stocks [24,33]; (2) IO models, which examine indirect emissions from construction activities and associated supply chains and are commonly applied in national and regional studies [34,35]; and (3) emission factor methods, which estimate emissions at various stages of construction based on macro-level statistical data [15]. While these methods provide valuable insights, they are constrained by uncertainties arising from incomplete activity data and emission factors, particularly for air pollutants. To mitigate these limitations, our analytical framework integrates IO model with emission factor methods and a detailed database of urban and rural construction activities to quantify construction-related emissions in China. This hybrid approach reduces uncertainties by cross-referencing two complementary approaches: first, IO models that refine the assessment of construction-indirect emissions through top–down constraints from national emission inventories; and second, emission factor methods that incorporate more detailed data on energy consumption in urban and rural construction. This approach establishes a comprehensive database of CO₂ and air pollutant emissions that spans onsite construction, the supply and demand of construction materials, and energy use in building operations. This database will provide critical data to inform policy development and support emission reduction strategies.

This study builds three sub-perspective emission databases for construction-related systems in urban and rural areas across China. We consider CO₂ and seven air pollutant (PM_{2.5}, CO, NO_x, SO₂, OC, BC, and NH₃) emissions, focusing on three main emission scopes: (1) the direct emissions from fossil fuel consumption of onsite construction activities, including construction, demolition, and renovation; (2) the indirect emissions from upstream supply chains linked to building construction activities, including power generation, machinery and equipment manufacturing, and the production, packaging, and transportation of building materials; and (3) the operational emissions from electricity and fuel consumption for heating, cooling, ventilation, lighting, and hot water supply in buildings. The overall methodological framework is presented in Supplementary Fig. S1.

First, we developed a production-based emission inventory for all the economic sectors in China from 2000 to 2019. This inventory was derived from the global emission modeling system (GEMS), a comprehensive high-resolution global emission database covering 149 fuel sub-types in five categories and eight sectors [36–38]. The GEMS provides CO₂ and air pollutant emissions

data across multiple sectors, including power generation, industry, transportation, commercial, and agriculture, as well as for various fuel types, such as coal, oil, natural gas, and biomass (Supplementary Table S1).

Second, the CO₂ and air pollutant emissions from the building operational phase were calculated by the following formula [37,38]:

$$E_t = \sum_{ij} (A_{t,ij} \times EF_{t,ij}) \quad (1)$$

where E represents the CO₂ or air pollutant emissions from the building operational phase; A is the activity level; EF denotes the emission factor; a represents an urban and rural setting; i denotes the energy category (fuel and electricity consumption for building heating, cooling, ventilation, lighting, and hot water supply); and t denotes the year.

Finally, we evaluated the indirect emissions associated with the construction sector using an IO model based on a production-based emission inventory. Provincial construction-indirect CO₂ and air pollutant emissions were constructed using a multi-regional IO (MRIO) table, a widely used approach for tracking emission transfers through goods and services across regional production sectors and final consumption sectors [34,39]. The environmental extended MRIO model can be expressed by introducing emission intensity as follows:

$$E = F(I - A)^{-1}Y \quad (2)$$

where E denotes the matrix of CO₂ or air pollutant emission transfers; $(I - A)^{-1}$ represents the Leontief inverse matrix, with A being the technical coefficient matrix, which reflects the input requirement for producing one unit of output, and I being the identity matrix; F represent the diagonalization matrix of the emission intensity vector for all economic sectors in all provinces; and Y is the final demand matrix. The emission intensity vector F covers 31 provincial-level divisions in China (excluding Taiwan, Hong Kong, and Macao) and includes 42 production sectors (Supplementary Table S2). The final demand matrix Y is categorized into seven components: rural residential consumption, urban residential consumption, government consumption, fixed capital formation, urban construction fixed capital formation, rural construction fixed capital formation, and inventory increase.

Detailed, provincial-specific CO₂ and air pollutant emissions associated with the final construction demand in given urban and rural settings can be calculated using equation (3):

$$E_{con} = F(I - A)^{-1}H \quad (3)$$

where E_{con} represents construction-indirect CO₂ and air pollutant emissions; H is the final construction demand, including urban and rural construction activity demand, quantified as the completed construction fixed capital formation. Capital investment data derived from official expenditure statistics [40] were utilized to distinguish between urban and rural construction demand. These data, including investment in residential buildings, public facilities, and other construction types, enabled analysis of the distinct impacts of urban versus rural construction activities on electricity consumption and building material use. Historical trajectories of urban and rural construction-indirect emissions across China were estimated using the national IO tables. To integrate production-based emissions into the IO framework (Supplementary Table S2), emissions were reallocated to specific sectors based on energy consumption data from the China Energy Statistical Yearbook [41] and the China Energy Inventory [42].

2.2. Estimates of CO₂ and air pollutant emissions from specific-measure

This study conducts an ex post evaluation of changes in CO₂ and air pollutant emissions resulting from mitigation measures implemented in China's construction sector between 2000 and 2019. The assessment is grounded in empirical implementation rates for individual mitigation measures, as documented in official government reports and academic reports. To isolate and quantify the health co-benefits of CO₂ mitigation, we employed a counterfactual scenario approach [43,44] within the GEMS, enabling us to attribute emission changes to specific policy interventions.

Baseline emissions for the period 2000–2020 were established using the GEMS framework, which integrates national statistical data, construction-related activity data, and rural residential energy survey data. For each mitigation strategy, emissions were recalculated under a counterfactual scenario in which the target variable (e.g., fuel mix, boiler consumption, building materials production, industrial technology) was held constant at its 2000 level, while all the other drivers evolved as observed. The difference between baseline and counterfactual emissions was interpreted as the net impact of the targeted measures. The emission changes for targeted measures were estimated with equation (4):

$$\Delta E_{t,i} = \sum_j (\Delta A_{i,j} \times EF_{t,ij} \times (1 - Q_{t,ij})) \quad (4)$$

where $\Delta E_{t,i}$ represents the reduction in CO₂ and air pollutant emissions from sector i attributable to a change in the activity data (energy/industrial products); the index j denotes a specific fuel type (such as, coal, oil, and gas) or industrial products; t denotes the year; ΔA reflects the changes in energy consumption or industrial production volume relative to the 2000 baseline; EF refers to the emission factors for boiler consumption or industrial processes; and Q refers to the removal efficiency for the air pollutants of end-of-pipe control technologies. Similarly, the emissions reduction from other specific measures can be estimated by changes in EF or Q alone, depending on the nature of the intervention.

Finally, we examined four major decarbonization strategies implemented across the construction lifecycle: (1) energy mix transition, involving the substitution of coal with lower-carbon energy sources, such as natural gas and renewables, in both upstream industrial sectors and onsite construction activities; (2) updates to combustion boilers, including the transition from traditional stoves to improved and high-efficiency stoves, aimed at enhancing energy efficiency and pollutant control performance; (3) building material production adjustments, with demand-side strategies aimed at reducing the output of carbon-intensive materials (e.g., cement, iron-steel) through material substitution and low-carbon design; and (4) industrial technology upgrades, involving the adoption of advanced manufacturing processes in building material industries to lower emission intensity per unit of output.

2.3. Health risk assessment using the community multiscale air quality modeling system-adjoint model

In this study, we first estimated the national total of PM_{2.5}-attributable premature deaths using satellite-derived ground-level PM_{2.5} concentrations combined with the global exposure mortality model (GEMM) [44]. The GEMM applies a concentration-response function stratified by sex and 12 adult age groups (Supplementary Table S3), applying the theoretical minimum risk exposure level adopted from Burnett et al. [44] and baseline mortality rates sourced from the global burden of disease

(GBD) study [45]. The GBD baseline mortality database encompasses non-accidental premature deaths from non-communicable diseases (NCDs) and lower respiratory infections (LRIs), which together account for almost all (>99%) non-accidental deaths in the 41 cohorts [44]. The NCD category includes ischemic heart disease, cerebrovascular disease (ischemic stroke and hemorrhagic stroke), lung cancer, and chronic obstructive pulmonary disease, while LRI mortality represents deaths caused by acute infectious pulmonary diseases [45,46]. Detailed computational procedures are provided in Supplementary Text S1.

We then applied an adjoint sensitivity analysis to attribute PM_{2.5}-related premature deaths to construction-related air pollutant emissions. Adjoint sensitivity analysis has been widely used to calculate the sensitivities of air quality, environmental metrics, and premature deaths with respect to pollutant emissions [47–49]. The inverse atmospheric model consists of a forward component based on the standard atmospheric model and a backward (adjoint) component that propagates sensitivities from a receptor (e.g., premature deaths) back to the emissions sources. This backward module efficiently computes the partial derivatives of the objective function with respect to the input conditions. Previous studies have applied this model to quantify the environmental impacts of emission sources on PM_{2.5} concentrations and air pollution-related mortality [48–51].

In this study, we applied the community multiscale air quality modeling system coupled with adjoint (CMAQ-adjoint v.5.0) to quantify the contribution of construction-related emissions to premature deaths associated with ambient PM_{2.5} exposure. The CMAQ-adjoint model covers East Asia using a 124 × 184 grid at a 36-km resolution. The objective function in the adjoint simulation is defined as the anthropogenic PM_{2.5}-related premature deaths associated with long-term PM_{2.5} exposure (detailed calculations in Supplementary Text S2). Model performance and validation procedures have been comprehensively documented in prior work [50]. Anthropogenic emissions were sourced from the GEMS inventory, with the species analyzed including PM_{2.5}, CO, NO_x, SO₂, OC, BC, and NH₃. The CMAQ-adjoint outputs the partial derivatives of premature deaths with respect to anthropogenic emissions across the domain, representing the sensitivities of PM_{2.5}-related premature deaths in the receptor region to emissions from various species, locations, and times.

The semi-normalized sensitivity ($SS_{i,j,k}$) is obtained by combining the sensitivity simulated by the CMAQ-adjoint model with the gridded air pollutant emission [48,49]:

$$SS_{i,j,k} = S_{i,j,k} \times E_{i,j,k} \quad (5)$$

where $SS_{i,j,k}$ represents the relative contribution rate of the emission of species k at model grid cell (i, j) to the total premature deaths attributed to ambient PM_{2.5} exposure. $S_{i,j,k}$ is the sensitivity output from the CMAQ-adjoint model (detailed in Supplementary Text S2), and $E_{i,j,k}$ is the total emission of substance k at (i, j) . Normalizing SS yields the percentage contribution ($P_{i,j,k}$) of a particular emission source to the total number of premature deaths in the target area:

$$P_{i,j,k} = \frac{SS_{i,j,k}}{\sum_i \sum_j \sum_k SS_{i,j,k}} \times 100\% \quad (6)$$

The number of premature deaths (M_c) caused by construction-related air pollutant emissions in China, is obtained as follows:

$$M_c = \sum_i \sum_j \sum_k (P_{i,j,k} \times ER_{i,j,k}) \times M_T \quad (7)$$

where $ER_{i,j,k}$ is the emission rate of species k from specific emission

sources at grid cell (i, j) , representing the share of construction-related emissions in total emissions. M_T is the national total of premature deaths in China.

2.4. Data availability

All input datasets used in this study are publicly available. Estimates of China's CO₂ and air pollutant emissions from primary anthropogenic sources were obtained from the GEMS (<https://gems.sustech.edu.cn>). National IO tables published by the National Bureau of Statistics were used to estimate construction-related indirect emissions and are available for the years 2000, 2005, 2007, 2010, 2012, 2015, 2017, and 2020. Geographic disparities in construction-related emissions across regions and sectors were assessed by combining the GEMS emission inventory with China's MRIO table, sourced from the CEADs database (https://www.ceads.net.cn/data/input_output_tables/). The gridded demographic data used for health impact assessments were obtained from the LandScan Global Population Database (<https://landscan.ornl.gov/>).

3. Results

3.1. Spatial heterogeneity of construction-related premature deaths

The construction-related premature deaths in our study are primarily attributed to air pollutant emissions associated with construction-related systems in China, as outlined in the Method section. Specifically, we categorized construction-related emissions into three stages: (1) direct emissions from onsite construction activities; (2) indirect emissions from power generation and goods and services supporting construction activities; and (3) operational emissions from building heating and electricity supplies. According to the conventional definition, cooking is excluded from construction emission sources [3].

In 2019, construction-induced air pollution was associated with approximately 1.10 million (95% confidence interval [CI]: 0.83–1.37 million) premature deaths in China (M_c), representing 50% (95% CI: 38–62%) of all deaths linked to ambient PM_{2.5} exposure in the country. The contributions of direct, indirect, and operational emissions to overall M_c were 1%, 46%, and 53%, respectively (Fig. 1 and Supplementary Fig. S2). From the perspective of sources, metal production (e.g., steel and metal products) in indirect sources accounted for the largest share of M_c (22%), followed by non-metal materials and petrochemical industries, each contributing 7%. In the operational phase, heating and electricity consumption contributed 31% and 22% to overall M_c , respectively (Fig. 1a). Regarding pollutants, primary PM, mainly from solid fuel use in heating (contributing 23%), along with emissions from metal production (18%), power generation (13%), non-metal material production (6%), and petrochemical industries (6%), accounted for 67% of the overall health burden. Secondary PM precursors, including SO₂ from power generation and heating (16%), NO_x from metal production and power plants (5%), and NH₃ from agriculture and forestry (2%), collectively accounted for 32% of the total (Supplementary Figs. S2–S3).

The premature deaths in this study are attributed to the geographic origins of construction-related emissions, namely, demand-induced mortality. By distinguishing urban and rural construction emissions, we found that urban areas were responsible for 0.81 million premature deaths (95% CI: 0.61–1.00 million), representing 74% of the total M_c (Supplementary Figs. S2–S3), whereas rural regions accounted for 0.29 million deaths (95% CI: 0.22–0.36 million) or 26% of the M_c (Supplementary Fig. S3). Consequently, M_c intensities (MI_c), defined as the number of

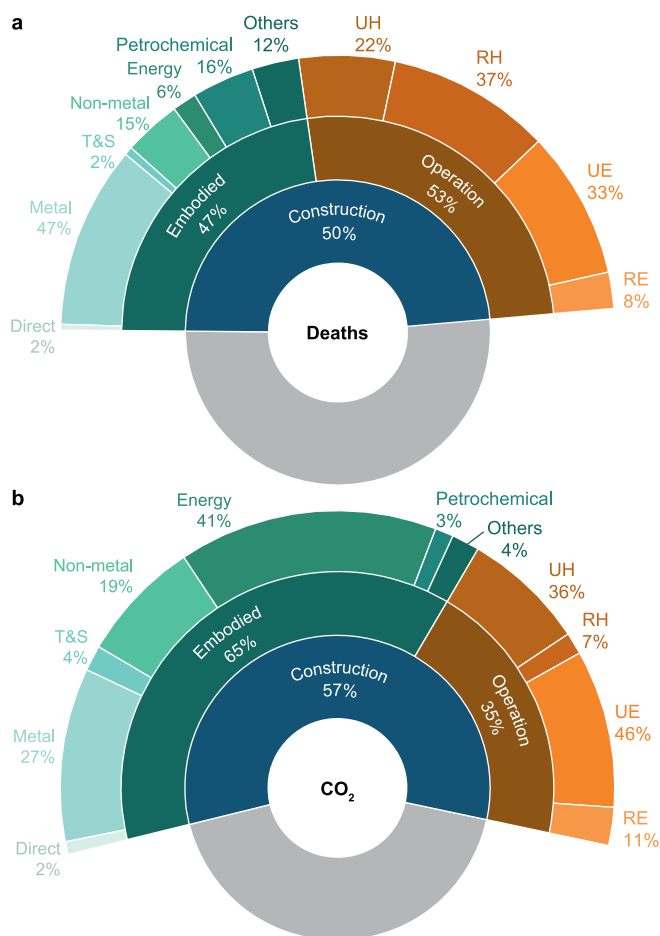


Fig. 1. Sectoral breakdown of construction-related premature deaths and CO₂ emissions in China for 2019. **a.** Premature deaths. **b.** CO₂ emissions. Results are disaggregated into embodied (direct and indirect) and operational (heating and operation) stages. Energy: production of electricity, heat, gas, and water; Metal: metal smelting and production; Non-metal: production of cement, brick, plaster, ceramics, etc.; Petrochemical: processing of petroleum, coking, and chemical products; Others: other industrial sectors excluding metal, non-metal, and petrochemical as well as agriculture and services; T&S: transportation and storage. Operational energy use is further separated into urban heating (UH) and urban electricity (UE), and rural heating (RH) and rural electricity (RE). The grey segment of the inner ring represents the contribution of non-construction-related sectors to China's total anthropogenic source.

annual premature deaths per unit building area, were estimated at 19 and 13 deaths km⁻² in urban and rural areas, respectively, indicating comparable health impacts across the two settings (Supplementary Fig. S4).

However, the spatial distributions of MI_c presented notable disparities between the two settings. Across China, rural MI_c showed a pronounced north-to-south gradient, in contrast to the more uniform distribution observed in urban MI_c (Supplementary Fig. S4). In the rural Northeast, the average MI_c reached 58 deaths km⁻²—4.5 times the rural average (13 deaths km⁻²) and approximately 7.3- and 13.5-fold higher than on the rural Southwest (7 deaths km⁻²) and Southeast coasts (4 deaths km⁻²), respectively (Supplementary Fig. S5). Elevated MI_c was also observed on the rural Northern coast (26 deaths km⁻²) and in the Northwest (23 deaths km⁻²). The higher MI_c in northern regions primarily stems from the extensive use of solid fuels for residential heating in winter, leading to substantial air pollutant emissions and accounting for 0.18 million premature deaths annually or 84% of the

total M_c in northern rural areas (Supplementary Figs. S6–S7).

Conversely, the adoption of central heating systems has markedly mitigated the disparities in urban MI_c between the Northern and Southern regions (Supplementary Fig. S4). The north-to-south MI_c ratio in urban areas was 1.8, which was much lower than that in rural areas (4.7). Although the Chinese government has implemented central heating systems in northern provinces, the widespread reliance on inefficient solid-fuel combustion for heating caused serious health-damaging air pollution [13,52,53]. In 2017, the government launched a comprehensive initiative to replace solid fuel use in the Beijing–Tianjin region, later extending these measures to surrounding areas through coal-to-electricity and coal-to-clean-fuel programs [20]. We estimated that a counterfactual scenario in which urban heating systems relied on the same energy mix as in rural areas could lead to an additional 0.20 million premature deaths annually, with the north-to-south MI_c ratio in urban settings rising to 2.2. These findings underscore the efficiency of clean heating policies in mitigating air quality-related health impacts and reducing regional inequalities.

3.2. Historical trends of construction-related health impacts

The differences in the spatial patterns of the urban and rural MI_c underscore distinct driving forces behind construction emissions and related health outcomes in these settings. In rural areas, operational emissions, especially heating, predominantly drive construction emissions, constituting 72% of the total rural M_c (Fig. 2c). Conversely, indirect emissions from the production of building materials, including petrochemicals, non-metals, and metals, serve as the primary contributors to urban construction emissions, representing 60% of the total urban M_c (Fig. 2a and b). These divergent emission drivers between urban and rural M_c have important health implications, given China's swift urbanization. In 2000, the national total M_c was valued at 1.21 million (95% CI: 0.94–1.46), with urban areas contributing 55% and rural areas 45% to this total (Supplementary Fig. S3). From 2000 to 2008, rural M_c saw a modest increase (13%), while urban M_c surged by 95%, fueled by extensive urban expansion (Fig. 2a). This urbanization led to an increased urban share of 68% of the national M_c by 2008 and an overall rise of 59% in national M_c , which peaked at 1.92 million (95% CI: 1.48–2.37) in 2008.

Between 2008 and 2019, China's M_c experienced a significant decline (43%), with reductions in both urban (38%) and rural (52%) areas (Fig. 2a–c). In urban areas, the initial decline in M_c was mainly attributed to the widespread installation of flue gas desulfurization (FGD) systems in coal-fired power plants and other major industrial sectors [17,54], which curtailed construction-related SO₂ emissions by 42% between 2008 and 2013 (Supplementary Fig. S8). This decline in SO₂ emissions resulted in a decrease of 97,000 (95% CI: 91,600–102,100) premature deaths, equivalent to 64% of the total reduction (Supplementary Fig. S2). Among these health benefits, power plants registered 72,000 (95% CI: 67,200–77,700) avoided premature deaths, while the figures for non-metallic material production and petrochemical industries were 11,000 (95% CI: 5960–16,500) and 4200 (95% CI: 1590–6870), respectively (Supplementary Fig. S9).

From 2013, a second phase of urban M_c reduction took place, driven by the implementation of China's Air Pollution Action Plan [55], which imposed stricter emission standards on energy-intensive sectors. Key measures included deploying end-of-pipe control technologies in iron and steel production [10,18], transitioning to dry-process cement manufacturing [27], enforcing ultra-low emissions standards in coal-fired power plants [16], and decommissioning outdated industrial facilities [56]. These interventions drove substantial declines in construction-related

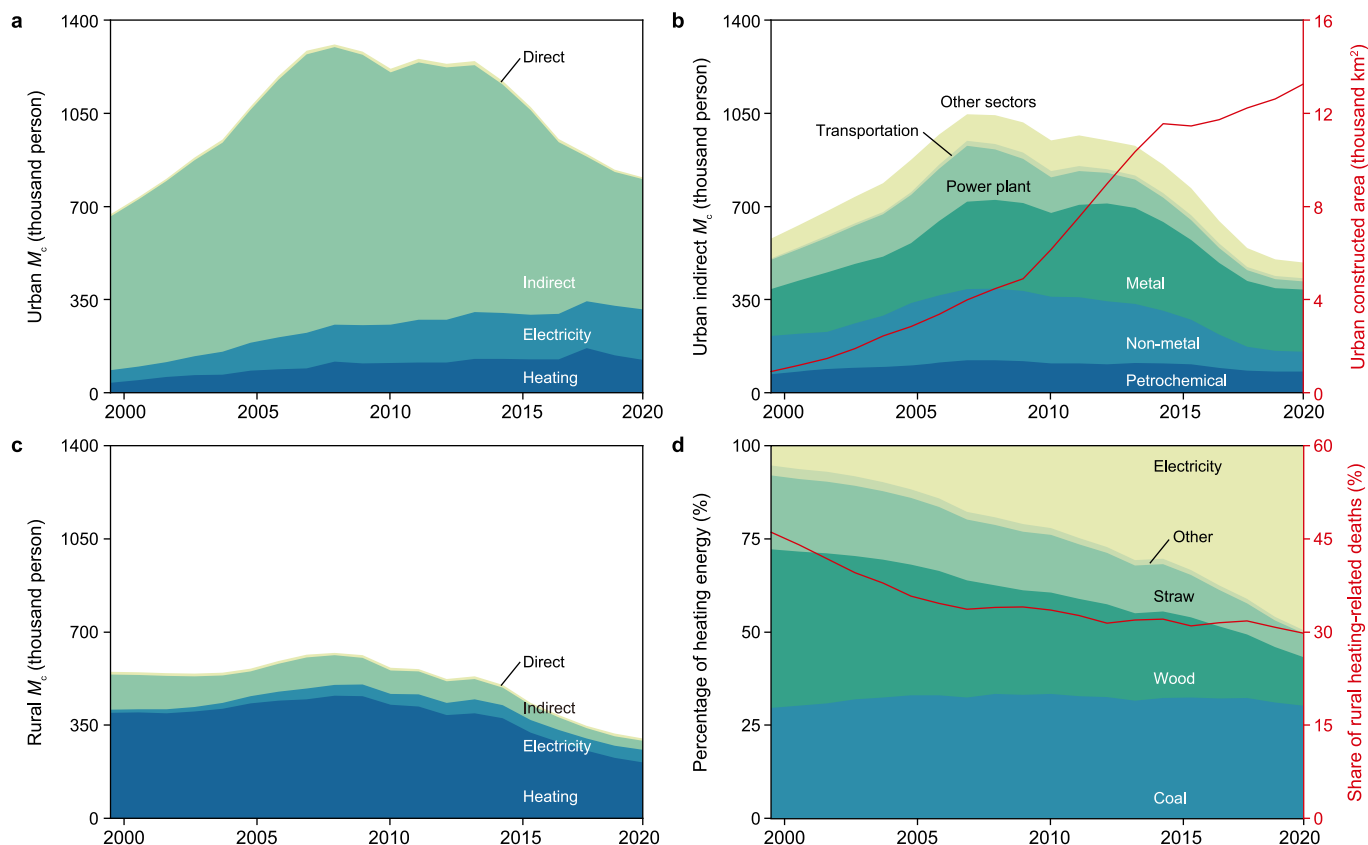


Fig. 2. Trends in premature deaths attributable to construction-related air pollution and associated factors across China from 2000 to 2019. **a,c,** Premature deaths associated with the three scopes of the construction-related emissions, i.e., direct, indirect, and operational emissions, in urban (**a**) and rural (**c**) areas. **b,** Premature deaths attributable to indirect construction emissions (left axis) and the expansion of newly constructed urban areas (right axis) in urban regions. **d,** Percentage of energy consumption from residential heating (left axis) in rural areas and its share within overall construction-related premature deaths (right axis).

indirect emissions between 2013 and 2019: SO_2 (−54%), NO_x (−33%), BC (−29%), OC (−33%), and other PM components (−44%) (Supplementary Fig. S10). Correspondingly, urban M_c decreased by 48%, equivalent to 0.44 million (0.33–0.54 million) avoided premature deaths annually, accounting for 65% of the total M_c reduction during this period (Supplementary Fig. S2).

The decline in rural M_c was predominantly driven by the transition toward cleaner residential heating energy (Fig. 2c). Between 2008 and 2017, rural households progressively shifted from solid fuel combustion to electric heating (Fig. 2d), a trend enabled by improved economic conditions and rising living standards that expanded access to clean energy alternatives [57,58]. Post-2017, the Clean Winter Heating Plan in northern China further accelerated this shift through targeted government subsidies and infrastructure investments [14]. Collectively, these measures reduced the rural heating-related emissions of BC (−42%), OC (−43%), NO_x (41%), and SO_2 (−18%) between 2008 and 2019 (Supplementary Figs. S7–S8). This change resulted in a 54% reduction in M_c linked to rural residential heating, or approximately 0.25 million deaths avoided annually (95% CI: 0.20–0.30 million), underscoring the health dividends of modernizing the energy mix in rural regions.

3.3. Drivers of CO_2 reduction co-benefits in the construction sector

We evaluated the health co-benefits (premature death avoidance) of targeted CO_2 mitigation measures in China's construction sector, including modernizing the energy mix, advancing combustion technology, adjusting building material production, and

upgrading production processes. Between 2000 and 2019, construction-related CO_2 emissions increased 2.4-fold, reaching 6.5 Pg (95% CI: 4.6–8.7 Pg) in 2019 and accounting for 59.4% of China's anthropogenic total. Using the GEMS [36,37,59], we quantified changes in CO_2 emissions and mortality attributable to each intervention relative to a 2000 baseline. Accordingly, the avoided premature deaths and CO_2 reductions associated with construction reported in this section represent changes relative to the baseline year. The analysis depicted outcomes across three phases: rapid urbanization (2000–2008), decoupling (2008–2015), and early low-carbon transition (2015–2019).

During China's rapid urbanization phase (2000–2008), construction-related CO_2 emissions increased by 130% compared to 2000, and there was a 45% rise in premature deaths, equating to 0.56 million deaths (95% CI: 0.23–0.89 million; Fig. 3a and Supplementary Fig. S11) annually. Industrial production expansion alone, fueled by rising building material outputs, resulted in a 71% growth in CO_2 emissions and a 44% surge in deaths (0.55 million, 95% CI: 0.23–0.87 million). Among these industrial processes, non-metal and metal-related material production contributed significantly, triggering 17% and 14% growth in CO_2 emissions and 19% (0.23 million; 95% CI: 0.10–0.37 million) and 11% (0.14 million; deaths 95% CI: 0.06–0.22 million) increments in premature deaths, respectively (Supplementary Fig. S12). Fossil fuel dependency followed, driving a 58% increase in CO_2 emissions and a 16% rise in mortality (0.20 million, 95% CI: 0.08–0.31 million; Fig. 3b) that is primarily attributable to rising coal usage, which alone caused a 55% growth in CO_2 emissions and a 21% rise in

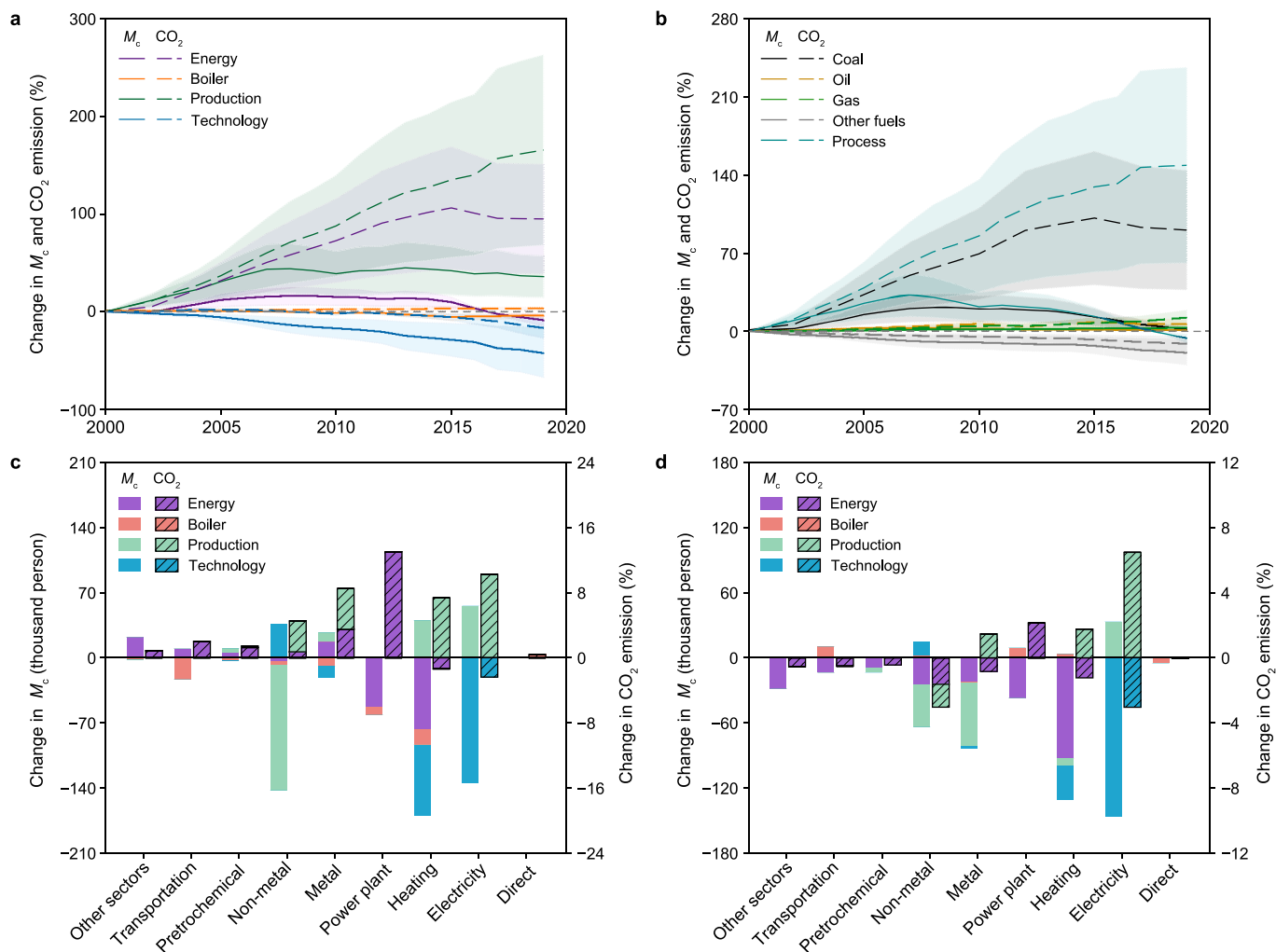


Fig. 3. Impacts of targeted measures on premature deaths and CO₂ emissions in China's construction sector. **a**, Annual relative changes (relative to 2000 baseline) in premature deaths and CO₂ emissions across mitigation measures. **b**, Stratified analysis of outcomes by fuel type and production processes (relative to 2000 baseline), distinguishing energy-related drivers (fuel consumption and combustion boiler upgrades) from process-related drivers (building materials production and industrial technologies). Shaded areas represent 95% confidence intervals. **c–d**, Changes in premature deaths and CO₂ emissions during 2008–2015 (**c**) and 2015–2019 (**d**). Key drivers are defined as follows: “Energy” corresponds to energy mix adjustments, “Boiler” denotes combustion boiler upgrades, “Production” denotes building material changes and substitution, “Technology” reflects manufacturing technology innovations, and “Process” represents the combined effects of “Production” and “Technology.” Annual premature deaths under different scenarios, along with their uncertainties, are shown in [Supplementary Tables S4 and S5](#).

mortality. However, reductions in biomass fuel use (−9%) and improvements in production technologies (−13%), such as the phase-out of open-hearth steelmaking in the iron–steel sector [60] and the elimination of small-capacity rotary kilns in the cement industry [9], partially offset these adverse health impacts ([Supplementary Fig. S12](#)).

The decoupling phase (2008–2015) witnessed a marked divergence: CO₂ emissions surged by 108% relative to 2008, while premature deaths declined by 29% (equating to 0.36 million deaths averted, 95% CI: 0.15–0.56 million). This decoupling was due to carbon-intensive industries adopting stringent pollution control measures during this period ([Fig. 3c](#)). For instance, the adoption of selective catalytic reduction technologies and enhanced coal quality in coal-fired power plants reduced air pollutants, averting 62,000 (95% CI: 26,000–98,000) deaths despite a 13% increase in CO₂ emissions ([Supplementary Fig. S12](#)). Similarly, metal and non-metal production processes—both carbon-intensive, being dependent on coke consumption and limestone calcination—yielded moderate growth in CO₂ emissions (+5% and +4%, respectively) but reduced health impacts (3600 and 97,000 deaths

averted, respectively). This change can be attributed to processes that contribute significantly to CO₂ from the thermal decomposition of limestone and coke reduction of iron ore, but release relatively fewer pollutants. End-of-pipe controls (e.g., FGD and dust removal systems) further exacerbated CO₂ emissions by raising energy demand [61]. In addition to upstream industries, operational emissions from residential heating exhibited decoupling (CO₂: +6%; deaths averted: 0.13 million, 95% CI: 0.05–0.20 million), driven by the adoption of cleaner centralized heating systems in urban areas and energy mix transitions in rural areas ([Supplementary Fig. S12](#)).

Between 2015 and 2019, construction-related premature deaths declined by 29% (0.45 million deaths avoided, 95% CI: 0.19–0.72 million) compared to 2015, while CO₂ emissions rose modestly (2%) ([Supplementary Fig. S11](#)). Indirect CO₂ emissions decreased by 2%, though rising electricity and heating demand partially counteracted this decline ([Supplementary Fig. S11c](#)). Sectoral co-benefits analysis identified energy mix optimization and industrial technology modernization as the most effective mitigation strategies ([Fig. 3d](#)), jointly reducing CO₂ emissions by

Table 1
Description of designed intervention scenarios.

Scenario	Sub-scenarios	Description	
		Weak strategies	Strong strategies
Baseline	BAU	Business as usual	Business as usual
Energy consumption	EC1	Coal-fired power plants: share decreases by 20%	Coal-fired power plants: share decreases by 50%
	EC2	Industrial coal use decreases by 15%	Industrial coal use decreases by 40%
	EC3	Ultra-low emission units: 90% PC, 10% CFB	Ultra-low emission units: 80% PC, 20% CFB
	EC4	CFB and PC units account for 15% of industrial boilers	CFB and PC units account for 30% of industrial boilers
	EC5	Rural heating: coal and biomass use reduced by 20% and 30%, respectively; electricity use increases by 50%	Rural heating: coal use is halved, biomass is nearly eliminated, and electricity consumption is doubled
Industrial processes	IP1	Cement substitution rate with alternative materials reaches 25%	Cement substitution rate with alternative materials reaches 50%
	IP2	Precalciner technology adopted in 100% of cement kilns	Precalciner technology adopted in 100% of cement kilns
	IP3	Electric arc furnaces account for 40% of iron–steel production	Electric arc furnaces account for 60% of iron–steel production

6.1% and averting 0.40 million (95% CI: 0.16–0.63 million) deaths, equivalent to 6.2% and 36% of the total construction-related CO₂ emissions and mortality in 2019. Within non-metallic material production, reduced coal dependency and the substitution of carbon-intensive materials with sustainable alternatives (e.g., high-strength steel, precast concrete, wood structures, and recyclable materials [25,61,62]), lowered CO₂ emissions by 1.6% and 1.4%, respectively, preventing 25,200 (95% CI: 10,400–40,000) and 38,800 (95% CI: 16,000–61,600) deaths, respectively. The metal sector exhibited similar synergies: energy mix improvements reduced emissions by 0.8% and averted 22,400 (95% CI: 9200–35,600) deaths, despite production-driven CO₂ increases (+1.5%). Conversely, surging electricity demand for building operations worsened both climate and health outcomes (+6.5% CO₂; 33,100 deaths, 95% CI: 13,600–52,600), highlighting the imperative to decarbonize electricity generation—particularly coal-fired power—to advance low-carbon transitions in the construction sector.

3.4. Synergistic effect of low-carbon transitions in the construction sector

We employed scenario-based simulations to assess whether targeted intervention strategies designed to reduce CO₂ emissions

and related health impacts could yield synergistic benefits in China's construction sector. The scenarios encompassed measures targeting energy consumption (EC1–5) and industrial processes (IP1–3) across the construction lifecycle, including the iron–steel industry, cement production, coal-fired power plants, and rural heating (Table 1). Two levels of policy ambition, weak and strong interventions, were evaluated relative to a business-as-usual (BAU) baseline. The avoided premature deaths and CO₂ reductions reported here represent changes relative to the BAU conditions in 2019. A detailed description of the intervention pathways is provided in Supplementary Text S3.

Our results reveal substantial co-benefits from decarbonization: the total construction-related CO₂ emissions would be reduced by 9.4% and 20.7% under weak and strong interventions, respectively, while premature deaths would decrease by 0.08 million (95% CI: 0.03–0.13 million) and 0.16 million (95% CI: 0.07–0.26 million), respectively (Fig. 4). Among all sub-scenarios, strategies targeting energy consumption, particularly EC1 (reducing the share of coal-fired power plants) and EC2 (cutting industrial coal use), would produce the most pronounced synergies. Under weak EC1 interventions, emissions would fall by 5.6%, with 17,700 (95% CI: 7300–28,000) premature deaths avoided; under strong EC1 interventions, these values would increase to 13.7% and 39,700 (95% CI: 16,400–63,100), respectively (Fig. 4a and b). These benefits reflect the sector's continued dependence on coal-powered electricity and industrial energy (Fig. 3b and Supplementary Fig. S12). By contrast, interventions targeting industrial processes (IP1–3) would yield modest synergies, particularly under weak policies. In the cement industry, increasing substitution with low-carbon material (IP1) and promoting precalciner technology (IP2) would together result in a 1.6% decrease in CO₂ emissions and 7600 (95% CI: 3000–12,000) avoided deaths; these values would double under strong interventions (3.2% reduction; 15,000 avoided deaths, 95% CI: 6200–23,800). In the steel sector, increasing electric arc furnace production under strong strategies would only lead to a 0.2% CO₂ reduction and 1400 (95% CI: 577–2200) avoided deaths. These findings suggest that further technological innovation, such as hydrogen-based direct-reduction steelmaking, coupled with strong policy enforcement, is needed to unlock comparable benefits in material production.

The EC5 scenario, which targets rural heating through changes in energy mix, reveals a notable decoupling between climate and health benefits. In rural settings, replacing coal and biomass with electricity or other cleaner energy sources significantly reduces premature deaths while leading to a modest increase in CO₂ emissions. Under weak interventions entailing a 20% reduction in coal use and a 30% reduction in biomass, approximately 4800 (95% CI: 2000–7600) premature deaths can be avoided. Stronger interventions, which eliminate biomass use and halve coal

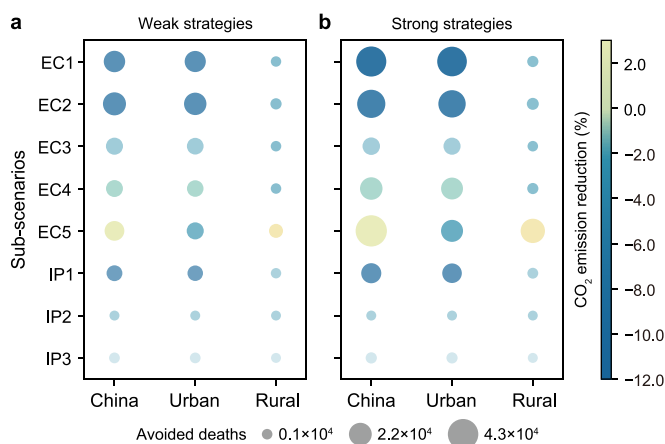


Fig. 4. Synergies between avoided deaths and CO₂ emissions reductions from the construction sector under different intervention strategies. a, b, Changes in premature deaths and CO₂ emissions under weak (a) and strong (b) intervention scenarios relative to business as usual. The analysis integrates the energy consumption (EC1–5) and industrial processes (IP1–3) associated with China's construction sector. Each scenario incorporates sub-scenarios that reflect the impacts of specific strategies on key emission-intensive sectors, including iron–steel, cement, coal-fired power plants, and heating (Table 1). Bubble color encodes CO₂ emission reductions, and bubble size indicates the number of premature deaths avoided. Estimates and associated uncertainties are provided in Supplementary Table S6.

consumption, yield health benefits up to fivefold greater, avoiding an estimated 24,000 (95% CI: 9900–38,000) deaths. However, escalating electricity demand associated with heating leads to a net rise in CO₂ emissions: 1.5% under weak interventions and 2.6% under strong ones. These results underscore the critical importance of identifying clean heating alternatives to enable a low-carbon transition in rural construction. In contrast, urban operational electricity use continues to deliver synergistic benefits, driven by the declining share of coal in the electricity generation mix. Under weak and strong interventions, CO₂ emissions are reduced by 0.9% and 1.8%, respectively, while 9500 (95% CI: 3900–15,000) and 19,000 (95% CI: 7800–30,000) premature deaths are avoided.

4. Discussion

Our analysis quantifies CO₂ emissions and air quality-related health burdens associated with construction in China, providing new evidence on the health co-benefits of decarbonizing this sector. We demonstrate that the construction sector accounts for half of China's total annual ambient PM_{2.5}-attributable mortality and three-fifths of its total anthropogenic CO₂ emissions (Fig. 1). Consequently, decarbonizing this sector represents a crucial opportunity to advance China's dual carbon goals while simultaneously improving public health outcomes.

China's construction sector, historically reliant on fossil fuels, has seen significant shifts, including a decoupling of CO₂ emissions and health burdens (2008–2015) and subsequent synergy (2015–2019). Early successes in reducing health burdens were driven by the boiler upgrades and implementation of end-of-pipe controls in the coal power, cement, and steel industries and the transition to cleaner rural heating (Fig. 2). Low-carbon transitions in recent years have conferred notable health co-benefits, chiefly via changes in the energy mix and production technologies within the industrial and power sectors (Fig. 3d). These findings delineate priorities for China's subsequent efforts to achieve a carbon-neutral construction sector.

In rural China, construction-related mortality is dominated by operational emissions from residential heating (Fig. 2c). In Northern coastal and Northeastern rural regions, heating alone accounts for 58 and 46 deaths per million people, respectively, far exceeding the impacts of indirect emissions (6 and 3 deaths per million; Supplementary Fig. S13). These figures reflect both the intensity of household solid fuel use and the vulnerability of rural residents to localized heating-related PM_{2.5} exposure. Recent government-led clean heating initiatives in northern regions [14,20] have generated significant climate and health co-benefits by substituting coal and biomass with cleaner energy sources (Fig. 3d). However, while further modernization of the energy mix (Scenario EC5) could avert 4800–24,000 deaths annually under weak-to-strong intervention scenarios, its reliance on grid electricity risks exacerbating CO₂ emissions (Fig. 4). This underscores an unresolved tension between near-term health gains and long-term decarbonization goals. Achieving a sustainable rural energy transition requires synergistic strategies beyond fuel-switching alone. These include (1) scaling highly efficient biomass pellet boilers, (2) deploying solar thermal systems and biogas systems, and (3) accelerating the uptake of air-to-air heat pumps, which are emerging as a key technology for low-carbon heating in cold regions [63–65]. These measures simultaneously mitigate air pollution, reduce carbon footprints, and address spatial mismatches in energy access.

In contrast, urban construction-related mortality is predominantly driven by indirect emissions from upstream industrial processes. Petrochemicals, non-metallic minerals, metals, and

power generation together account for 60% of the sector's urban health burden (Fig. 2b). Mitigating these supply-chain-wide emissions remains a persistent challenge for sustainable urbanization. Urban centers externalize environmental costs onto marginalized upstream regions that host energy generation and industrial activities. For example, in Northern coastal regions, urban construction-indirect emissions account for 78 deaths per million people, while the impacts from central heating and electricity use account for 66 and 29 deaths per million, respectively (Supplementary Fig. S13). This systemic spatial inequity underscores the need to integrate justice frameworks into decarbonization strategies. Long-term solutions include (1) scaling green building materials (e.g., precast concrete components, steel structures, modular assemblies, and recyclable composites) to reduce lifecycle emissions [25,62]; (2) deploying distributed energy systems, such as rooftop photovoltaics, to decouple energy demand from centralized grids [66]; and (3) repurposing underutilized urban infrastructure and dwelling units to curb material-intensive new construction [67,68].

From a sectoral perspective, modernizing the energy mix in both the electricity and industrial sectors offers the most substantial climate and health co-benefits. Expanding renewable energy sources such as wind, solar, and hydro, alongside reducing reliance on coal-fired power plants, can achieve synergistic emission reductions (Fig. 4). Within steel production, which remains predominantly reliant on blast furnace-basic oxygen furnace (90% of production in 2020) [69], significant mitigation could be achieved through a transition to electric arc furnaces and green hydrogen direct reduction technologies, which are currently responsible for less than 10% of production. Accelerating this transition would also incentivize the use of steel structures and prefabricated materials, curbing reliance on energy-intensive materials such as cement. Furthermore, deploying carbon capture and storage in heavy industries and scaling carbon-sequestering building materials (e.g., biogenic carbon and carbonate mineral materials) would reduce both CO₂ and pollutant emissions [70,71]. Integrating these energy and industrial transitions with public health priorities positions China's construction sector to deliver marked declines in both carbon footprints and public health burdens.

Health benefits associated with reductions in PM_{2.5} exposure in our studies are estimated using the GEMM, which is based on long-term cohort studies and captures persistent chronic health effects. Short-term time-series and experimental studies have shown that increases in ambient PM_{2.5} can cause measurable rises in cardiopulmonary events within days to months [72,73]. For instance, cardiovascular hospital admissions are typically associated with shorter pollutant lags, whereas respiratory admissions exhibit larger effects at longer lags [73]. In contrast, long-term cohort evidence indicates that a portion of avoided premature deaths arises from cumulative exposure reduction and slower disease progression, unfolding over multiple years [44,45]. Accordingly, our estimates represent steady-state annual health impacts under each emission scenario, with full health benefits likely to accrue gradually as cumulative exposure declines. This study does not explicitly model temporal adjustment dynamics, which may lead us to overlook near-term health gains. Future work incorporating dynamic exposure–response relationships would enhance the temporal accuracy and policy relevance of health impact assessments.

5. Conclusion

In this study, we developed an integrated framework to quantify the CO₂ emissions and PM_{2.5}-related mortality burdens

associated with China's construction-related system and to evaluate the potential health co-benefits of sectoral decarbonization. Our analysis reveals that construction-related activities, spanning upstream industrial production, onsite operations, and building energy use, constitute a major driver of both national CO₂ emissions and PM_{2.5}-attributable premature deaths, with substantial spatial heterogeneity between urban and rural areas. Over the past two decades, policy measures have shifted the sector from pollution-intensive growth toward partial decoupling and early low-carbon transition, demonstrating that coordinated controls can simultaneously reduce health burdens and curb emissions. Scenario analysis further indicates that interventions targeting the energy mix and industrial technologies offer the greatest synergistic mitigation potential in urban areas. Furthermore, rural clean-heating policies must be paired with power sector decarbonization to avoid counteracting CO₂ increases. These findings highlight the construction sector as a strategic leverage point for China's integrated "pollution reduction and carbon mitigation" agenda. Prioritizing structural changes in upstream industries, accelerating clean energy transitions, and designing differentiated urban-rural pathways will be essential to maximize public health gains while advancing the nation's dual-carbon goals.

CRediT authorship contribution statement

Zhanxiang Wang: Writing - Review & Editing, Writing - Original Draft, Visualization, Validation, Investigation, Formal Analysis. **Huizhong Shen:** Writing - Review & Editing, Writing - Original Draft, Visualization, Supervision, Funding Acquisition, Conceptualization, Formal Analysis, Investigation, Methodology, Validation. **Ruixin Zhang:** Writing - Review & Editing, Methodology, Validation. **Ruibin Xu:** Data Curation, Methodology, Validation, Visualization, Writing - Review & Editing. **Peng Guo:** Writing - Review & Editing, Methodology, Data Curation, Validation, Visualization. **Zhiyu Zheng:** Writing - Review & Editing, Validation, Methodology, Visualization. **Jinling He:** Writing - Review & Editing, Methodology, Data Curation, Validation. **Siqi Wu:** Writing - Review & Editing, Conceptualization, Software. **Yilin Chen:** Writing - Review & Editing, Conceptualization, Software. **Dong Xie:** Writing - Review & Editing, Conceptualization, Data Curation. **Jinjian Zhang:** Writing - Review & Editing, Conceptualization, Data Curation, Software. **Lianming Zheng:** Writing - Review & Editing, Methodology, Software. **Hang Su:** Writing - Review & Editing, Conceptualization, Software. **Dabo Guan:** Writing - Review & Editing, Conceptualization, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Dr. Huizhong Shen, an Editorial Board Member of *Environmental Science and Ecotechnology*, was not involved in the editorial review or the decision to publish this article.

Acknowledgments

This research is supported by the National Natural Science Foundation of China (42330709), National Key R&D Program of China (2023YFE0112901), Shenzhen Science and Technology Program (KQTD20240729102048052), the National Natural Science Foundation of China (42475108, 42192512, and 42571087), the European Union's Horizon Europe research and innovation program (101137905), Shenzhen Science and Technology Program (JCYJ20241202152804007 and JCYJ20220818100611024),

Guangdong Provincial Field Observation and Research Station for Coastal Atmosphere and Climate of the Greater Bay Area (2021B1212050024), High-level Special Funds (G03034K006), and Center for Computational Science and Engineering at Southern University of Science and Technology.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ese.2026.100666>.

References

- [1] W. Wei, J. Li, B. Chen, M. Wang, P. Zhang, D. Guan, et al., Embodied greenhouse gas emissions from building China's large-scale power transmission infrastructure, *Nat. Sustain.* 4 (8) (2021) 739–747, <https://doi.org/10.1038/s41893-021-00704-8>.
- [2] T. Huo, X. Li, W. Cai, J. Zuo, F. Jia, H. Wei, Exploring the impact of urbanization on urban building carbon emissions in China: evidence from a provincial panel data model, *Sustain. Cities Soc.* 56 (2020) 102068, <https://doi.org/10.1016/j.scs.2020.102068>.
- [3] Professional Committee of Building Energy and Emissions, CABEE, China Building Energy Consumption and Carbon Emissions Research Report, CABEE, Chongqing, 2022 (in Chinese), 2022.
- [4] Professional Committee of Building Energy and Emissions, CABEE, China Building Energy Consumption and Carbon Emissions Research Report, CABEE, Chongqing, 2016 (in Chinese), 2016.
- [5] Y. Chen, H. Shen, G. Shen, J. Ma, Y. Cheng, A.G. Russell, et al., Substantial differences in source contributions to carbon emissions and health damage necessitate balanced synergistic control plans in China, *Nat. Commun.* 15 (1) (2024) 5880, <https://doi.org/10.1038/s41467-024-50327-8>.
- [6] A. Huang, W. Cheng, L. Zhang, G. Wang, P. Guan, T. Cai, et al., Quantifying embodied energy consumption and air pollutant emissions in China's real estate development in 2000–2020, *Environ. Impact Assess. Rev.* 108 (2024) 107616, <https://doi.org/10.1016/j.eiar.2024.107616>.
- [7] W. Cai, L. Wan, Y. Jiang, C. Wang, L. Lin, Short-lived buildings in China: impacts on water, energy, and carbon emissions, *Environ. Sci. Technol.* 49 (24) (2015) 13921–13928, <https://doi.org/10.1021/acs.est.5b02333>.
- [8] X. Zhang, F. Wang, Hybrid input-output analysis for life-cycle energy consumption and carbon emissions of China's building sector, *Build. Environ.* 104 (2016) 188–197, <https://doi.org/10.1016/j.buildenv.2016.05.018>.
- [9] J. Liu, D. Tong, Y. Zheng, J. Cheng, X. Qin, Q. Shi, et al., Carbon and air pollutant emissions from China's cement industry 1990–2015: trends, evolution of technologies, and drivers, *Atmos. Chem. Phys.* 21 (3) (2021) 1627–1647, <https://doi.org/10.5194/acp-21-1627-2021>.
- [10] J. Zhang, H. Shen, Y. Chen, J. Meng, J. Li, J. He, et al., Iron and steel industry emissions: a global analysis of trends and drivers, *Environ. Sci. Technol.* 57 (43) (2023) 16477–16488, <https://doi.org/10.1021/acs.est.3c05474>.
- [11] K. Li, M. Ma, X. Xiang, W. Feng, Z. Ma, W. Cai, et al., Carbon reduction in commercial building operations: a provincial retrospective in China, *Appl. Energy* 306 (2022) 118098, <https://doi.org/10.1016/j.apenergy.2021.118098>.
- [12] W. Zhang, X. Yun, W. Meng, H. Xu, Q. Zhong, X. Yu, et al., Urban residential energy switching in China between 1980 and 2014 prevents 2.2 million premature deaths, *One Earth* 4 (11) (2021) 1602–1613, <https://doi.org/10.1016/j.oneear.2021.10.013>.
- [13] X. Yun, G. Shen, H. Shen, W. Meng, Y. Chen, H. Xu, et al., Residential solid fuel emissions contribute significantly to air pollution and associated health impacts in China, *Sci. Adv.* 6 (44) (2020), <https://doi.org/10.1126/sciadv.aba7621>.
- [14] W. Meng, Q. Zhong, Y. Chen, H. Shen, X. Yun, K.R. Smith, et al., Energy and air pollution benefits of household fuel policies in northern China, *Proc. Natl. Acad. Sci. USA* 116 (34) (2019) 16773–16780, <https://doi.org/10.1073/pnas.1904182116>.
- [15] Z. Zhang, B. Wang, Research on the life-cycle CO₂ emission of China's construction sector, *Energy Build.* 112 (2016) 244–255, <https://doi.org/10.1016/j.enbuild.2015.12.026>.
- [16] L. Tang, J. Qu, Z. Mi, X. Bo, X. Chang, L.D. Anadon, et al., Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards, *Nat. Energy* 4 (11) (2019) 929–938, <https://doi.org/10.1038/s41560-019-0468-1>.
- [17] G. Wang, J. Deng, Y. Zhang, Q. Zhang, L. Duan, J. Hao, et al., Air pollutant emissions from coal-fired power plants in China over the past two decades, *Sci. Total Environ.* 741 (2020) 140326, <https://doi.org/10.1016/j.scitotenv.2020.140326>.
- [18] X. Wang, Y. Lei, L. Yan, T. Liu, Q. Zhang, K. He, A unit-based emission inventory of SO₂, NO_x and PM for the Chinese iron and steel industry from 2010 to 2015, *Sci. Total Environ.* 676 (2019) 18–30, <https://doi.org/10.1016/j.scitotenv.2019.04.241>.
- [19] Y. Wang, H. Yi, X. Tang, Y. Wang, H. An, J. Liu, Historical trend and decarbonization pathway of China's cement industry: a literature review, *Sci. Total Environ.* 891 (2023) 164580, <https://doi.org/10.1016/j.scitotenv.2023>.

- 164580.
- [20] Ministry of Ecology and Environment of the People's Republic of China, Air Pollution Prevention and Control Plan of Beijing, Tianjin, Hebei and Surrounding Areas in 2017, Ministry of Ecology and Environment, Beijing, 2017 [in Chinese]. https://www.mee.gov.cn/ywdt/hjywnews/201703/t20170330_409037.shtml.
- [21] T. Zhu, X. Liu, X. Wang, H. He, Technical development and prospect for collaborative reduction of pollution and carbon emissions from iron and steel industry in China, *Engineering* 31 (2023) 37–49, <https://doi.org/10.1016/j.eng.2023.02.014>.
- [22] Y. Chen, Z. Wang, Q. Wen, J. Meng, J. Huo, S. Li, et al., A building-scale modeling framework for urban net-zero transitions in Nanjing, *Nat. Commun.* 16 (1) (2025) 8954, <https://doi.org/10.1038/s41467-025-64016-7>.
- [23] Z. Ge, Y. Geng, W. Wei, M. Jiang, B. Chen, J. Li, Embodied carbon emissions induced by the construction of hydropower infrastructure in China, *Energy Policy* 173 (2023) 113404, <https://doi.org/10.1016/j.enpol.2022.113404>.
- [24] B. Huang, F. Zhao, T. Fishman, W.Q. Chen, N. Heeren, E.G. Hertwich, Building material use and associated environmental impacts in China 2000–2015, *Environ. Sci. Technol.* 52 (23) (2018) 14006–14014, <https://doi.org/10.1021/acs.est.8b04104>.
- [25] China Building Materials Federation, China Building Materials Industry Carbon Emission Report, China Building Materials Federation, Beijing, 2020 (in Chinese).
- [26] United Nations Framework Convention on Climate Change (UNFCCC), China's achievements, new goals and new measures for nationally determined contributions, United Nations Framework Convention on Climate Change, https://unfccc.int/NDCREG?gclid=CjwKCAjw9pGjBhB-EiwAa5j3PtyTtOsvBSjtxajragqACUrSQj7uONh3B68_PQfvoewatsOZfCxoCaVkJQAvD_BwE, 2021.
- [27] China Building Materials Federation, China Building Materials Industry Economic Report, China Building Materials Federation, Beijing, 2020 (in Chinese), (2020).
- [28] L. Yang, S. Hong, Impact of the clean energy structure of building operation on the co-benefits of CO₂ and air pollutant emission reductions in Chinese provinces, *J. Clean. Prod.* 413 (2023) 137400, <https://doi.org/10.1016/j.jclepro.2023.137400>.
- [29] S. Zhu, M. Mac Kinnon, A. Carlos-Carlos, S.J. Davis, S. Samuelsen, Decarbonization will lead to more equitable air quality in California, *Nat. Commun.* 13 (1) (2022) 5738, <https://doi.org/10.1038/s41467-022-33295-9>.
- [30] H. Qian, S. Xu, J. Cao, F. Ren, W. Wei, J. Meng, et al., Air pollution reduction and climate co-benefits in China's industries, *Nat. Sustain.* 4 (5) (2021) 417–425, <https://doi.org/10.1038/s41893-020-00669-0>.
- [31] State Council of the People's Republic of China, Notice of the general office of the state council on issuing the three-year action plan for winning the blue sky defense battle. http://www.gov.cn/zhengce/content/2018-07/03/content_5303158.htm.
- [32] G. Geng, Y. Liu, Y. Liu, S. Liu, J. Cheng, L. Yan, et al., Efficacy of China's clean air actions to tackle PM_{2.5} pollution between 2013 and 2020, *Nat. Geosci.* (2024), <https://doi.org/10.1038/s41561-024-01540-z>.
- [33] D.B. Müller, G. Liu, A.N. Løvik, R. Modaresi, S. Pauliuk, F.S. Steinhoff, et al., Carbon emissions of infrastructure development, *Environ. Sci. Technol.* 47 (20) (2013) 11739–11746, <https://doi.org/10.1021/es402618m>.
- [34] L. Huang, G. Kringsvoll, F. Johansen, Y. Liu, X. Zhang, Carbon emission of global construction sector, *Renew. Sustain. Energy Rev.* 81 (2018) 1906–1916, <https://doi.org/10.1016/j.rser.2017.06.001>.
- [35] L. Zhang, B. Liu, J. Du, C. Liu, H. Li, S. Wang, Internationalization trends of carbon emission linkages: a case study on the construction sector, *J. Clean. Prod.* 270 (2020) 122433, <https://doi.org/10.1016/j.jclepro.2020.122433>.
- [36] R. Wang, S. Tao, P. Ciais, H.Z. Shen, Y. Huang, H. Chen, et al., High-resolution mapping of combustion processes and implications for CO₂ emissions, *Atmos. Chem. Phys.* 13 (10) (2013) 5189–5203, <https://doi.org/10.5194/acp-13-5189-2013>.
- [37] T. Huang, X. Zhu, Q. Zhong, X. Yun, W. Meng, B. Li, et al., Spatial and temporal trends in global emissions of nitrogen oxides from 1960 to 2014, *Environ. Sci. Technol.* 51 (14) (2017) 7992–8000, <https://doi.org/10.1021/acs.est.7b02235>.
- [38] Y. Huang, H. Shen, Y. Chen, Q. Zhong, H. Chen, R. Wang, et al., Global organic carbon emissions from primary sources from 1960 to 2009, *Atmos. Environ.* 122 (2015) 505–512, <https://doi.org/10.1016/j.atmosenv.2015.10.017>.
- [39] Y. Shan, D. Guan, K. Hubacek, B. Zheng, S.J. Davis, L. Jia, et al., City-level climate change mitigation in China, *Sci. Adv.* 4 (6) (2018), <https://doi.org/10.1126/sciadv.aag0390> eaa0390.
- [40] National Bureau of Statistics of China (NBSC), China Urban-Rural Construction Statistical Yearbook, 2002–2020. Beijing: China Planning Press.
- [41] National Bureau of Statistics of China (NBSC), China Energy Statistical Yearbook, 1986–2021. Beijing: China Statistics Press.
- [42] CEADs, China energy inventory 1997–2021, carbon emission accounts and datasets. <https://www.ceads.net.cn/data/nation/>.
- [43] H. Shen, S. Tao, Y. Chen, P. Ciais, B. Güneralp, M. Ru, et al., Urbanization-induced population migration has reduced ambient PM_{2.5} concentrations in China, *Sci. Adv.* 3 (7) (2017) e1700300, <https://doi.org/10.1126/sciadv.1700300>.
- [44] R. Burnett, H. Chen, M. Szyszkwicz, N. Fann, B. Hubbell, C.A. Pope, et al., Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter, *Proc. Natl. Acad. Sci. USA* 115 (38) (2018) 9592–9597, <https://doi.org/10.1073/pnas.1803222115>.
- [45] M. Naghavi, K.L. Ong, A. Aali, H.S. Ababneh, Y.H. Abate, C. Abbafati, et al., Global burden of 288 causes of death and life expectancy decomposition in 204 countries and territories and 811 subnational locations, 1990–2021: a systematic analysis for the global burden of disease study 2021, *Lancet* (2024) S0140673624003672, [https://doi.org/10.1016/S0140-6736\(24\)00367-2](https://doi.org/10.1016/S0140-6736(24)00367-2).
- [46] A.J. Cohen, M. Brauer, R. Burnett, H.R. Anderson, J. Frostad, K. Estep, et al., Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the global burden of diseases study 2015, *Lancet* 389 (10082) (2017) 1907–1918, [https://doi.org/10.1016/S0140-6736\(17\)30505-6](https://doi.org/10.1016/S0140-6736(17)30505-6).
- [47] H. Shen, G. Shen, Y. Chen, A.G. Russell, Y. Hu, X. Duan, et al., Increased air pollution exposure among the Chinese population during the national quarantine in 2020, *Nat. Hum. Behav.* 5 (2) (2021) 239–246, <https://doi.org/10.1038/s41562-020-01018-z>.
- [48] H. Zhao, G. Geng, Q. Zhang, S.J. Davis, X. Li, Y. Liu, et al., Inequality of household consumption and air pollution-related deaths in China, *Nat. Commun.* 10 (1) (2019) 4337, <https://doi.org/10.1038/s41467-019-12254-x>.
- [49] L. Zheng, W. Adalibieke, F. Zhou, P. He, Y. Chen, P. Guo, et al., Health burden from food systems is highly unequal across income groups, *Nat. Food* (2024), <https://doi.org/10.1038/s43016-024-00946-7>.
- [50] S. Zhao, M.G. Russell, A. Hakami, S.L. Capps, M.D. Turner, D.K. Henze, et al., A multiphase CMAQ version 5.0 adjoint, *Geosci. Model Dev. (GMD)* 13 (7) (2020) 2925–2944, <https://doi.org/10.5194/gmd-13-2925-2020>.
- [51] R. Zhang, Z. Chen, X. Wu, Q. Liu, Z. Mai, Z. Zheng, et al., Adjoint analysis of PM_{2.5} and O₃ episodes in priority control zones in China, *Environ. Sci. Ecotechnol.* 27 (2025) 100612, <https://doi.org/10.1016/j.ese.2025.100612>.
- [52] G. Shen, M. Ru, W. Du, X. Zhu, Q. Zhong, Y. Chen, et al., Impacts of air pollutants from rural Chinese households under the rapid residential energy transition, *Nat. Commun.* 10 (1) (2019) 3405, <https://doi.org/10.1038/s41467-019-11453-w>.
- [53] S. Archer-Nicholls, E. Carter, R. Kumar, Q. Xiao, Y. Liu, J. Frostad, et al., The regional impacts of cooking and heating emissions on ambient air quality and disease burden in China, *Environ. Sci. Technol.* 50 (17) (2016) 9416–9423, <https://doi.org/10.1021/acs.est.6b02533>.
- [54] F. Liu, Q. Zhang, D. Tong, B. Zheng, M. Li, H. Huo, et al., High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010, *Atmos. Chem. Phys.* 15 (23) (2015) 13299–13317, <https://doi.org/10.5194/acp-15-13299-2015>.
- [55] Clean Air Alliance of China (CAAC), Air Pollution Prevention and Control Action Plan, 2013. Beijing, China.
- [56] Q. Zhang, Y. Zheng, D. Tong, M. Shao, S. Wang, Y. Zhang, et al., Drivers of improved PM_{2.5} air quality in China from 2013 to 2017, *Proc. Natl. Acad. Sci. USA* 116 (49) (2019) 24463–24469, <https://doi.org/10.1073/pnas.1907956116>.
- [57] S. Tao, M.Y. Ru, W. Du, X. Zhu, Q.R. Zhong, B.G. Li, et al., Quantifying the rural residential energy transition in China from 1992 to 2012 through a representative national survey, *Nat. Energy* 3 (7) (2018) 567–573, <https://doi.org/10.1038/s41560-018-0158-4>.
- [58] X. Zhang, C.P. Barrington-Leigh, B.E. Robinson, Rural household energy transition in China: trends and challenges, *J. Clean. Prod.* 450 (2024) 141871, <https://doi.org/10.1016/j.jclepro.2024.141871>.
- [59] R. Wang, S. Tao, H. Shen, Y. Huang, H. Chen, Y. Balkanski, et al., Trend in global Black Carbon emissions from 1960 to 2007, *Environ. Sci. Technol.* 48 (12) (2014) 6780–6787, <https://doi.org/10.1021/es5021422>.
- [60] K. Wang, H. Tian, S. Hua, C. Zhu, J. Gao, Y. Xue, et al., A comprehensive emission inventory of multiple air pollutants from iron and steel industry in China: temporal trends and spatial variation characteristics, *Sci. Total Environ.* 559 (2016) 7–14, <https://doi.org/10.1016/j.scitotenv.2016.03.125>.
- [61] Q. Shi, B. Zheng, Y. Zheng, D. Tong, Y. Liu, H. Ma, et al., Co-benefits of CO₂ emission reduction from China's clean air actions between 2013–2020, *Nat. Commun.* 13 (1) (2022) 5061, <https://doi.org/10.1038/s41467-022-32656-8>.
- [62] Ministry of Industry and Information Technology of the People's Republic of China (MIIT), Green Manufacturing Engineering Implementation Guide (2016–2020). Beijing: Ministry of Industry and Information Technology.
- [63] T. Ma, S. Zhang, Y. Xiao, X. Liu, M. Wang, K. Wu, et al., Costs and health benefits of the rural energy transition to carbon neutrality in China, *Nat. Commun.* 14 (1) (2023) 6101, <https://doi.org/10.1038/s41467-023-41707-7>.
- [64] M. Deng, P. Li, M. Shan, X. Yang, Characterizing dynamic relationships between burning rate and pollutant emission rates in a forced-draft gasifier stove consuming biomass pellet fuels, *Environ. Pollut.* 255 (2019) 113338, <https://doi.org/10.1016/j.envpol.2019.113338>.
- [65] T. Luo, B. Shen, Z. Mei, A. Hove, K. Ju, Unlocking the potential of biogas systems for energy production and climate solutions in rural communities, *Nat. Commun.* 15 (1) (2024) 5900, <https://doi.org/10.1038/s41467-024-50091-9>.
- [66] Y.Q. Ang, Z.M. Berzolla, S. Letellier-Duchesne, C.F. Reinhart, Carbon reduction technology pathways for existing buildings in eight cities, *Nat. Commun.* 14 (1) (2023) 1689, <https://doi.org/10.1038/s41467-023-37131-6>.
- [67] H. Zheng, R. Zhang, X. Yin, J. Wu, Unused housing in urban China and its carbon emission impact, *Nat. Commun.* 16 (1) (2025) 1985, <https://doi.org/10.1038/s41467-025-57217-7>.
- [68] L. Shi, T. Leichtle, X. Huang, M. Wurm, H. Taubenböck, (The decreasing housing utilization efficiency in China's cities, *Nat. Cities* 2 (1) (2025) 70–80, <https://doi.org/10.1038/s44284-024-00177-8>.

- [69] W. Wu, Q. Tang, W. Xue, X. Shi, D. Zhao, Z. Liu, et al., Quantifying China's iron and steel industry's CO₂ emissions and environmental health burdens: a pathway to sustainable transformation, *Env. Sci. Ecotechnol.* 20 (2024) 100367, <https://doi.org/10.1016/j.ese.2023.100367>.
- [70] D. Tong, G. Geng, Q. Zhang, J. Cheng, X. Qin, C. Hong, et al., Health co-benefits of climate change mitigation depend on strategic power plant retirements and pollution controls, *Nat. Clim. Chang.* 11 (12) (2021) 1077–1083, <https://doi.org/10.1038/s41558-021-01216-1>.
- [71] E. Van Rooijen, S.A. Miller, S.J. Davis, Building materials could Store more than 16 billion tonnes of CO₂ annually, *Science* 387 (6730) (2025) 176–182, <https://doi.org/10.1126/science.adq8594>.
- [72] W. Yu, R. Xu, T. Ye, M.J. Abramson, L. Morawska, B. Jalaludin, et al., Estimates of global mortality burden associated with short-term exposure to fine particulate matter (PM_{2.5}), *Lancet Planet. Health* 8 (3) (2024) e146–e155, [https://doi.org/10.1016/S2542-5196\(24\)00003-2](https://doi.org/10.1016/S2542-5196(24)00003-2).
- [73] S.Y. Kim, J.L. Peel, M.P. Hannigan, S.J. Dutton, L. Sheppard, M.L. Clark, et al., The temporal lag structure of short-term associations of fine particulate matter chemical constituents and cardiovascular and respiratory hospitalizations, *Environ. Health Perspect.* 120 (8) (2012) 1094–1099, <https://doi.org/10.1289/ehp.1104721>.