npj | clean air

Article

https://doi.org/10.1038/s44407-026-00062-9

Integrated pollution and carbon mitigation delivers major health and economic co-benefits in China

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Synergistic mitigation of air pollutants and greenhouse gases is crucial for achieving clean air and carbon neutrality, but quantitative evidence of sectoral and regional health co-benefits in China remains limited. We develop an integrated Energy-Economy-Air Quality-Health framework coupling CEEPA, GAINS, and a province-level health module to simulate fourteen policy scenarios from 2020 to 2050. Coordinated strategies reduce CO_2 and pollutants (SO_2, NO_X, $PM_{2.5}$) by 75% relative to 2020, avoiding more than 500,000 premature deaths by 2050 and yielding monetized gains of 1.07 trillion CNY. Health benefits concentrate in industrially dense and populous provinces, with near-term $PM_{2.5}$ reductions driven by pollution control and long-term improvements reliant on decarbonization. The integrated approach achieves a benefit-to-cost ratio of 1.42, lowering abatement costs by 11% relative to pollution-only measures. Our findings highlight the value of coordinated, sector- and region-specific strategies for simultaneous climate mitigation, air quality improvement, and public health protection.

Climate change and air pollution are twin crises that threaten human health, ecosystems, and economic stability. Global warming intensified in 2024, with average temperatures reaching record highs and causing approximately 500,000 deaths from heat exposure[1]. At the same time, air pollution accounted for 8.1 million premature deaths worldwide, 28% of which occurred in China[2]. As the world's largest carbon emitter, responsible for approximately 30% of global carbon emissions, China's actions are pivotal for achieving global climate and health goals[3]. Despite substantial progress under the Clean Air Action (2013–2020), China's $PM_{2.5}$ concentrations remain far above the World Health Organization (WHO) guideline value of 5 μg/m^3 [4,5]. Meanwhile, the national commitment to peak carbon emissions before 2030 and achieve carbon neutrality before 2060 (hereafter referred to as the "dual-carbon goals") underscores the need for coordinated strategies that deliver simultaneous climate and air-quality benefits.

Greenhouse gases and conventional air pollutants share common emission sources, primarily fossil-fuel combustion in power generation, industry, and transport, making synergistic mitigation technically and economically feasible[6–9]. A large body of research demonstrates that low-carbon transitions can yield substantial co-benefits for air quality and health. Top-down Computable General Equilibrium (CGE) models show that optimizing the energy structure and advancing industrial restructuring can simultaneously reduce CO_2 and pollutant emissions, improving global $PM_{2.5}$ co-mitigation efficiency by 10–28%[10]. Bottom-up models, such as the MESSAGE framework, reveal that coupling clean energy transitions with advanced end-of-pipe air pollution controls reduces CO_2, NO_X, SO_2, and $PM_{2.5}$ emissions across multiple regions, yielding substantial improvements in air quality and health[11]. These findings highlight the technical potential of integrated climate–pollution management.

China has increasingly adopted this integrated approach, embedding "pollution reduction" and "climate action" into a unified policy framework that aligns carbon neutrality with air-quality and health goals. Synergistic mechanisms—such as linking carbon markets with emissions trading and combining carbon capture, utilization, and storage (CCUS) with advanced end-of-pipe pollution controls—have been promoted to achieve "Carbon mitigation-Pollution reduction-Health improvement" co-benefits[12]. This shift from parallel to coordinated governance provides a model for developing economies seeking multi-objective sustainability.

Previous Climate-Pollution-Health integrated assessments have advanced understanding of the co-benefits of emission reduction policies. Many focus on how carbon mitigation pathways improve air quality and

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health outcomes[13–15] while others evaluate the health benefits of pollution control measures. For instance, the “coal-to-electricity” policy in the residential energy sector of the Beijing-Tianjin-Hebei region significantly reduced $PM_{2.5}$ and SO_2 emissions, preventing approximately 22,200 premature deaths and 607,800 cases of illness[16], and generating net social benefits of 18.7–19.9 billion CNY. Together, these findings confirm that both carbon mitigation and pollution control actions generate substantial health co-benefits.

Nevertheless, important research gaps remain. First, most assessments operate at the national level, masking substantial provincial heterogeneity in industrial structure, energy mix, and population exposure. Empirical evidence shows that China’s provinces differ markedly in emission sources and reduction potentials due to variations in economic structure, energy intensity, and demographic distribution[17]. Neglecting these spatial disparities can bias estimates of both co-benefits and policy cost-effectiveness.

Second, existing studies often apply uniform policy assumptions, overlooking sectoral differentiation in mitigation potential across energy, industrial, transport, and residential sectors. For instance, Li et al.[18], Liu et al.[19], and Markandya et al.[14] applied nationally homogeneous policy intensities in their integrated frameworks, while studies by Reis et al.[20], Tibrewal and Venkataraman[21], and Zheng et al.[22] used generalized technology parameters across sectors. Such simplifications limit the realism of simulations and their relevance for sector-targeted policymaking.

Third, health benefits are frequently estimated using aggregate exposure–response functions that neglect region-specific mortality risks, population aging, and baseline disease prevalence, leading to under- or overestimation of health co-benefits. For example, studies such as Liu et al.[19], Markandya et al.[14], and Rao et al.[11] adopt uniform concentration–response coefficients or national mortality baselines, while more recent work[7,23,24] has emphasized the importance of incorporating spatially resolved demographic and health data to improve accuracy. These limitations constrain the precision and policy relevance of current integrated assessments.

To address these gaps, we develop a high-resolution Energy–Economy–Air Quality–Health (EEAH) framework that couples a computable general equilibrium energy-economy model, a detailed pollution control technology model, and a province-specific health impact module (Fig. 1). Specifically, the framework links the China Energy and Environmental Policy Analysis (CEEPA) model, the Greenhouse Gas and Air Pollution Interactions and Synergies model (GAINS) model and a health assessment calibrated using the Health Benefits (HEALTH) model through a soft-linked, one-way architecture. Under alternative mitigation pathways, CEEPA provides sectoral output and fuel-specific energy consumption, which drive GAINS estimates of pollutant emissions, end-of-pipe technology deployment, control costs, and ambient $PM_{2.5}$ concentrations. These outputs are then used by the HEALTH module to estimate premature mortality and monetized health co-benefits. Pollution-control costs are not fed back into the macroeconomic equilibrium. Detailed data harmonization procedures and temporal interpolation approaches are described in the Methods.

Drawing from more than 100 national and regional policy documents, we design 14 integrated policy scenarios that reflect provincial industrial diversity and incorporate over 80 end-of-pipe technologies. The analysis spans 2020–2050, with 2050 chosen as the final horizon year given its role as the terminal year of the GAINS scenario database and a standard mid-century benchmark for deep decarbonization assessments in China and worldwide. Using China as a case study, we quantify (1) national and provincial emission trajectories, (2) changes in $PM_{2.5}$ concentrations, (3) avoided premature deaths and associated economic benefits, and (4) cost–benefit trade-offs between synergistic and single-objective policies, explicitly capturing subnational heterogeneity and cross-sector interactions.

Overall, the contributions of this study lie in two key aspects. First, it develops a policy-oriented scenario design that provides coordinated, sector- and region-specific mitigation pathways at the provincial level in China, offering granular evidence to complement existing national-level co-mitigation studies and supporting more targeted policy design under heterogeneous economic and industrial structures. Second, it establishes an EEAH integrated assessment framework that enables consistent translation of macroeconomic transition pathways into technology-level emission control and health impact outcomes, improving the policy interpretability of multi-model scenario analysis. Through these contributions, this study aims to provide both empirically grounded policy insights and transferable analytical tools for integrated climate and environmental governance.

Results

Building upon the integrated analytical framework described in the “Methods” section, this study examines how alternative policy scenarios influence carbon emissions, air quality, and associated health co-benefits.

National emission pathways

China’s carbon emissions are projected to peak around 2030, reaching 9.7–10.3 Gt, before declining to 2.4–5.8 Gt by 2050. Achieving carbon neutrality on schedule depends critically on two parameters: the peak emission levels and the post-peak reduction intensity. As shown in Fig. 2, under the Reference Energy Transition (RET) scenario, national carbon emissions peak at 10.3 Gt in 2030 (+6.8% relative to 2020), and decline to 5.8 Gt in 2050, reflecting a “slow-peaking, weak-reduction” trajectory with a cumulative reduction of 40.2%. In contrast, the Deep Decarbonization Pathway (DDP) scenario, characterized by stricter mitigation measures, limits the peak to 9.7 Gt in 2030 (+0.9% relative to 2020) and doubles the annual reduction rate to 4.2%, compared with 2.1% in RET. By 2050, emissions drop sharply to 2.4 Gt, representing a 74.7% cumulative decline, 34.5% greater than under RET.

Sectoral contributions to decarbonization

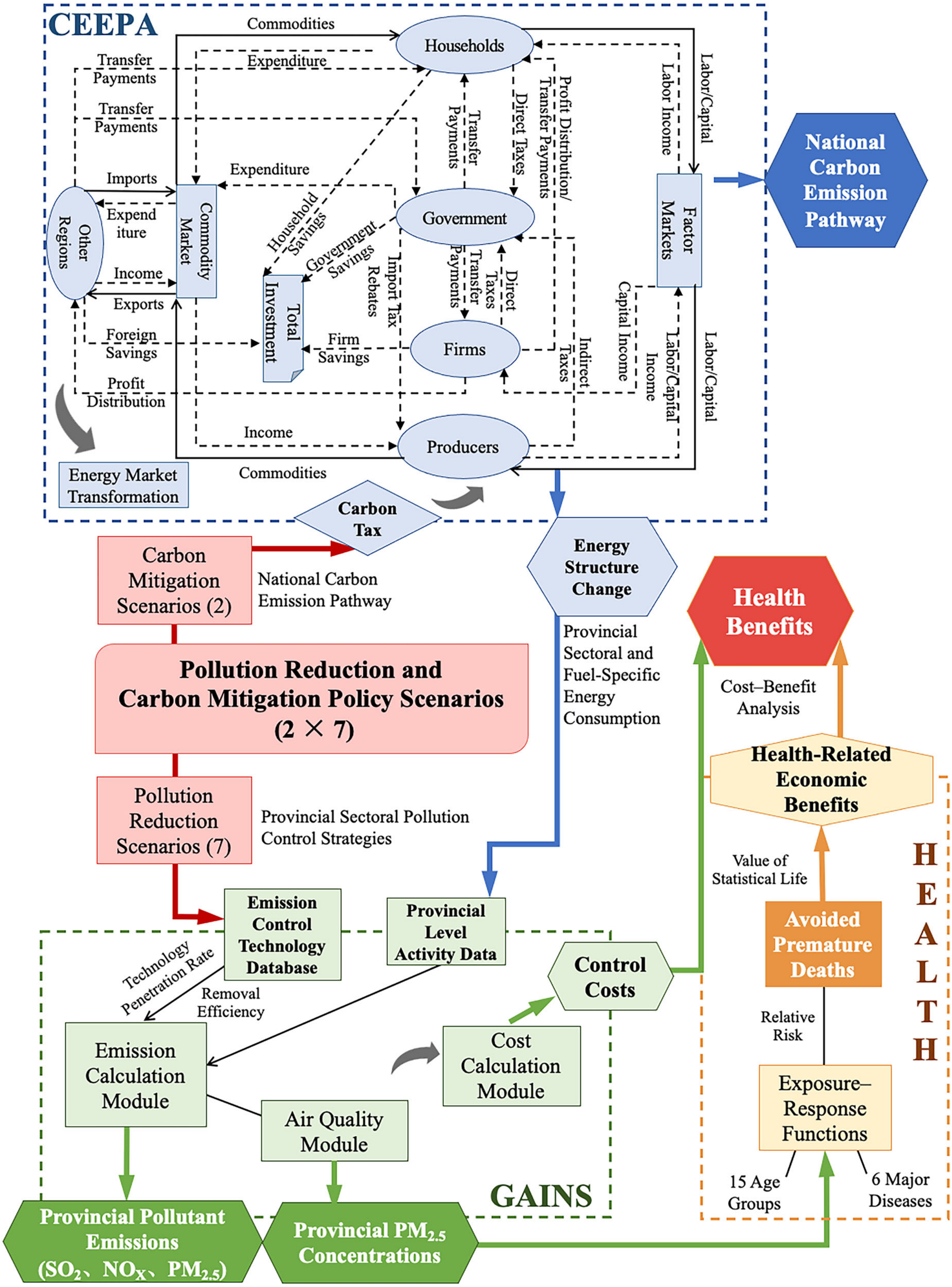
The energy sector is the dominant drive of early-stage emission reductions, while the industrial sector emerges as the primary contributor in the later phase. Between 2020 and 2035, the energy sector is the only one exhibiting sustained emission declines, falling from 2.6 Gt to 0.98–1.4 Gt, thereby offsetting emission growth in other sectors. After 2035, as emissions from other sectors begin to contract, the energy sector’s relative contribution decreases to 12.4–19.6% of total reductions. In contrast, the industrial sector’s mitigation potential remains limited before 2035 but becomes central thereafter. Under the RET scenario, industrial emissions rise to a peak of 5.5–5.7 Gt in 2030 before entering a steep decline. Between 2035 and 2050, industrial emissions decrease by 1.35–3.33 Gt, contributing 30–46.3% of the total national reductions. However, the industrial sector still accounts for up to 66.4% of remaining emissions by 2050, highlighting its structural rigidity and the challenges of achieving deep decarbonization.

End-use sector dynamics and lifestyle transitions

Emission trajectories in end-use sectors highlight the growing importance of lifestyle and behavioral transitions in sustaining long-term decarbonization. Under RET, emissions from the building and residential sectors continue to rise, increasing by 61.6% and 75% respectively, by 2050, with the residential sector’s share expanding to 15.8%, becoming the second-largest emitter. In contrast, under the DDP scenario, both sectors initially follow similar upward trends until 2035, after which carbon pricing mechanisms and improved energy efficiency curb demand (see Table S1 and Fig. S1). By 2040, emissions in both sectors begin to decline, and by 2050, they fall by 50.8% (buildings) and 28.3% (residential) relative to 2020 levels. These results indicate that once the structural transformation of the energy system reaches its limits (around 2035–2040), low-carbon transitions in end-use sectors, including electrification, energy efficiency, and sustainable consumption, will become the next critical driver of deep decarbonization.

Air pollutant emission trajectories

The co-benefits of air quality improvement vary across pollutants and are driven by different mechanisms. SO_2 and $PM_{2.5}$ reductions primarily rely on end-of-pipe controls, whereas NO_X reduction is largely governed by low-carbon transition measures. As shown in Fig. 3, under the reference policy



combination (RET-BP), China's emissions of SO_2, NO_X, and $PM_{2.5}$ decline by 43.2%, 42.8%, and 35.2%, respectively, by 2050 relative to 2020 levels. Strengthening carbon constraints (DDP-BP) substantially alters the pollutant-to-CO_2 abatement ratios: for every 10,000-ton reduction in CO_2, emissions of SO_2, NO_X, and $PM_{2.5}$ decrease by 3.8, 5.6, and 0.9 tons, respectively. When stringent carbon policies are coupled with enhanced end-of-pipe measures (DDP-EP), these co-benefits rise markedly to 5.1, 7.9, and 1.7 tons, corresponding to emission reductions of 80.1%, 80.5%, and 85.9% relative to 2020 levels. The additional declines in SO_2 (−50.6%) and $PM_{2.5}$ (−75.1%) are primarily attributed to end-of-pipe measures, with the industrial sector contributing 25.9–55.5% and the residential sector 22.7–33.8% of the total reduction. In contrast, NO_X reductions exhibit a

Fig. 1 | The Energy-Economy-Air Quality-Health (EEAH) framework. This figure illustrates the structure and information flows of the Energy–Economy–Air Quality–Health (EEAH) integrated modeling framework. The framework links macroeconomic activity, energy systems, pollutant emissions, air quality, and health outcomes through three components: CEEPA (China Energy and Environmental Policy Analysis model), GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies model), and HEALTH (health impact assessment module). Two carbon mitigation scenarios are implemented in CEEPA as carbon tax policies, generating national carbon emission pathways and energy consumption changes. Energy consumption changes provide activity data to GAINS. Seven pollution control scenarios are implemented in GAINS through the emission control technology database. GAINS produces provincial emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_X), and fine particulate matter ($PM_{2.5}$), provincial $PM_{2.5}$ concentrations, and associated control costs. The HEALTH module applies exposure–response functions to provincial $PM_{2.5}$ concentrations to estimate avoided premature deaths. These are monetized using the Value of Statistical Life to calculate health-related economic benefits. Net health benefits are derived by comparing monetized health benefits with pollution control costs from GAINS. Arrows indicate the direction of information flow and causal linkages among modules.

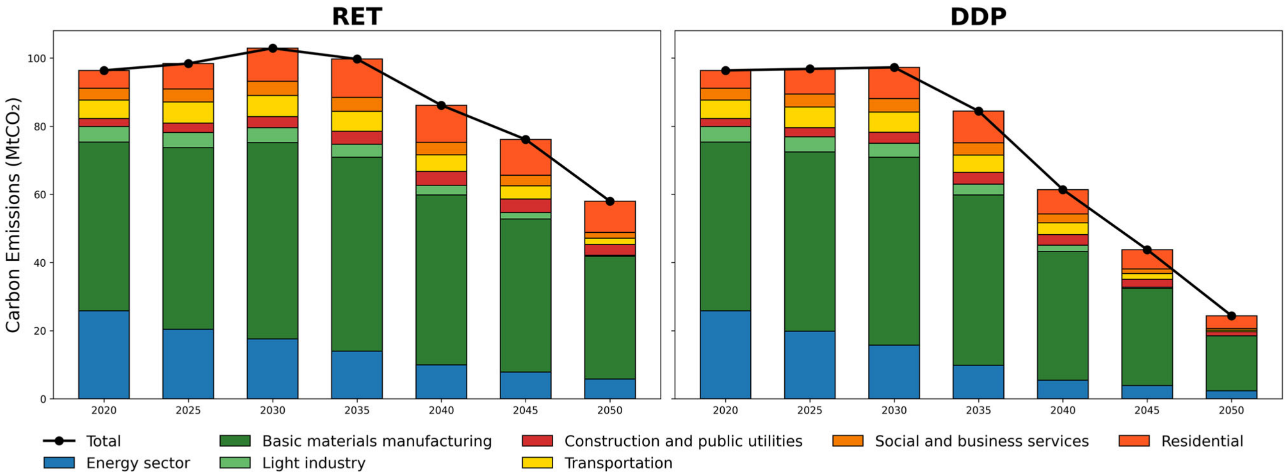


Fig. 2 | National carbon emissions from 2020 to 2050. This two-panel figure presents sectoral carbon dioxide (CO_2) emissions from 2020 to 2050 under alternative energy transition pathways. The left figure shows emissions under the Reference Energy Transition (RET) scenario. The right figure shows emissions under the Deep Decarbonization Pathway (DDP) scenario. Stacked bars represent emissions from the energy sector (blue bars), basic materials manufacturing (dark green bars), light industry (light green bars), construction and public utilities (yellow bars), transportation (orange bars), social and business services (light orange bars), and the residential sector (red bars). A black solid line with circular markers indicates total national CO_2 emissions. Emissions are expressed in megatons of carbon dioxide ($MtCO_2$).

distinct low-carbon-dominated pattern: stricter carbon constraints (DDP-BP vs. RET-BP) lead to an additional 3.7 Mt reduction, driven mainly by transport sector electrification and the associated decline in fossil fuel combustion.

Sectoral and regional drivers of air pollutant reductions

Emission reductions in this analysis are driven by sector-specific mitigation measures implemented through policy scenarios, including ultra-low emission retrofits and other end-of-pipe controls in the power and industrial sectors, fleet turnover and emission standard upgrades in transport, clean fuel and stove substitution in the residential sector, and improved fertilizer use and manure management in agriculture. The relative importance of these measures varies regionally with provincial economic structure. For example, industrial controls are more prominent in heavy-industry provinces such as Hebei and Henan, whereas transport and shipping-related measures are more important in economically developed coastal provinces such as Guangdong.

SO_2 and $PM_{2.5}$ reductions are dominated by the industrial sector, while NO_X reduction is primarily driven by the transport sector, reflecting the influence of heterogeneous regional economic structures (Detailed cumulative provincial emission reduction rates under each scenario are provided in Tables S2-1–S2-6). For SO_2 and $PM_{2.5}$, the provinces with the highest 2020 emissions—Shandong, Hebei, Sichuan, Shanxi, and Henan for SO_2 (accounting for 33.8% of the national total), and Hebei, Shandong, Henan, Jiangsu, and Sichuan for $PM_{2.5}$ (35.8%)—depend heavily on industrial end-of-pipe control technologies (Fig. 4). Under the enhanced industrial scenario (-IT), the industrial sector contributes 48.3–69% of national SO_2 reductions between 2020 to 2050. For $PM_{2.5}$, industrial dust removal in Hebei, Shandong, and Henan accounts for 36.5–46.6% of national reductions.

The performance of residential controls varies markedly by pollutant. In Shanxi, where residential combustion contributes nearly 30% of SO_2 emissions, additional measures beyond 2025 yield limited marginal gains due to the saturation of low-sulfur coal and clean stove adoption. By contrast, residential measures play a significant role in reducing $PM_{2.5}$. In Sichuan, for example, improved combustion efficiency and enhanced dust removal collectively deliver 36.2% of total $PM_{2.5}$ reductions. This contrast highlights the superior potential of residential end-of-pipe technologies for $PM_{2.5}$ control compared to SO_2, as dust removal directly targets primary $PM_{2.5}$ emissions—demonstrating the technical feasibility of multiple pollutant co-control.

For NO_X, the five leading emitting provinces—Shandong, Jiangsu, Guangdong, Hebei, and Henan—which together contribute 34.7% of national emissions, pursue differentiated pathways reflecting their industrial structures. Shandong adopts a balanced strategy combining industrial denitrification (e.g., cement kilns, 34.9%) with transport-sector measures (e.g., phase-out of heavy-duty diesel vehicles, 30.5%). Guangdong leverages its coastal advantage, prioritizing marine transport controls (40.2%). Hebei and Henan, as traditional industrial bases, focus on power plant denitrification (14.5% and 17.8%, respectively) and steel-sector retrofits (54.4% and 41.4%, respectively). Meanwhile, Jiangsu, with its diversified economic base, implements a mixed portfolio across industry (28.2%), transport (19.6%), and power generation (18.1%). Together these heterogeneous provincial strategies underscore how regional economic structures and industrial compositions fundamentally shape emission reduction pathways, emphasizing the need for regionally differentiated policy design to achieve coordinated carbon–pollution mitigation.

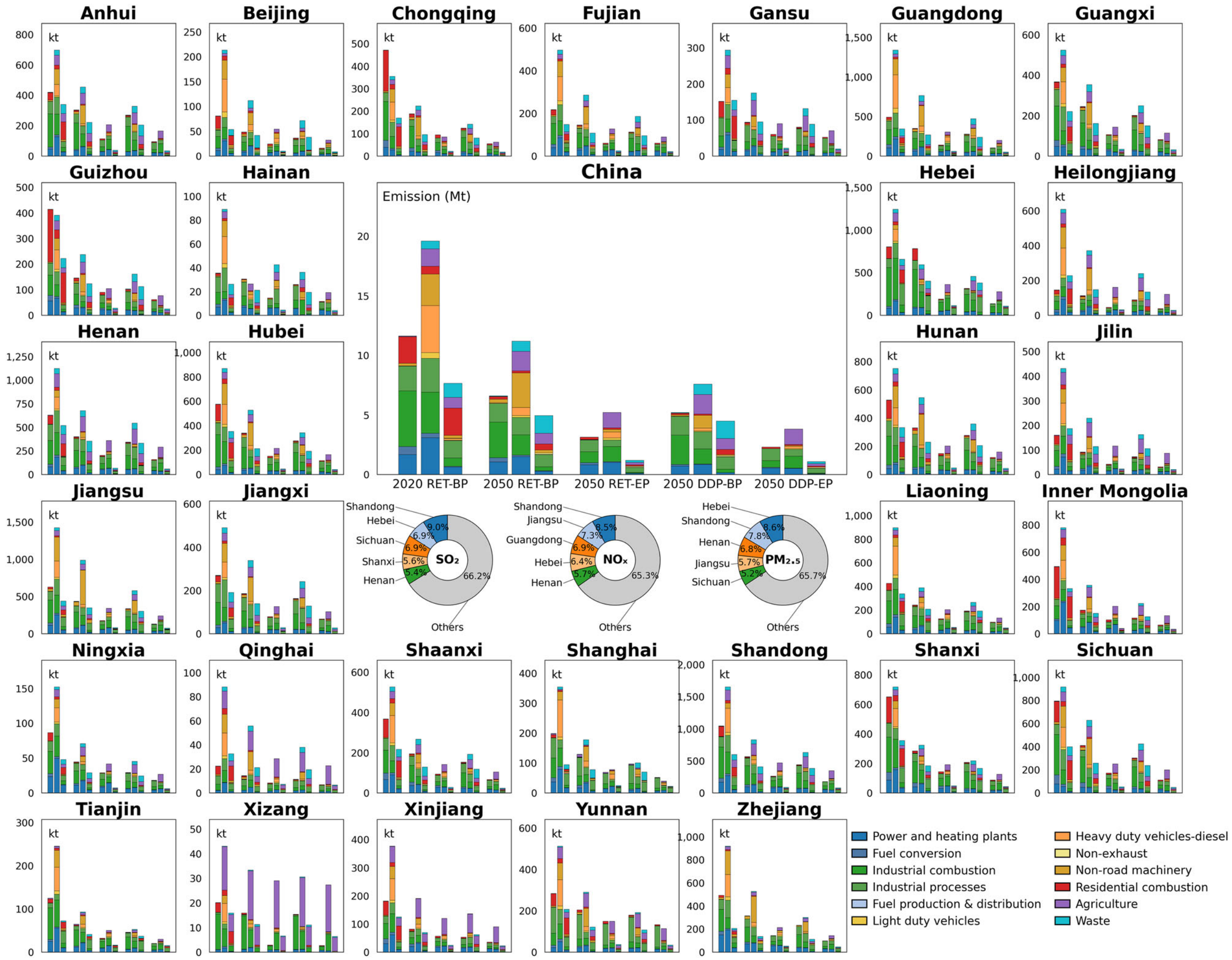


Fig. 3 | Sectoral and regional differences in major air pollutant emissions in 2020 and 2050 under selected scenarios. This multi-panel figure compares sectoral and regional emissions of major air pollutants in 2020 and 2050 under alternative policy scenarios. The central panel presents national totals in megatons (Mt), while surrounding panels show provincial totals in kilotons (kt). Bars display emissions in 2020 under the baseline Reference Energy Transition–Baseline Policy (RET-BP) scenario and in 2050 under four scenarios: RET-BP, RET-Enhanced Policy (RET-EP), Deep Decarbonization Pathway–Baseline Policy (DDP-BP), and Deep Decarbonization Pathway–Enhanced Policy (DDP-EP). Within each group, sulfur dioxide (SO_2), nitrogen oxides (NO_X), and fine particulate matter ($PM_{2.5}$) are shown from left to right. Colored bars denote sectors: power and heating plants (blue), fuel conversion (dark green), industrial combustion (light green), industrial processes (yellow), fuel production and distribution (brown), light-duty vehicles (light orange), heavy-duty diesel vehicles (orange), non-exhaust sources (gray), non-road machinery (purple), residential combustion (red), agriculture (dark red), and waste (cyan). Pie charts illustrate provincial contributions to national SO_2, NO_X, and $PM_{2.5}$ emissions in 2020 under the reference scenario.

Air quality improvements

Pollution control measures can significantly reduce $PM_{2.5}$ concentrations in the short term, while deep decarbonization alone shows limited immediate impact. However, carbon policies are crucial for ensuring sustained, long-term compliance with national air quality standards. As shown in Fig. 5, under the reference scenario (RET-BP), only 18 provinces meet China's National Standard II ($PM_{2.5} \leq 35$ μg/m^3) by 2050, an increase of merely three provinces relative to 2020, indicating that continuation of existing policies is insufficient for nationwide attainment. In the DDP-BP scenario, which introduces deep decarbonization alone without enhanced end-of-pipe control, only Chongqing achieves compliance by 2050, a marginal improvement over the baseline. This slow progress highlights that the air quality co-benefits of climate policy are realized over longer timescales, as they depend on the gradual turnover of capital stock and the phase-out of fossil-fuel-based infrastructure. Within the time horizon of this study, deep decarbonization in isolation is therefore insufficient to bring the majority of provinces into compliance.

In contrast, the DDP-EP scenario—contributing deep decarbonization with strengthened pollution controls—demonstrates the effectiveness of this integrated policy package. The primary driver of near-term compliance is clear: Short-term benefits from end-of-pipe measures drive near-universal compliance by 2030 (except in the Beijing-Tianjin-Hebei region). By 2050, this widespread compliance is sustained. In this longer term, the structural shifts toward low-carbon energy play an important supporting role by addressing the root cause of emissions from the energy system, thereby achieving lower $PM_{2.5}$ concentrations across the regions, therefore preventing potential rebounds. Nonetheless, relative to the more stringent WHO guideline ($PM_{2.5} \leq 5$ μg/m^3), substantial gaps remain: even under the DDP-EP scenario, only Xizang meets the WHO target by 2050. This underscores the need for continued technology innovation and deeper carbon mitigation to address residual pollution.

Temporal and spatial heterogeneity

The spatiotemporal heterogeneity of air quality improvements reflects both policy stringency and regional endowments. Temporally, pollution control measures produce significant early benefits—by 2030, average $PM_{2.5}$ concentrations in key regions decline by nearly 40%—

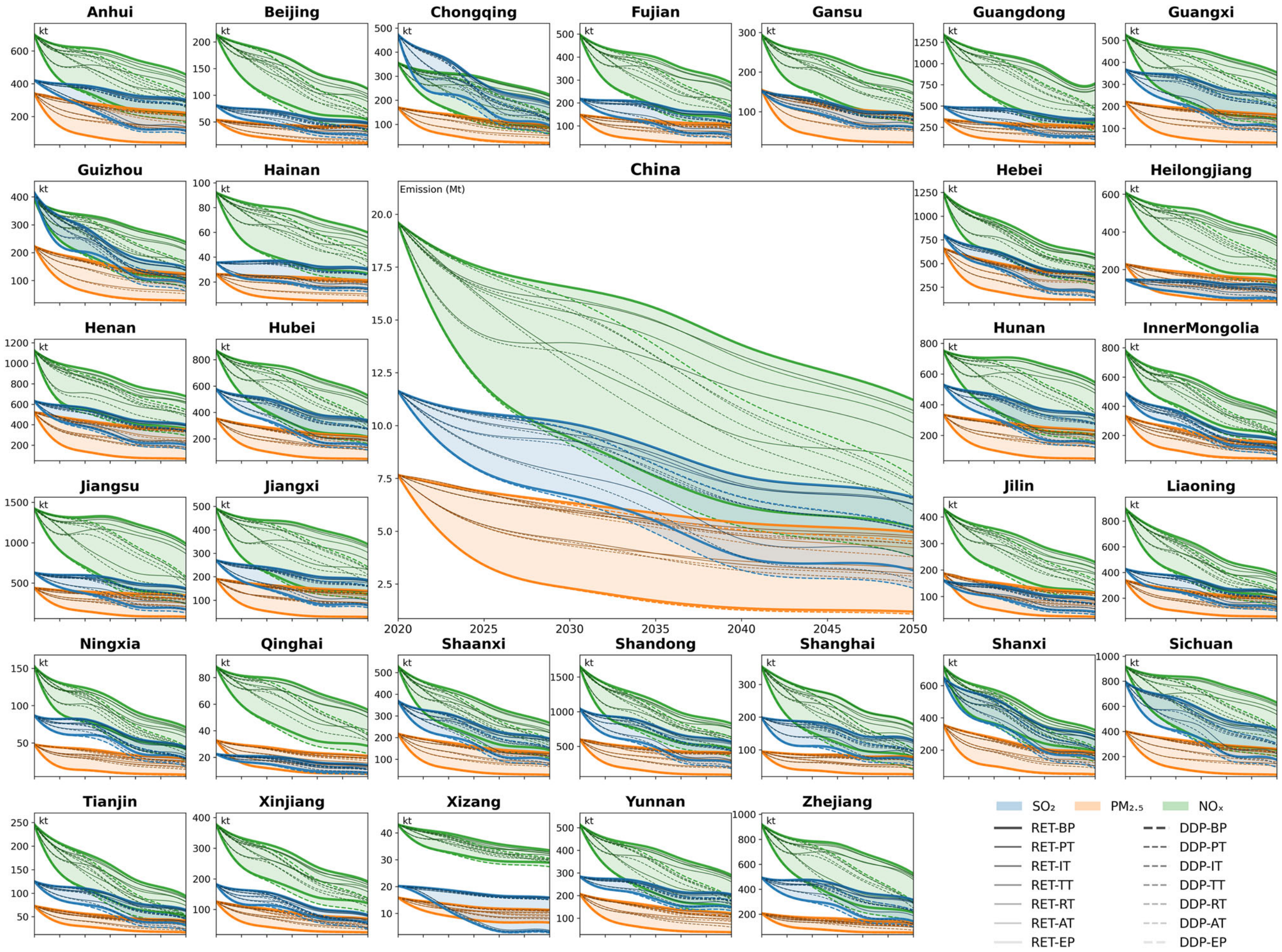
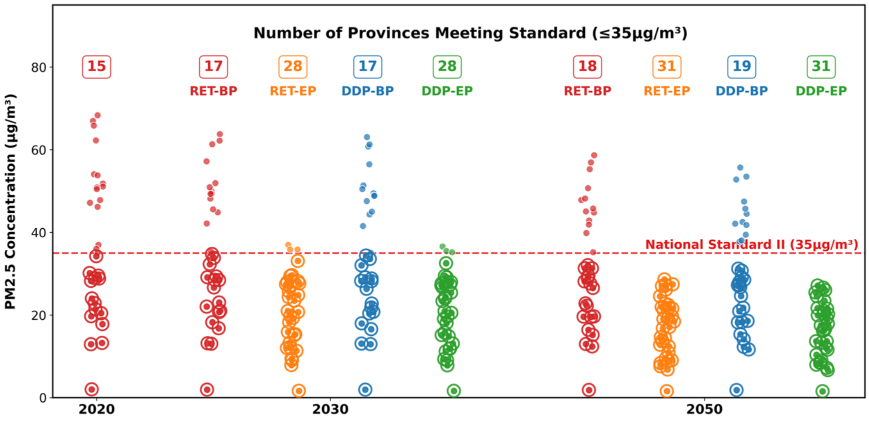


Fig. 4 | Regional emission trends of major air pollutants in China under alternative scenarios during 2020–2050. This multi-panel figure presents national and provincial emission trajectories of major air pollutants from 2020 to 2050. The central panel shows national totals in megatons (Mt), and provincial panels show emissions in kilotons (kt). Time series are shown for sulfur dioxide (SO_2; blue lines), nitrogen oxides (NO_X; green lines), and fine particulate matter ($PM_{2.5}$; orange lines). Solid lines represent Reference Energy Transition (RET) scenarios, and dashed lines represent Deep Decarbonization Pathway (DDP) scenarios. Within each pathway, pollution control technology variants are distinguished by shade intensity, from darkest to lightest: Baseline Policy (BP), Power Target (PT), Industry Target (IT), Transport Target (TT), Residential Target (RT), Agriculture Target (AT), and Enhanced Policy (EP). Shaded envelopes represent the full range of emission outcomes across all technology scenarios for each pollutant.

Fig. 5 | Provincial $PM_{2.5}$ concentrations in 2020, 2030, and 2050. This figure presents provincial annual mean $PM_{2.5}$ concentrations under four policy scenarios for 2020, 2030, and 2050. The vertical axis shows $PM_{2.5}$ concentrations in micrograms per cubic meter (μg/m^3). Red points represent the RET-BP scenario, orange points represent RET-EP, blue points represent DDP-BP, and green points represent DDP-EP. Solid circular points indicate concentrations exceeding the Chinese National Ambient Air Quality Standard II threshold (35 μg/m^3), whereas hollow circular points indicate compliance. Numbers above each scenario cluster indicate the number of provinces meeting the standard. It is important to note that achieving the 35 μg/m^3 standard in any scenario is a calculated outcome of the simulated policy package, not a preset model constraint.



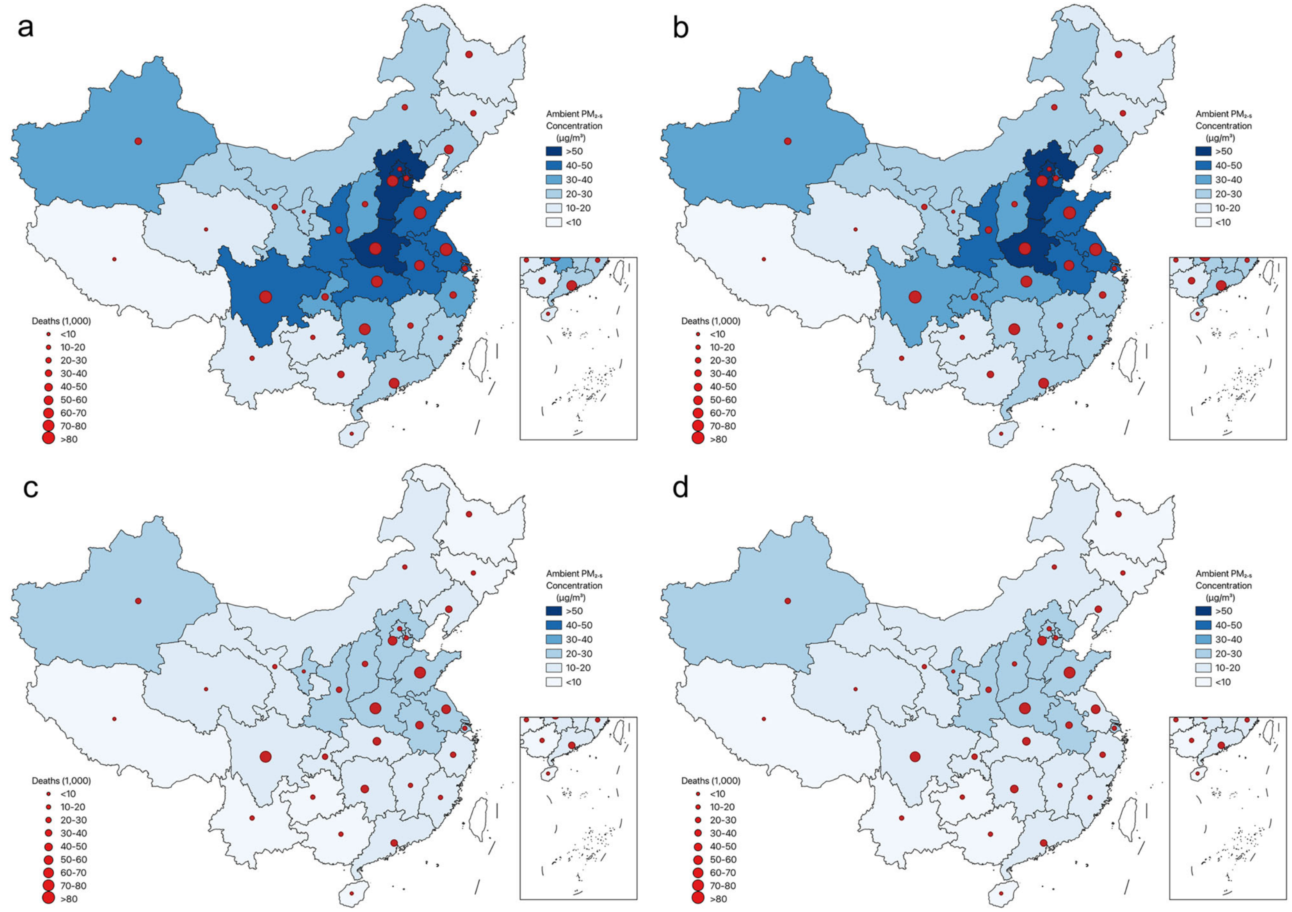


Fig. 6 | Air quality and premature deaths in 2050. This four-panel figure shows provincial $PM_{2.5}$ concentrations and associated premature mortality in 2050. **a** RET-BP; **b** DDP-BP; **c** RET-EP; **d** DDP-EP. Background color shading represents annual mean $PM_{2.5}$ concentrations (μg/m³), ranging from white (<10 μg/m³) to progressively darker blue shades (10–20, 20–30, 30–40, 40–50 μg/m³) and dark blue (>50 μg/m³). Red circular markers indicate premature deaths in thousands, with marker size proportional to mortality (<10, 10–20, 20–30, 30–40, 40–50, 50–60, 60–70, 70–80, >80 thousand). Insets show Taiwan and South China Sea islands.

but their marginal effectiveness plateaus by 2050. In contrast, low-carbon strategies initially yield modest reductions (1–2% by 2030) but their influence strengthens over time, achieving approximately 10% reductions by mid-century. This dynamic indicates that while end-of-pipe controls drive rapid early gains, sustained long-term air quality improvement and alignment with international standards depend on structural energy transitions such as clean energy substitution and carbon capture deployment.

Spatially, geographic, and economic heterogeneity shapes regional outcomes. Traditional heavily polluted regions such as Beijing-Tianjin-Hebei, the Fenwei Plain, and central China experience significant reductions under stringent policies (e.g., Beijing from 68.3 μg/m³ in 2020 to 27–28.6 μg/m³ in 2050). However, $PM_{2.5}$ concentrations remain higher than those in coastal provinces (e.g., Fujian, 10.4–13.1 μg/m³) due to adverse atmospheric dispersion, frequent dust storms, and industrial concentration[25]. Northwestern provinces such as Xinjiang and Ningxia begin with lower baseline concentrations (29.5–37.0 μg/m³ in 2020) but exhibit limited improvement (21.5–26.6 μg/m³ by 2050), reflecting new high-pollution zones driven by dust emissions and the westward relocation of coal and chemical industries[26]. In contrast, Southwestern (Sichuan-Chongqing) and Yangtze River Delta (Jiangsu-Anhui) regions show the highest responsiveness, with $PM_{2.5}$ reductions exceeding 60% (from 51.1–53.8 μg/m³ to 19.9–20.2 μg/m³).

Health co-benefits

Both carbon mitigation and air pollution control policies substantially reduce mortality risks over time, with low-carbon measures delivering stronger long-term benefits. In 2050, the reference scenario (RET-BP) projects approximately 1.3 million premature deaths (Fig. 6a). By contrast, the integrated deep decarbonization and enhanced pollution reduction scenario (DDP-EP) limits premature deaths to 829,000 (95% CI: 549,000–1,084,000), thereby preventing 514,000 premature deaths and sustaining a steady decline in mortality from 2020 to 2050 (Fig. 6d).

End-of-pipe measures account for the majority of health gains in the early phase. Under the enhanced pollution control only scenario (RET-EP), approximately 304,000 premature deaths are avoided by 2030, increasing to 478,000 by 2050 (Fig. 7b; see Fig. S2 for sectoral details). In contrast, deep decarbonization yields more pronounced long-term benefits; while the enhanced low-carbon policies only scenario (DDP-BP) prevents just over 6000 premature deaths by 2030, this number rises sharply to 53,000 by 2050 (Figs. 6b, 7a), underscoring the sustained effectiveness of carbon mitigation in improving public health.

Overall, these results demonstrate that synergistic implementation of carbon mitigation and air pollution reduction achieves both immediate and lasting health co-benefits. Although population growth and aging increase baseline health risks, while stringent carbon policies amplify the short-term impacts of pollution control and further alleviate long-term mortality burdens.

Provincial health co-benefits display a clear population-economic gradient (Table 1), with densely populated and industrially intensive provinces forming the primary benefit zone. The first tier comprises highly exposed, populous provinces—Sichuan, Shandong, Henan—where approximately 138,000 premature deaths are avoided under the DDP-EP scenario in 2050, accounting for nearly 27% of total national health gains.

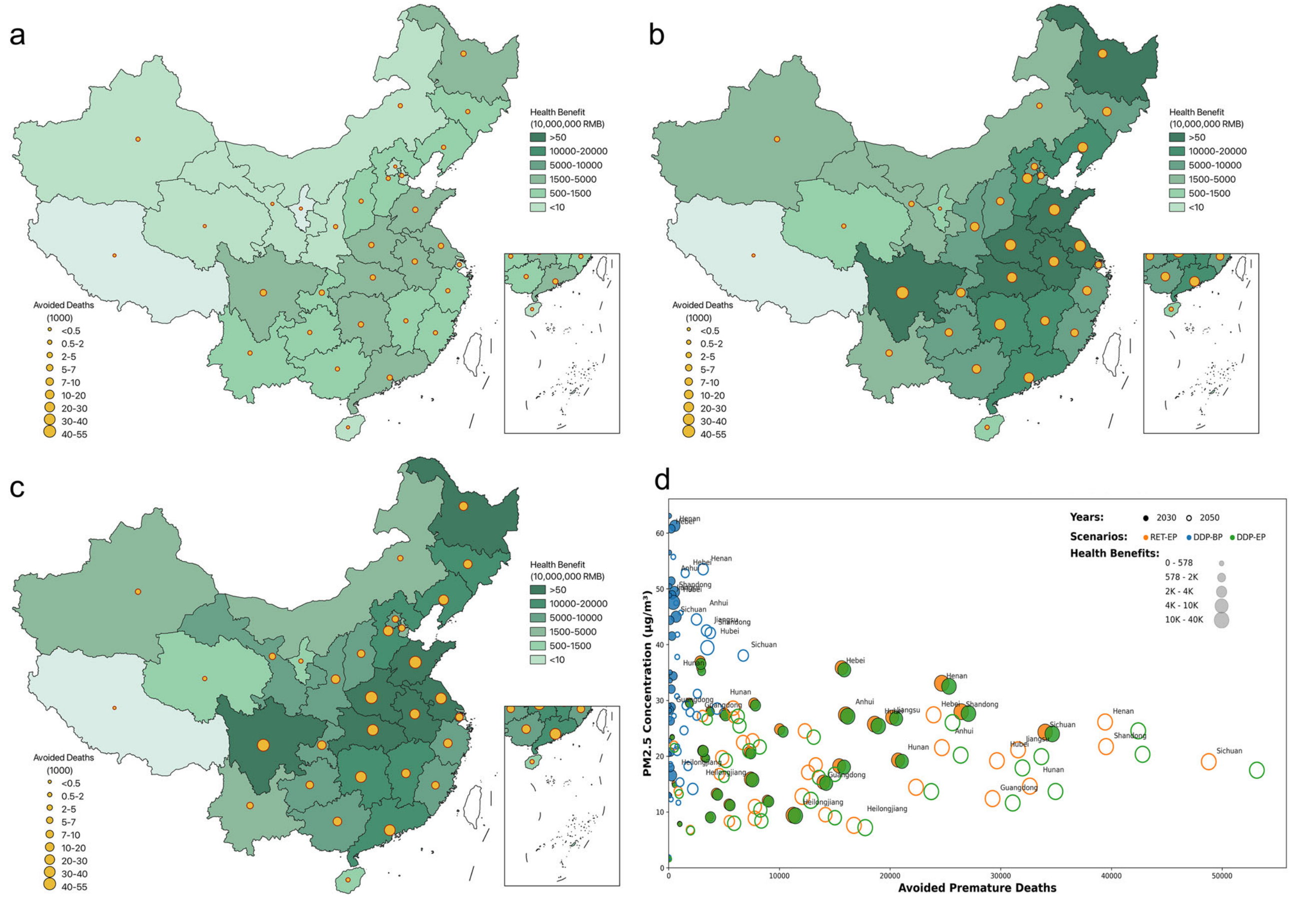


Fig. 7 | Health benefits and avoided premature deaths. This four-panel figure illustrates provincial health co-benefits in 2050. Compare three scenarios relative to the reference scenario: **a** DDP-BP; **b** RET-EP; **c** DDP-EP. Green shading represents monetized health benefits (10 million RMB), with darker shades indicating higher values (<10; 500–1500; 1500–5000; 5000–10,000; 10,000–20,000; >20,000). Orange circular markers represent avoided premature deaths in thousands (<0.5; 0.5–2; 2–5; 5–7; 7–10; 10–20; 20–30; 30–40; 40–55). **d** shows the relationship between avoided premature deaths (horizontal axis) and $PM_{2.5}$ concentrations (vertical axis, μg/m^3) in 2030 (solid points) and 2050 (hollow points). Orange points denote RET-EP, blue points denote DDP-BP, and green points denote DDP-EP. Marker size reflects health benefit magnitude.

Table 1 | Regional differences in health co-benefits

Tier	Typical provinces	Avoided deaths	Key features
Tier 1 (>40,000)	Shandong, Henan, Sichuan	42,419–53,137	Industrial and populous provinces
Tier 2 (20,000–40,000)	Hunan, Jiangsu, Hubei, Guangdong, Hebei	23,725–34,945	Heavy industry clusters, medium population;
			Guangdong exception: high population, low industrial emissions
Tier 3 (<20,000)	Heilongjiang, Chongqing, Zhejiang	5167–17,756	Low industrial intensity or low population density
Peripheral regions	Xizang, Qinghai, Hainan	<5000	Sparse population, low industrialization

Economically advanced coastal provinces experience marginal improvements. For example, although Guangdong maintains relatively good baseline air quality, its large population—approximately 15% of the national total—sustains considerable health risks. The integration of low-carbon industrial transitions with stringent end-of-pipe controls prevents roughly 31,000 premature deaths by 2050 (6% of the national total), placing Guangdong in the second tier of beneficiaries. By contrast, low-density, less developed western provinces such as Xizang and Qinghai yield limited health benefits (<5000 avoided deaths), underscoring the constraining influence of population size and economic activity on the magnitude of health co-benefits. Detailed provincial outcomes are provided in Figs. S3 and S4.

Cost-benefit trade-offs of emission reductions

Health co-benefits exhibit pronounced regional disparities across China. The highest values occur in densely populated and industrially active provinces of central and eastern regions (e.g., Hubei, Henan, Shandong), where total health gains exceed CNY 250 billion under the DDP-EP scenario. Traditional industrial bases in the northeast, such as Heilongjiang (CNY 235.8 billion) and Liaoning (CNY 130.4 billion), also achieve substantial benefits due to industrial restructuring and a declining reliance on heavy industry. In contrast, provinces in the ecologically fragile northwest (e.g., Xizang and Qinghai) contribute less than 0.5% of the national total, reflecting the constraining effects of low population density and limited industrial activity (Figs. S5 and S6). This spatial gradient underscores the strong coupling between population exposure, air quality improvement potential, and regional development patterns.

Integrated strategies that combine carbon mitigation and air pollution control delivers health benefits 1.42 times greater than their associated costs, underscoring their economic sustainability. On one hand, deep decarbonization substantially reduces pollution reduction costs by lowering dependence on fossil fuels. Compared with a strategy focused solely on end-of-pipe measures (CNY 2.9 trillion), the synergistic pathway reduces total control costs by 11% to CNY 2.6 trillion, highlighting the economic efficiency of energy system transformation. On the other hand, synergistic governance substantially amplifies health gains, yielding CNY 3.6 trillion in total benefits—an increase of CNY 3.3 trillion relative to the DDP-BP scenario and CNY 248.5 billion relative to the RET-EP scenario. Overall, the magnitude of health benefits ($3.6 > 2.6$ trillion CNY) far exceeds the corresponding mitigation costs, demonstrating the positive socioeconomic returns of coordinated carbon and pollution control.

Discussion

This study demonstrates that synergistic pollution-reduction and carbon-mitigation strategies can deliver substantial environmental, health, and economic co-benefits for China. By integrating macroeconomic, technological, and health-assessment models, the EEAH framework provides an internally consistent approach to quantify multi-sectoral and regional impacts under coordinated policies. The findings reaffirm that joint actions yield greater benefits than single-objective measures, offering evidence to support China's transition from parallel to integrated environmental governance.

The results highlight clear advantages of synergistic policy design. Compared with single-objective approaches, integrated measures achieve larger emission reductions across CO_2 and conventional pollutants while reducing overall abatement costs. The observed 11% cost saving reflects structural complementarities between energy transition and pollution control, particularly in sectors where clean energy substitution reduces the need for end-of-pipe technologies. Similar synergistic patterns have been observed in global integrated assessment studies[11,14,20], supporting the economic efficiency of coordinated actions. Furthermore, the findings indicate that co-mitigation potential varies across sectors and timeframes. The industrial and power sectors dominate near-term reductions through pollution-control technologies, while deep decarbonization of the energy system drives long-term gains. This sequential pattern aligns with previous evidence that combining short-term air-quality management with long-term low-carbon transition yields optimal co-benefits[8,19].

Beyond mitigation outcomes, the quantified reductions in $PM_{2.5}$ exposure and premature mortality indicate reduced population vulnerability to climate-sensitive health risks, thereby supporting climate adaptation objectives. The observed improvements in air quality monitoring indicators, sectoral emission transparency, and regional policy targeting provide a measurable evidence base for integrated mitigation–adaptation governance. This aligns with recent studies[27–30] highlighting the importance of transparent mitigation accounting systems, national climate monitoring and evaluation frameworks, and sector-specific climate risk management in strengthening adaptive capacity and policy coherence across sectors.

Provincial disparities underscore the importance of region-specific policy design. Industrially intensive and coal-dependent provinces—such as Shandong, Henan, and Shanxi—achieve the largest absolute emission and health benefits but also face the highest marginal abatement costs. In contrast, economically diversified coastal provinces exhibit smaller emission reductions but higher efficiency gains per unit of GDP. This spatial heterogeneity reflects differences in industrial structure, energy intensity, and population exposure, consistent with findings from provincial-level analyses[5,8]. The relative synergy index above 1.0 for most provinces indicates that air-pollution reduction outpaces carbon reduction, suggesting that local pollution controls amplify the benefits of national low-carbon policies. Tailoring strategies to provincial conditions, such as considering factors such as energy mix, demographic exposure, and economic capacity, will therefore be critical for maximizing national co-benefits.

Health gains from integrated policies are substantial. The prevention of approximately half a million premature deaths by 2050 not only represents a major public-health achievement but also generates economic benefits exceeding one trillion CNY. This outcome highlights the public-health value of coordinated mitigation, reinforcing the idea that environmental and health objectives can be mutually reinforcing rather than competing. The estimated benefit–cost ratio of 1.42 suggests that every unit of investment in integrated policies yields significant returns in health and economic terms. These findings complement earlier work showing that health co-benefits can offset a large share of mitigation costs[14,15,31]. Moreover, integrating demographic trends into health assessment—particularly population aging—reveals that future health gains could be partially offset by increasing vulnerability among older populations[4,32]. This underscores the importance of combining air-quality management with broader health and demographic policies.

The transition from short-term end-of-pipe controls to long-term energy restructuring forms a two-phase strategy for achieving both near-term air-quality targets and long-term carbon neutrality. Rapid pollutant abatement technologies can provide immediate improvements in heavily polluted regions, while structural reforms—such as electrification, renewable energy expansion, and industrial upgrading—secure sustainable reductions.

Given strong regional heterogeneity, policy design should follow differentiated pathways. Heavy-industry and coal-dependent provinces (e.g., Shandong, Hebei, Henan) should prioritize ultra-low emission retrofits and fuel substitution, while coastal and service-oriented regions (e.g., Guangdong) should focus on transport electrification, port emission control, and building efficiency. Provinces facing unfavorable dispersion conditions or higher transition costs (e.g., Sichuan) may benefit from a coordinated approach that combines local end-of-pipe measures with regional energy supply optimization and gradual structural adjustment. Policy packages should be dynamically optimized based on provincial emission structures, exposure levels, and marginal control costs, supported by regular integrated assessment and scenario evaluation.

Policymakers should therefore pursue integrated governance frameworks that align emission standards, carbon pricing, and energy-transition incentives. Linking carbon markets with pollutant trading schemes, as piloted in several Chinese provinces, represents a promising step toward institutionalized co-management. The inclusion of health-impact metrics in policy evaluation could further enhance cross-sectoral coordination, enabling decision-makers to prioritize actions with the greatest combined climate and health returns.

These insights are also relevant beyond China. The integrated Energy–Economy–Air Quality–Health framework can be adapted to other rapidly industrializing or energy-transitioning economies by harmonizing national macroeconomic baselines, technology-specific control pathways, and country-specific health exposure data. Aligning mitigation and adaptation governance—through transparent monitoring systems, coordinated climate and air-quality policies, and incorporation of health indicators into evaluation frameworks—can further strengthen institutional coherence and maximize combined climate and public-health benefits across diverse national contexts.

While the EEAH framework improves upon existing models, several limitations remain. First, uncertainties persist in emission factors and health-exposure relationships, particularly regarding secondary pollutants and spatially heterogeneous exposure. Second, the health module relies on province-level averages and does not yet incorporate intra-urban variability or vulnerable subpopulations. Third, dynamic feedbacks between climate change and air quality—such as temperature-induced changes in pollutant formation—are not explicitly simulated. Fourth, the unidirectional soft-linking structure may slightly underestimate total mitigation costs, as feedbacks of end-of-pipe abatement costs to macroeconomic structure are not fully captured. Future research could address these limitations by integrating dynamic atmospheric-chemistry models, finer-scale exposure data, and adaptive policy evaluation methods. Extending the framework to include climate–economic feedbacks and co-benefits beyond health (e.g., ecosystem services and agricultural productivity) would provide a more comprehensive assessment of integrated mitigation pathways.

This study develops a comprehensive Energy–Economy–Air Quality–Health (EEAH) framework to quantify the environmental, health, and economic co-benefits of synergistic pollution-reduction and carbon mitigation strategies in China. Our findings demonstrate that coordinated air-pollution control and carbon-mitigation measures substantially outperform single-objective approaches, achieves deep emission reductions and substantial health and economic co-benefits, with benefits far outweighing mitigation costs. Sectoral and temporal patterns highlight the need to balance near-term control technologies with long-term structural transformation. Provincial heterogeneity calls for flexible, region-specific strategies to optimize co-benefit distribution. Therefore, institutionalizing integrated governance, like linking carbon and pollutant markets and embedding health metrics, can substantially enhance policy coherence and efficiency. The findings also highlight that integrated EEAH frameworks can support coordinated mitigation–adaptation governance and maximize joint climate and public-health benefits across diverse national contexts.

Overall, this study provides a robust analytical foundation and quantitative evidence base for designing cost-effective, health-oriented air–climate strategies in China and offers transferable insights for other developing countries pursuing sustainable and inclusive environmental governance.

Methods

To quantify the health and economic co-benefits of synergistic pollution reduction and carbon mitigation, we developed an integrated Energy–Economy–Air Quality–Health (EEAH) framework. The framework integrates three core modules: CEEPA (China Energy & Environmental Policy Analysis model), a Computable General Equilibrium model capturing macroeconomic and energy-system responses to policy measures; GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies model), which projects emissions under diverse technological and policy scenarios; and the HEALTH (Health Benefits model) estimating provincial-level population exposure, premature mortality, and related economic benefits.

This multi-sector, multi-region framework enables internally consistent estimation of emissions, pollutant concentrations, and health outcomes under integrated climate–air policy scenarios. It incorporates feedback between energy use, technological transitions, and pollution-control strategies, offering both economy-wide and sector-specific insights.

CO_2, as a global pollutant/gas, has climate and environmental impacts that extend beyond provincial boundaries. Under China's "dual carbon" policy framework, provinces dynamically adjust to nationally determined targets, warranting an integrated manner, national-level analysis of carbon emissions. By contrast, the conventional air pollutants exhibit significant spatial heterogeneity, with concentrations, exposures, and associated health impacts shaped by provincial emissions, industrial structure, control technologies, and population distribution. Accordingly, these pollutants are modeled at the provincial level.

To ensure consistency across modules, the CEEPA–GAINS linkage was established using harmonized provincial, sectoral, and fuel classifications. Energy activity data from CEEPA, representing sector- and fuel-specific energy consumption under each carbon mitigation scenario, were adopted as inputs for GAINS. The GAINS model is run independently for each anchor year (2020, 2025, 2030, 2035, 2040, 2045, and 2050), using activity data (energy consumption) provided by the CEEPA model for the corresponding year, with CEEPA calibrated to a 2017 base year and GAINS calibrated to 2020 conditions, while scenario linkage is implemented using CEEPA outputs from 2020 onward. Consistency is ensured because scenario linkage is performed using harmonized activity projections beginning in 2020. Tables S3-1 and S3-2 show the matching between energy types and sectors from CEEPA to GAINS. This ensures that GAINS emission estimates are based on the same energy structures, technologies, and policy assumptions as those in CEEPA. Although the linkage is unidirectional, consistency is maintained through aligned base-year calibration, unified scenario settings, and synchronized projections of economic and energy drivers.

Consequently, GAINS emission and cost results remain compatible with the macroeconomic and sectoral framework generated by CEEPA.

China Energy & Environmental Policy Analysis (CEEPA) model

The CEEPA model is a multi-sector, recursive dynamic computable general equilibrium (CGE) model independently developed by the Center for Energy and Environmental Policy Research at Beijing Institute of Technology. It comprises five core modules: production, income, expenditure, investment, and foreign trade, and represents key economic agents, including households, enterprises, and government[33]. The model captures complex interactions among these different actors within China's macroeconomic system, with its dynamics driven by capital accumulation, population growth, and total factor productivity (TFP) improvement. Equations (1) and (2) define the carbon mitigation policy settings.

$$TOTCTAX = \sum_{fe,i} CT_{fe,i} * CPI * Q_{Pro_{fe,i}} + \sum_{fe,i} CT_{fe,h} * CPI * CD_{fe,h} \tag{1}$$

$$CT_{fe,ih} = \sum_{gas} CTAX * PFfactor_{fe,ih} \tag{2}$$

In these equations, TOTCTAX represents carbon tax revenue (included in government income); $CT_{fe,i}$ is the ad valorem tax rate on use of fossil fuel fe in sector i's production or household h's consumption; CPI is the consumer price index; $Q\_Pro_{fe,i}$ is fossil fuel fe's consumption in production process in sector i; $CD_{fe,h}$ is fossil fuel fe's consumption by households h (urban and rural); CTAX represents the carbon tax rate; and $PFfactor_{fe,ih}$ denotes the emission factor.

Equations (3) and (4) describe gas emissions from production sectors and households, respectively.

$$SecCgas_i = \sum_{fe} PFfactor_{fe,i} * Q_{Pro_{fe,i}} \tag{3}$$

$$HohCgas_h = \sum_{fe} PFfactor_{fe,h} * CD_{fe,h} \tag{4}$$

Here, $SecCgas_i$ represents carbon emissions from sector i, while $Hohgas_h$ represents carbon emissions from households h.

Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model

The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model, developed by the International Institute for Applied Systems Analysis (IIASA), is an integrated assessment framework that simultaneously analyzes air pollutant (e.g., SO_2, NO_X, $PM_{2.5}$) and greenhouse gas emissions. GAINS combines detailed information on emission sources, control technologies, costs, and atmospheric dispersion to project future emission trajectories under varying policy and technology scenarios. It quantifies the interactions between climate and air quality policies by linking economic activities, energy use, and technological choices to pollutant emissions and ambient concentrations. Through its multi-pollutant, multi-sector approach, GAINS enables the evaluation of cost-effective strategies for achieving environmental and health objectives across spatial and temporal scales[34]. Detailed descriptions of the GAINS model are provided by Amann et al.[35], Klimont et al.[36] and Purohit et al.[37]. In this study, GAINS is employed to simulate how sector-specific combinations of emission control technologies influence pollutant emissions, annual average $PM_{2.5}$ concentrations, and associated abatement costs. Emissions are computed using Eq. (5):

$$E_{i,p} = \sum_{k}\sum_{j} A_{i,k} e_{i,k,j,p} x_{i,k,j,p} \tag{5}$$

In Eq. (5), $E_{i,p}$ represents emissions from pollutant p in region i; $A_{i,k}$ denotes activity data level of type k in region i; $e_{i,k,j,p}$ is the emission factor of pollutant p for activity k in region i after application of control strategy j; $x_{i,k,j,p}$ is the share of total activity of type k in region i to which a control strategy j for pollutant p is applied.

Equation (6) represents a simplified linear source-receptor relationship, describing how annual mean $PM_{2.5}$ concentrations respond to precursor emissions of SO_2, NO_X, NH_3, and primary $PM_{2.5}$. This formulation considers only anthropogenic primary PM emissions and the secondary formation of inorganic aerosols contributing to $PM_{2.5}$.

$$PM_n = \sum_{m} pm_m \times PP^A_{mn} + \sum_{m} s_m \times S^A_{mn} + \sum_{m} a_m \times A^A_{mn} + k_{0,m} \tag{6}$$

In Eq. (6), PM_n represents the annual average $PM_{2.5}$ concentration at receptor n ; pm_m, s_m and a_m denote emissions of primary $PM_{2.5}$, SO_2, and NO_X in region m ; PP^A_{mn}, S^A_{mn} and A^A_{mn} represent their respective transfer coefficient matrices ; $k_{0,m}$ is a constant accounting for background concentration.

Health benefit model—HEALTH

The HEALTH model is grounded in the comparative risk assessment framework, which is widely applied in the Global Burden of Disease (GBD) and World Health Organization (WHO) assessments at both global and regional scales. Within this framework, deaths attributable to $PM_{2.5}$ pollution (DAPP) are determined by four key factors: total population, age structure, age- and disease-specific mortality rates, and the population attributable fraction (PAF). Equation (7) defines the DAPP calculation:

$$DAPP = \sum_{a,d}\left(PAF_{a,d} * POP * Rate_{a,d} * AgeP_a\right) \tag{7}$$

In Eq. (7), a and d denote different age groups and diseases, respectively. POP represents the population; AgeP is age group (25–30, 30–35, …, >95, with 15 intervals), based on population data from the SSP2 scenario in Chen et al.[38]. Rate denotes age- and disease-specific mortality rates across six disease categories: ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, acute lower respiratory infections, and type 2 diabetes. PAF represents the proportion of deaths attributable to a given risk factor, determined by $PM_{2.5}$ concentration and the exposure-response function, as defined in Eq. (8).

$$PAF_{a,d} = \frac{RR_{a,d} - 1}{RR_{a,d}} \tag{8}$$

In Eq. (8), RR is the relative risk for different age groups and diseases under a specific $PM_{2.5}$ concentration. This study applies the most recent meta-regression-based exposure-response function (MR-BRT) developed by ref. 39. While this MR-BRT function is estimated at the national level, substantial spatial heterogeneity in air pollution impacts exists across Chinese provinces[32]. To capture this variability, data from China's Disease Surveillance Points system—covering 605 sites, 323.8 million people, and over 80% of deaths—were used to select six $PM_{2.5}$-related causes of death from 359 disease categories. Provincial risk factors were then calibrated against national average mortality risks[40]. These adjusted parameters were integrated with provincial mortality data to construct a health impact assessment model that robustly reflects interprovincial heterogeneity across China's 31 provinces.

To monetize health benefits, this study applies the Value of a Statistical Life (VSL) approach to evaluate the economic benefits from avoided premature deaths due to air pollution reduction, as defined in Eq. (9).

$$VSL_{k,t} = VSL_b \times \left(\frac{G_{k,t}}{G_{2010}}\right)^{\beta} \tag{9}$$

In Eq. (9), $VSL_{k,t}$ denotes the value of VSL for province k in year t, VSL_b is the reference VSL of Beijing in 2010 (1.68 million RMB)[41]. β is the income elasticity of health costs (set to 0.8 per OECD recommendations). G_{2010} is Beijing's per capita GDP in 2010, and $G_{k,t}$ is the per capita GDP for province k in year t.

Scenario design

To evaluate the synergies between carbon mitigation and air pollution control, we developed 14 integrated policy scenarios spanning the period 2020–2050 (Table 2). These scenarios encompass two national-scale carbon mitigation pathways and seven province-level, sector-specific pollution control schemes, yielding a comprehensive matrix of combined policy

Table 2 | Carbon mitigation and pollution reduction scenarios

Carbon mitigation scenarios (2)	Description	Pollution reduction scenarios (7)	Description
RET (Reference energy transition)	**Reference scenario**, simulating a conventional energy transition pathway; carbon emissions in 2050 decline by 40% relative to 2020.	**BP** (Baseline policy)	**Reference scenario**, simulating existing end-of-pipe control policies.
		PT (Power sector target)	**Enhanced control in the power sector:** 100% of captive power plants in key regions achieve full-process ultra-low emission retrofitting; 80% in other regions complete such retrofitting.
		IT (Industrial sector target)	**Enhanced control in the industrial sector:** full coverage of ultra-low emission retrofitting for coal-fired boilers in key regions; phased implementation in other regions.
DDP (Deep decarbonization pathway)	**Deep decarbonization scenario**, simulating an accelerated low-carbon transition; carbon emissions in 2050 decline by 75% relative to 2020.	**TT** (Transport sector target)	**Enhanced control in the transport sector:** phased elimination and upgrading of outdated locomotives.
		RT (Residential sector target)	**Enhanced control in the residential sector:** elimination of bulk coal use in plains regions; increased recycling of municipal solid waste.
		AT (Agriculture sector target)	**Enhanced control in the agricultural sector:** improved efficiency of fertilizer and pesticide use; comprehensive utilization of over 80% of livestock and poultry manure.
		EP (Enhanced policy)	**Enhanced control measures across all sectors, integrating each of the sector-specific targets described above.**

settings. Although carbon mitigation targets are defined at the national level, the modeling framework explicitly captures provincial heterogeneity in energy structure, industrial composition, technology penetration, and baseline emission characteristics across China. As a result, identical national policy targets can lead to differentiated emission and air quality outcomes across provinces. The carbon mitigation scenarios were designed in alignment with China's "dual-carbon" targets and the energy transition pathways outlined by Wang et al[42]. Two variants are considered: Reference Energy Transition (RET)—representing the continuation of existing energy and emission policies; and Deep Decarbonization Pathway (DDP)—depicting an accelerated low-carbon transition consistent with the national carbon peaking and neutrality goals.

The pollution control scenarios draw on more than 100 national and provincial policy documents (see Tables S4-1–S4-3), including the Opinions of the CPC Central Committee and the State Council on Deepening the Fight Against Pollution and the 14th Five-Year Plan for "Zero-Waste City" Development. Based on the stringency of control measures, seven province-specific, sectoral schemes (Table S4-4) were formulated to represent progressive improvements in end-of-pipe technologies, emission standards, and industrial upgrading. The classification of key regions and other regions follows China's official policy designations (see Table S4-5). Across all scenarios, the two principal dimensions of variation are: Carbon-mitigation intensity, ranging from a business-as-usual (BAU) trajectory to a deep decarbonization pathway aligned with China's dual-carbon strategy; and Pollution-control stringency, reflecting differing degrees of technological deployment and regulatory enforcement.

Each scenario integrates sector-specific interventions across the power, industry, transport, and residential sectors, ensuring internal consistency, comparability, and policy relevance. Together, these 14 scenarios provide a robust analytical basis for assessing the co-benefits and trade-offs between carbon reduction and air quality improvement under alternative development pathways.

Cost–benefit analysis

To assess the cost-effectiveness of synergistic strategies, total abatement costs from the GAINS model, which includes the technology-specific costs of end-of-pipe and process-related control measures, are compared with the monetized health benefits from the HEALTH module. This allows evaluation of trade-offs and synergies among single-objective (climate-only or pollution-only) and integrated policies. The framework also identifies sectoral and regional variations in marginal abatement costs and benefits, providing a quantitative basis for prioritizing policy actions.

Data sources

Data inputs for energy consumption, emission coefficients, control technologies, population, and health parameters are derived from official national and provincial statistical yearbooks, the China Energy Statistical Yearbook, China Health Statistical Yearbook, and the GAINS-China database. All monetary values are expressed in constant 2015 CNY for comparability.

Model validation

Model outputs were validated against multiple independent emission inventories, including EDGAR v6.1, CEDS v2024, ABaCAS, and CAMS-GLOB-ANT v6.2, as well as official statistics from the Ministry of Ecology and Environment[43–48]. Detailed comparison figures are provided in Fig. S7.

Simulated CO_2 emissions from energy activities in 2020 closely match the official national report (9.64 Gt vs. 9.66 Gt)[49], confirming the reliability and representativeness of the integrated framework.

Simulated air pollutant emissions for 2015–2020 show consistent declining trends across all datasets (SO_2: −29–83%; NO_X: −18–45%; $PM_{2.5}$: −20–40%), indicating that the integrated modeling framework captures the major structural changes in China's emission pathways. Notably, the officially reported values by MEE are substantially lower than those in research-based inventories, primarily due to differences in accounting scope and definitions. MEE data represent verified post-treatment emissions from key industrial sources, whereas model-based inventories estimate total actual emissions from all sectors. This systematic difference does not imply model bias but reflects methodological divergence between statistical reporting and scientific estimation.

Data availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the corresponding author (liulijing@bit.edu.cn).

Received: 13 November 2025; Accepted: 5 March 2026;

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Acknowledgements

We gratefully acknowledge the financial support of the National Natural Science Foundation of China (grant nos. 72474021, 72293605, and 72488101) and the National Social Science Foundation of China (grant no. 23VRC019), and the Natural Science Foundation of Beijing Municipal (grant no. 9252001). We thank our colleagues for their support and acknowledge help from CEEP-BIT.

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Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s44407-026-00062-9.

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