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Future air quality and human health benefits of net-zero CO_2 emissions pathway in China

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ABSTRACT

While growing attention has been paid to the co-benefits of climate policies, existing research often lacks granularity in evaluating diverse low-carbon transition strategies and their effects on air pollution and public health, particularly within the context of China's rapidly aging demographic. Here, we assess the $PM_{2.5}$ air quality and health co-benefits of a net-zero CO_2 emissions (NZE) pathway aligned with the 1.5 °C global climate target by integrating the Greenhouse Gas-Air Pollution Interactions and Synergies model with updated exposure-response relationships. Compared with China's initial nationally determined contribution scenario – peaking CO_2 emissions around 2030, the NZE pathway reduces SO_2, NO_x and $PM_{2.5}$ emissions by roughly 3900 kt, 4500 kt and 770 kt, respectively, by 2050. These reductions lower national population-weighted $PM_{2.5}$ concentrations to 18.9 μg/m^3, preventing approximately 260,000 premature deaths annually. Guangdong, Shandong, Henan, Sichuan, Jiangsu, and Hubei provinces account for 44 % of the avoided deaths, highlighting significant spatial disparities. Despite these improvements, $PM_{2.5}$-related mortality reductions plateau after 2035, suggesting that climate policy alone may not fully offset health risks from population aging and residual pollution. Nationally, the marginal health benefits of CO_2 abatement rise over time, reaching 77 avoided deaths per million tons of CO_2 reduced by 2050, with particularly high values in Beijing and Hainan. The coefficient of variation for avoided $PM_{2.5}$-related premature deaths per unit CO_2 abatement rises from 1.12 in 2035 to 1.60 in 2050, indicating growing regional inequality. Our findings demonstrate that ambitious decarbonization delivers pronounced air quality and public health benefits while emphasizing the need for regionally tailored policies to ensure equitable outcomes.

1. Introduction

Greenhouse gases (GHG) emissions, primarily carbon dioxide (CO_2), are often co-emitted with air pollutants that contribute to both primary and secondary fine particulate matter ($PM_{2.5}$) formation. Ambient $PM_{2.5}$ pollution represents a severe public health concern in China, responsible for more than one million premature deaths each year (Xie et al., 2020; Huang et al., 2018; Zhang et al., 2019a; Zheng et al., 2018) despite notable air quality improvements since 2013 (Xie et al., 2020; Huang et al., 2018; Zhang et al., 2019a; Zheng et al., 2018). With the country's rapidly aging population, vulnerability to air pollution is expected to rise (Burnett et al., 2018; GBD, 2017 Risk Factor Collaborators, 2018), underscoring the urgency of continued emission reductions to counteract the effects of demographic change. Further improving air quality and reducing associated health losses can not be achieved without concurrent efforts to mitigate climate change, given the mutual origins of CO_2 and air pollutants in human activities. The Paris Agreement has motivated countries worldwide to announce or consider net-zero CO_2 emissions (NZE) targets, and as of 2023 such pledges cover more than 80 % of global emissions (Wang, 2023; International Energy Agency, 2021). Achieving these goals requires fundamental transitions in the energy system, which in turn have the potential to deliver substantial air quality and health co-benefits.

As the world's largest emitter of CO_2, China has progressively updated its climate and energy policies in response to global commitments (Xinhua News Agency, 2022; Liu et al., 2022a). Previous studies have discussed extensively the environmental co-benefits of decarbonization, including reductions in air pollutants (Rafaj et al., 2013; Zhou

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et al., 2019; Lu et al., 2019), improvements in air quality (He et al., 2010; Rive and Aunan, 2010), and associated health gains (Deng et al., 2018; Dong et al., 2015; Chang et al., 2020), under global- and national-scale scenarios. At the global level, these co-benefits exhibit regional disparities, often being more pronounced in developing countries. For example, Rafaj et al. (2013) indicated that the co-reduction of air pollutant emissions from GHG mitigations were estimated to be higher in China compared to the EU-27 and the United States, largely owing to more ambitious shifts in the energy sector and the relatively lower penetration of current air pollution control technologies. West et al. (2013) found that achieving the representative concentration pathway 4.5 (RCP4.5) could prevent approximately 0.4 ± 0.2 million early deaths globally from $PM_{2.5}$ exposure by 2030, with nearly two-third of the benefits accruing to China. Markandya et al. (2018) found that China's CO_2 mitigation efforts aligned with the 1.5 °C target of the Paris Agreement would deliver substantial net benefit ($ 0.27–2.3 trillion), a scale of co-benefit not observed in most developed countries. Additionally, a study in Asia showed that mitigating climate change in line with the 2 °C goal could prevent 0.79 (95 % confidence interval: 0.8–1.8) million premature deaths by 2050 owing to improved air quality, with India and China being the largest contributors, accounting for 0.46 and 0.22 million averted deaths, respectively (Xie et al., 2018).

At the national level, several studies have evaluated the impacts of China's climate or environmental policies on air pollution and public health. For instance, Li et al. (2019) and Xing et al. (2020) investigated the co-benefits for air quality and human health arising from China's NDC commitment. They found that while air pollution will improve under the policy scenario, some areas may still not meet the NAAQS by 2035. Cheng et al. (2023) reported that the joint implementation of clean air initiatives and carbon neutrality strategies can prevent 2.6 (95 % CI: 2.1–3.2) million deaths each year by 2060, with the health benefits increasingly driven by carbon-neutrality measures in the long term. Tang et al. (2022) indicated that implementing the most ambitious climate scenario, namely Shared Socioeconomic Pathways 1 combined with Representative Concentration Pathways 1.9 (SSP1_RCP1.9), is insufficient to prevent the growth of $PM_{2.5}$-related mortality in China. Approximately 800 million people will still be exposed to ambient air with annual average $PM_{2.5}$ concentrations above 35 μg/m^3 in 2050. These studies suggest that relying solely on the co-benefit of climate policies may not be sufficient for China to meet the World Health Organization 2005 Air Quality Guidelines, despite the notable gains in air quality and health outcomes driven by decarbonization efforts. In addition, other studies have examined specific mitigation strategies, including carbon price adjustments (Li et al., 2018), end-use energy electrifications (Peng et al., 2017; Liang et al., 2019), and reductions in residential solid fuel consumption (Liu et al., 2019; Meng et al., 2019). The common conclusion is that the human health co-benefits of CO_2 mitigation can be substantial, depending on the strength and coverage of the decarbonization path.

Despite this progress, there is a lack of comprehensive assessments that quantify the health co-benefits of China's NZE target with provincial resolution, incorporating both long-term population dynamics and spatial disparities in exposure. Health benefits resulting from decarbonization efforts are likely to be unevenly distributed across regions due to the localized nature of $PM_{2.5}$ exposure. This spatial heterogeneity introduces uncertainty regarding the equitable distribution of health co-benefits from climate policies. In this study, we address these gaps by assessing how China's NZE pathway may reduce $PM_{2.5}$ exposure and premature mortality between 2020 and 2050. Using the Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) model combined with the Global Exposure Mortality Model (GEMM), we compare two scenarios: i) NDC2030: reflecting China's NDC under the 2015 Paris Agreement to peak carbon emissions around 2030, and ii) NZE: aligning with a 1.5 °C global warming scenario. These two scenarios translate energy use into CO_2 and key air pollutant emissions – including sulfur dioxide (SO_2), primary $PM_{2.5}$, nitrogen oxides (NO_x), volatile organic compounds (VOCs) and ammonia (NH_3). Our analysis makes three contributions. First, we provide the most up-to-date national and provincial estimates of $PM_{2.5}$ exposure and health burdens under alternative climate policy pathways. Second, we explicitly account for demographic change and population aging, which shape future vulnerability. Third, we evaluate regional disparities in marginal health benefits per unit CO_2 reduction, offering insights into the equity implications of decarbonization. Together, these innovations enhance understanding of the synergies between climate mitigation and public health, informing more integrated and regionally differentiated policy strategies.

China has officially pledged to achieve net-zero CO_2 emissions by 2060. In this study, we focus on the potential air quality and health co-benefits of an accelerated NZE pathway reaching net-zero by 2050. This earlier horizon aligns with the global 1.5 °C climate stabilization target, enabling a more stringent assessment of co-benefits under ambitious decarbonization. It also provides a near-term timeframe to evaluate policy-relevant impacts on population exposure, health outcomes, and regional disparities across provinces.

2. Method

2.1. GAINS model

Air pollutant emissions and associated $PM_{2.5}$ exposure of climate policies are computed using the GAINS model, with energy system activity projections derived from the Global Change Assessment Model (GCAM). GCAM model specifications are summarized in Supplementary Text 1 and further elaborated in the published literature (Ou et al., 2018; Sun et al., 2024). This study employs energy scenarios generated by the Net Zero by 2050 – A Roadmap for the Global Energy Sector project (International Energy Agency, 2021) by introducing the NDC2030 target, along with the NZE target, into GCAM model. These energy consumption outputs are subsequently translated into sectoral energy and industrial activities in the GAINS model. By combining these activity estimations with emission factors in the absence of controls, the removal efficiency of abatement technologies, and their implementation rates, GAINS simulates pollutant emissions under each scenario. The emission of each pollutant is estimated using the following general formula:

$$E_p = \sum_k \sum_m A_k ef_{k,p} (1 - eff_m) \chi_{k,m,p} \tag{1}$$

where, k, m, and p represent the activity, measure, and pollutant, respectively; E_p denotes the emissions of p; A_k is the activity level of k; $ef_{k,p}$ is the 'uncontrolled' emission factor of p for k; eff_m refers to the removal efficiency of measure m, and $\chi_{k,m,p}$ indicates the implementation rate of m for p in activity k.

Given the differences in sector definitions and fuel-type classifications between GCAM and GAINS, mapping matrices are employed to harmonize activity variables between the two models (Supplementary Table S1). While GCAM provides energy sector inputs up to 2050, certain emission sources are not directly covered. To address this, missing information is supplemented based on existing GAINS scenarios or extrapolated from socio-economic indicator such as population and gross domestic product (GDP).

The GAINS model estimates the impacts of climate strategies on air quality using simplified source-receptor relationships. Such relationships are obtained from simulations with the European Monitoring and Evaluation Program (EMEP) chemistry transport model with a spatial resolution of 0.5° × 0.5° (Kiesewetter et al., 2014), which assesses the atmospheric dispersion and chemical transformation of pollutants. In the EMEP simulations, key air pollutant emissions, including SO_2, primary $PM_{2.5}$, NO_x, NH_3 and VOCs, were individually reduced by 15 % for each Chinese province (Amann et al., 2011). This approach captures the nonlinear interactions among precursors in the formation of secondary inorganic aerosols, such as sulfates and nitrates, particularly under wintertime conditions. However, natural sources, along with both primary and secondary organic aerosols, are not considered in the model. Meteorological fields were obtained from the EMEP chemistry transport model's standard meteorological dataset, which is based on the year 2015 and has been widely applied in previous GAINS-related studies (Liu et al., 2019; Purohit et al., 2019). This year was selected as the baseline meteorological condition to ensure consistency across historical and future scenarios. This design isolates the influence of emission changes across scenarios, while holding meteorological variability constant, thereby allowing us to focus on the co-benefits of emission reduction and climate mitigation policies. The resulting $PM_{2.5}$ concentration estimates exhibit general agreement with ground-based observations, indicating the model's capability to replicate observed spatial patterns of air quality (Supplementary Fig. S1). Population and demographic projections were initially processed at a fine spatial resolution of 1 km × 1 km. These were then aggregated to 0.5° × 0.5° grid cells to match the resolution of $PM_{2.5}$ concentrations calculated by the GAINS modeling framework. Within each province, the age group structure was assumed to be spatially homogeneous, and the aggregated population in each grid cell was divided accordingly (Yin et al., 2020). $PM_{2.5}$ exposure was calculated applying the following equation:

$$\rho_k(PM_{2.5}) = \sum_{j\in k} \frac{pop_j}{pop_k} PM_{2.5}(j) \tag{2}$$

where $\rho_k(PM_{2.5})$ is population exposure in region k; pop_k represents the total population of region k; and pop_j indicates the population at receptor j residing in region k.

2.2. Health impact assessment and regional disparities

The long-term health consequences of ambient $PM_{2.5}$ exposure – including stroke (STK), ischemic heart disease (IHD), lung cancer (LC), chronic obstructive pulmonary disease (COPD), and lower respiratory infections (LRIs) – are quantified following the GEMM developed by Burnett et al. (2018). Specifically, premature mortality caused by $PM_{2.5}$ pollution is estimated using the relative risk (*RR*) model, as follows:

$$\Delta Y = A \times Y \times P \tag{3}$$

where ΔY refer to the $PM_{2.5}$-induced health burden; A = 1-1/RR represents the fraction of disease burden attributable to population exposure, with *RR* representing the relative risk for a specific health endpoint; *Y* refers to the background mortality rate for the health endpoint; and *P* stands for the size of the age-specific exposed population. Baseline mortality rates are derived from the Global Burden of Disease (GBD) dataset provided by the Institute for Health Metrics and Evaluation (IHME), and are assumed to remain constant from 2020 to 2050. Similarly, spatial distribution of population is held static throughout the analysis.

The *RR* values are calculated using the GEMM exposure-response function:

$$RR = e^{\left\{\frac{\theta \times \log\left(\frac{C-2.4}{\alpha}+1\right)}{1+e^{\left(-\frac{C-2.4-\mu}{\nu}\right)}}\right\}} \tag{4}$$

where θ, α, μ and ν are parameters that determine the shape of the exposure-response relationships (Burnett et al., 2018); C refers to the ambient $PM_{2.5}$ exposure; Age-specific *RR* are used for IHD and STK, while all-age *RR* estimates are applied for LC, COPD and LRIs. The 95 % confidence intervals (CIs) for health burdens are calculated using the standard error of the *RR* parameter θ, as reported in Burnett et al. (2018).

To address the regional disparities in health co-benefits per unit of carbon reduction across China's provinces, we employ the coefficient of variation (CV) as the indicator (Jbaily et al., 2022), calculated as follows:

$$CV = \frac{STD(B)}{\overline{B}} \tag{5}$$

where B denotes the health benefits per unit of carbon reduction for each province; $\overline{B}$ represents the average value of these benefits across all considered provinces; and *STD (B)* refers to the standard deviation of B across provinces.

2.3. Scenarios

To examine the implications of CO_2 mitigation policies on $PM_{2.5}$ air quality and associated health burdens in China between 2020 and 2050, we developed two emission scenarios: NDC2030 and NZE (Table 1). Both scenarios are grounded in the SSP1, reflecting a sustainable development trajectory characterized by high economic growth and low population growth (Van Vuuren et al., 2017; Riahi et al., 2017). Under SSP1, China's population will peak in 2020 and then decline, while per capita GDP continues to rise (Supplementary Fig. S2).

The NDC2030 scenario serves as the reference pathway, aligning with China's originally submitted version of NDC. Key targets include peaking CO_2 emissions around 2030, reducing emission per unit of GDP by 65 % compared to 2005 levels by 2030, and enhancing the fraction of non-fossil fuels in primary energy use to approximately 20 % by 2030. Besides, the proportion of renewable electricity generation increases from 12 % to 46 % during 2020–2050, while the coal share in primary energy use will drop to 33 % by 2050.

Relative to NDC2030, the NZE scenario delineates a more ambitious mitigation pathway, compatible with limiting global warming to 1.5 °C. In this scenario, the fraction of renewable electricity generation will increase from 12 % to 29 % during 2020–2030 and then increase to 69 % in 2050. By reducing the fossil fuels, the rapid energy transition will happen in China and the coal share in primary energy use will drop to less than 7 % by 2050. Notably, NDC2030 and NZE scenarios assume identical air pollutant emission controls, enabling the isolation of the effects of CO_2 mitigation measures on $PM_{2.5}$ air quality and health outcomes. Detailed climate policy implementations for each scenario are provided in Supplementary Table S2.

3. Results

3.1. Energy use and CO_2 emissions

Fig. 1 illustrates the annual evolution of primary energy consumption and CO_2 emissions under NDC2030 and NZE scenarios during 2020–2050. Achieving a national energy transition leads to a reduction in total energy use and accelerates the shift toward to low-carbon energy technologies (Fig. 1a). In 2020, total primary energy consumption was about 165,000 PJ, with coal accounting for 56 % of total. In the NDC2030 scenario, total primary energy use is projected to rise to

Table 1
Summary of scenarios developed in this study.

Scenario	Socioeconomic assumptions	Climate constraints during 2020–2030	Climate constraints during 2030–2050
NDC2030	SSP 1	CO_2 emissions peak at approximately 12,900 Mt around 2030	CO_2 emissions decrease by 0.2–2.1 % per year in 2030–2050
NZE	SSP 1	CO_2 emissions peak at approximately 12,700 Mt in 2020	CO_2 emissions decrease by 4.4–12.2 % per year in 2030–2050

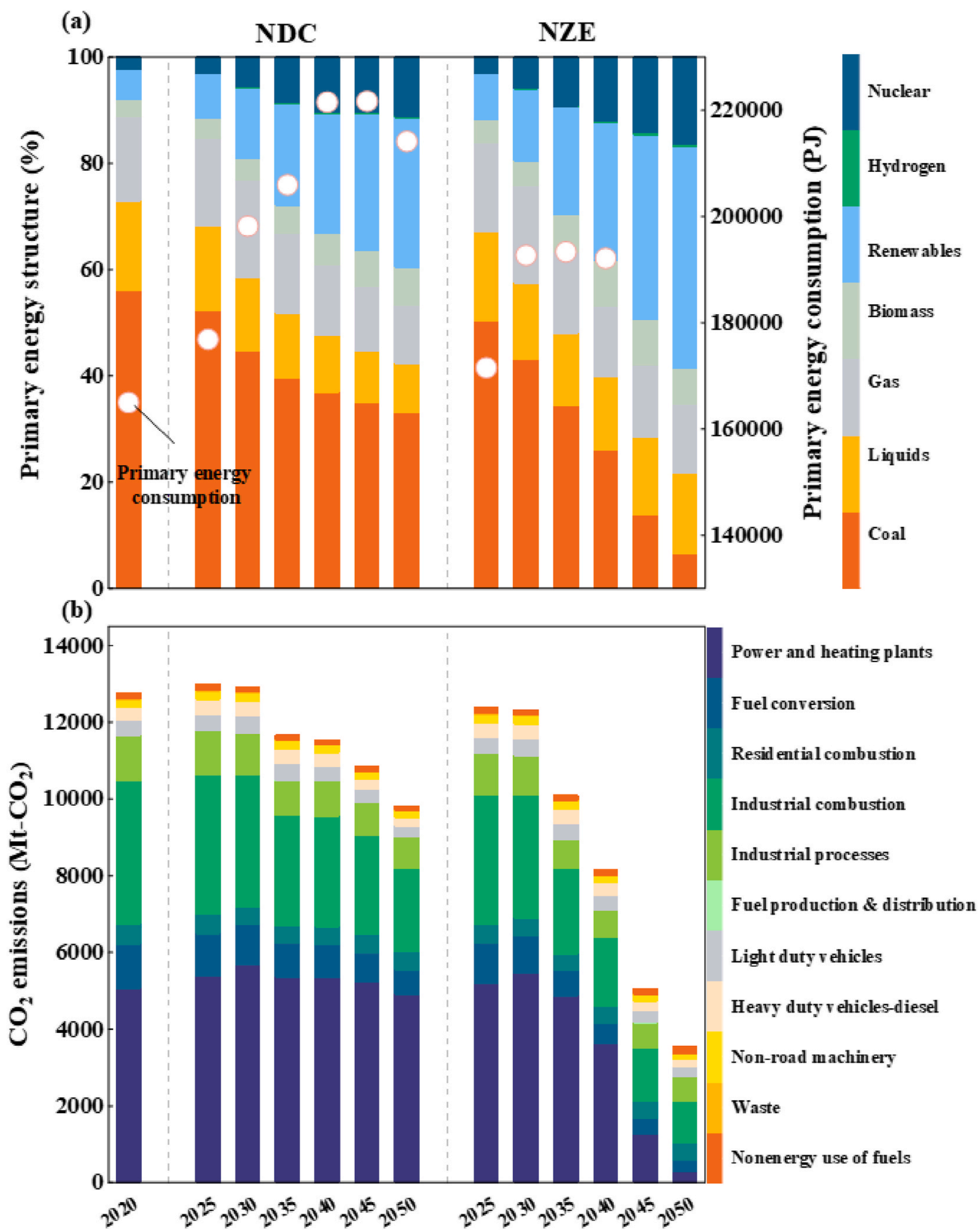

Fig. 1. Evolution of primary energy consumption and CO_2 emissions under NDC2030 and NZE scenarios during 2020–2050. (a) Primary energy structure (stacking histogram with the left Y-axis) and total consumption (circles with the right Y-axis). (b) CO_2 emissions by key sectors.

around 220,000 PJ by 2045 before declining to 210,000 PJ in 2050. Coal will remain the dominant energy source, maintaining a share of over 33 % in total primary energy consumption until 2050.

In contrast, the NZE scenario, which target net-zero emissions, brings significant changes to the energy landscape. On the supply side, there is a gradual transition from fossil fuels to renewable energy sources. On the demand side, key transformations include efficiency improvements, behavioral shifts that reduce energy service demand, and increased electrification. By 2050, total final energy use in the NZE scenario will be 32 % less than in the NDC2030 scenario. The coal share falls to 7 %, reflecting an average annual decrease of 1.6 % from 2020 to 2050. Meanwhile, the renewable fraction rises from 6 % in 2020 to 42 % in 2050. Additionally, nuclear energy will contribute to 16 % of primary energy consumption in NZE by 2050. The proportions of oil and gas remain relatively stable throughout the study period in both scenarios.

The net-zero emissions pathway represented in the NZE scenario results in substantial and earlier CO_2 emission reductions (Fig. 1b). In 2020, national CO_2 emissions were estimated at about 12,800 Mt, with power and heating plants, along with industrial combustion sectors, being the two major sources. Due to their heavy reliance on coal, these two sectors accounted for over 68 % of total emissions (Supplementary Fig. S3). Under the NDC2030 scenario, CO_2 emissions will peak between 2025 and 2030 at about 12,900–13,000 Mt, meeting the 2015 NDC target of reaching peak emissions "around 2030" (Supplementary Table S3). However, in the absence of a net-zero pledges, post-2030 reductions are modest, with CO_2 emissions declining by only 24 % between 2030 and 2050.

Compared to the NDC2030 scenario, CO_2 emissions will keep decrease over time under the NZE scenario, to approximately 3500 Mt by 2050–a 72 % reduction relative to 2020 levels. This is in line with the RCP1.9 scenario (Tang et al., 2022), which projects a CO_2 peak around 2020 (Supplementary Table S3). Under the NZE scenario, the largest reductions occur in the power and heating plants, where emissions decrease by 94 % between 2020 and 2050, primarily due to a substantial decline in coal's share in power generation (Supplementary Fig. S3). Emissions from industrial combustion and industrial processes sectors see relatively smaller reductions of 71 % and 47 %, respectively, over the same period. As a result, these two sectors become the first- and second-largest sources of CO_2 emissions in 2050. In the transportation sector (on-road vehicle and non-road machinery), CO_2 emissions fall by 35 % from 2020 to 2050, driven by widespread electrification. However, emission reductions in the residential combustion sector are limited due to persistent challenges in transitioning away from fossil fuels in rural areas (Jiang et al., 2024).

3.2. Air pollutant emissions

Owing to the 2015-NDC pledges and current clean air policies, emissions of SO_2, NO_x, $PM_{2.5}$, VOCs and NH_3 in 2050 will decrease by 42 %, 44 %, 53 %, 18 %, and 23 % respectively under the NDC2030 scenario, relative to 2020 levels. Under the NZE scenario, these emissions will be further reduced by 65 %, 67 %, 64 %, 21 %, and 25 %, respectively (Supplementary Fig. S4). The following analysis compares the NZE and NDC2030 scenarios for the years 2035 and 2050, as illustrated in Fig. 2.

By 2035, under the NZE scenario, emissions are projected to decline relative to the NDC2030 scenario by about 1350 kt for SO_2, 1130 kt for NO_x, 170 kt for $PM_{2.5}$, −150 kt for VOCs and 14.7 kt for NH_3 compared to the NDC2030 scenario. These reductions are largely ascribed to the deployment of high-efficient technologies, capacity reductions, and the electrification of industrial processes. Collectively, the industry sector (including combustion and process) is estimated to contribute 95 %, 84

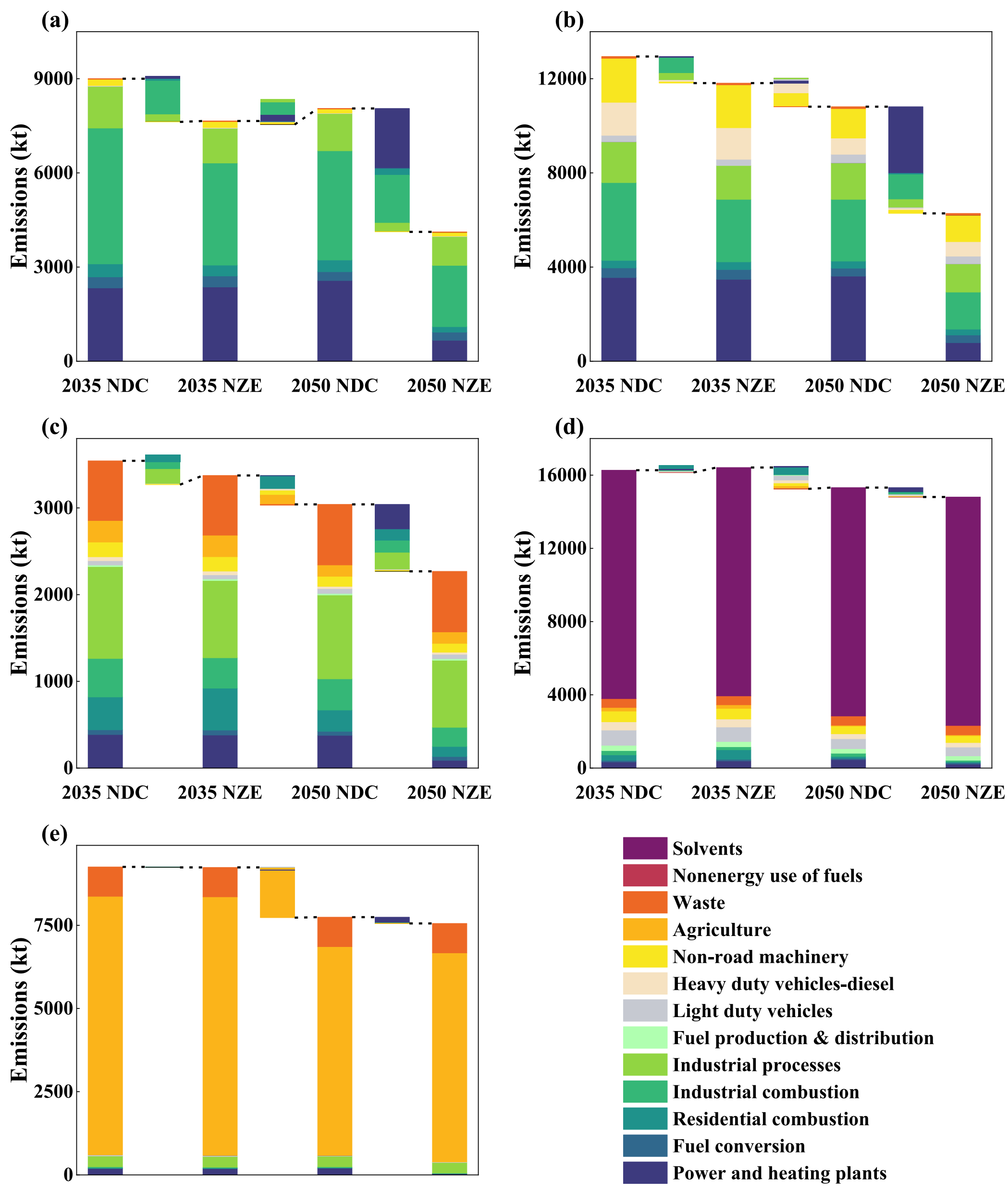

Fig. 2. Sectoral contribution to emission reduction of air pollution under different two scenarios. (a) SO_2, (b) NO_x, (c) $PM_{2.5}$, (d) VOCs and (e) NH_3.

%, and 155 % of the reductions in SO_2, NO_x, and $PM_{2.5}$ emissions, respectively, in 2035 under NZE relative to NDC2030. However, due to the absence of effective emission control measures, emissions of VOCs and $PM_{2.5}$ from the residential combustion sector will increase by 28 % and 73 %, respectively.

The anticipated emission reductions are even more pronounced by 2050 under the NZE scenario, with decreases of approximately 3900 kt for SO_2, 4500 kt for NO_x, 770 kt for $PM_{2.5}$, 510 kt for VOCs and 189 kt for NH_3 compared to the NDC2030 scenario. Power and heating plants emerge as the dominant contributors to these reductions, responsible for 48 % of the SO_2 reduction, 62 % of the NO_x reduction, 37 % of the $PM_{2.5}$ reduction, 47 % of the VOCs reduction, and 89 % of the NH_3 reduction. These substantial decreases are primarily driven by the substitution of fossil fuel-based power generation with renewable and nuclear energy sources (Supplementary Fig. S3). Moreover, the sector of industry (including combustion and process) collectively contributes 46 %, 31 %, and 43 % of the reductions in SO_2, NO_x, and $PM_{2.5}$ emissions, respectively. Promoting clean fuels in the residential combustion sector will lead to 17 % and 5 % cuts in $PM_{2.5}$ and SO_2 emissions, respectively.

While significant declines in SO_2, NO_x and $PM_{2.5}$ emissions are observed when comparing the NZE and NDC2030 scenarios, a similar trend is not evident for VOCs and NH_3. This is because the major sources of VOCs and NH_3 – namely solvent use and agriculture, respectively, – are distinct from the main sources of CO_2 (Supplementary Fig. S5). Given that VOCs and NH_3 are key contributors to secondary $PM_{2.5}$ pollution, clean air measures should place greater emphasis on VOCs abatement from solvent use and NH_3 reductions in agriculture in future.

3.3. Improvements in air quality

Enforcing more stringent climate strategies is expected to improve China's air quality, with more pronounced improvement in the long run (Fig. 3). Under the NDC2030 scenario, the national population-weighted concentration of $PM_{2.5}$ decreases from 30.2 μg/m^3 in 2020 to 24.3 μg/m^3 in 2035 and 22.4 μg/m^3 in 2050, Adopting the more ambitious NZE scenario can further reduce these concentrations to 23.2 μg/m^3 in 2035 and 18.9 μg/m^3 in 2050, representing additional reductions of 4 % and 16 %, respectively, compared to the NDC2030 scenario.

Different spatial patterns of $PM_{2.5}$ reductions are observed when comparing NZE and NDC2030 for the years 2035 and 2050. In 2035, Sichuan province experiences the greatest $PM_{2.5}$ reductions under the NZE scenario compared to the NDC2030 scenario. By 2050, substantial reductions extend to Henan, Shannxi, Chongqing and Hubei provinces, in addition to Sichuan. In addition, these spatial patterns of changes in population-weighted concentrations do not follow the same spatial patterns as the emission changes. For example, emission reduction

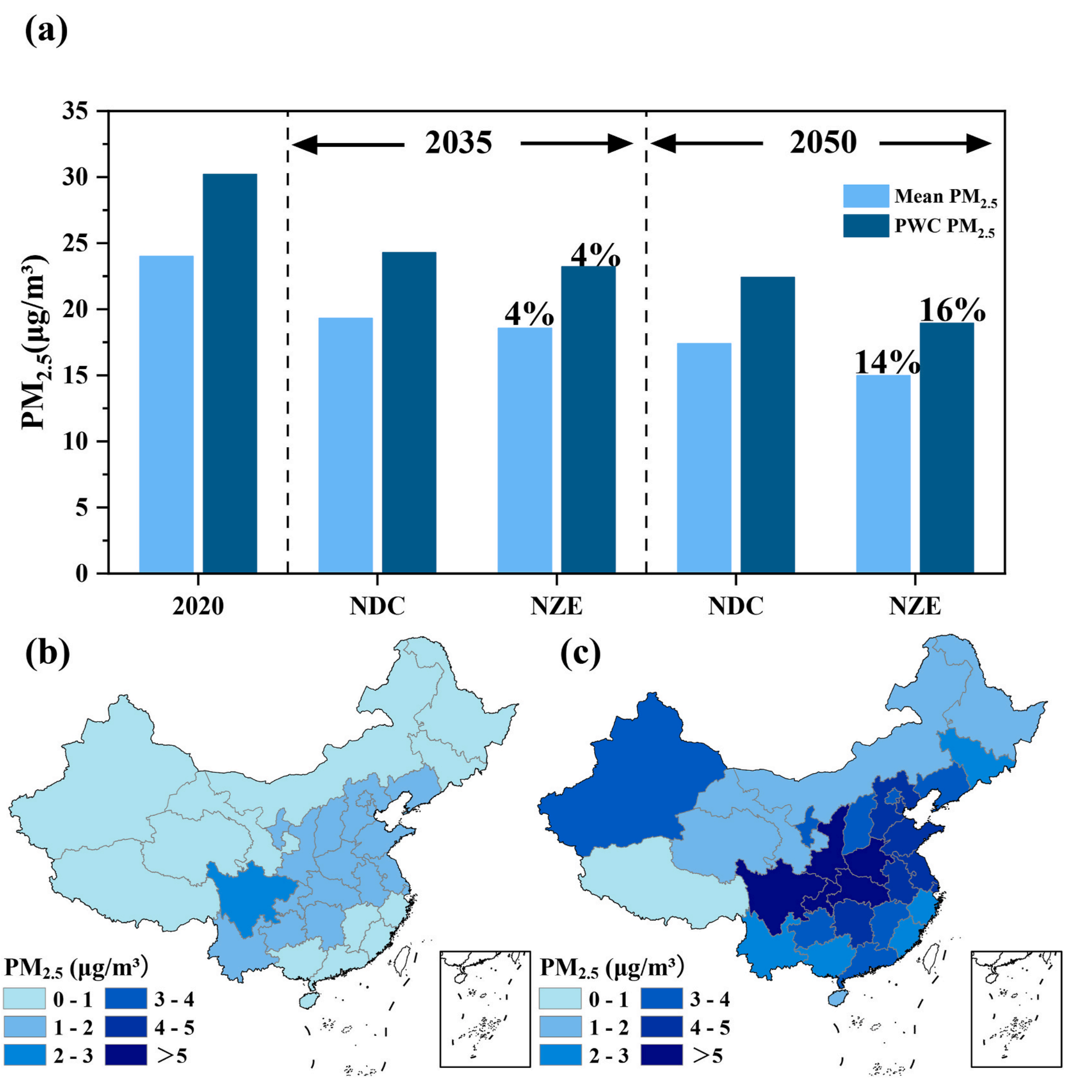

Fig. 3. Changes in $PM_{2.5}$ concentrations from climate policies under two scenarios. (a) The population-weighted $PM_{2.5}$ concentrations (PWC-$PM_{2.5}$) and the annual mean $PM_{2.5}$ concentrations under two scenarios in 2035 and 2050. Fractional changes relative to the NDC2030 scenario are noted; (b, c) Spatial distribution of the PWC-$PM_{2.5}$ changes between the NZE scenario and the NDC2030 scenario in 2035 and 2050, respectively.

hotpots are observed in Hebei provinces when comparing the NZE and NDC2030 scenarios in 2035 (Supplementary Fig. S6). This discrepancy arises because the formation and transport dynamics of secondary $PM_{2.5}$ from gaseous precursors (e.g. VOCs, SO_2 and NO_x) can weaken the spatial relationship between emission reductions and concentration decreases (Zhai et al., 2019; Cai et al., 2018).

Despite the air quality improvements brought by climate policies, these measures alone may be insufficient. Even under the NZE scenario, Hebei, Henan and Tianjin are projected to have population-weighted $PM_{2.5}$ contents exceeding the national standard grade II of 35 μg/m^3 in 2035 (Supplementary Fig. S7). This outcome falls short of the "Beautiful China" strategy's objective, which aims to reduce $PM_{2.5}$ concentrations in all Chinese cities to 35 μg/m^3 or lower by 2035. These indicate that more extensive efforts are necessary to mitigate air pollution, especially targeting VOCs and NH_3 emissions.

3.4. related health impacts

Fig. 4 illustrates the health risks associated with exposure to ambient $PM_{2.5}$. The estimated number of premature deaths in China due to ambient $PM_{2.5}$ exposure in 2020 is about 1.24 million (95 % CI, 0.81–1.62 million). The leading causes were ischemic heart disease (IHD), followed by stroke and lower respiratory infections (LRI), which is broadly consistent with prior studies (Huang et al., 2018; Zhang et al., 2021a). By 2035, premature deaths are projected to increase to approximately 1.41–1.46 million under both the NZE and NDC2030 scenarios and further to 1.46–1.72 million by 2050, even though population-weighted $PM_{2.5}$ concentrations are expected to decline by 4 % and 16 % in 2035 and 2050, respectively. The primary driver behind this increase is the aging of the population (Supplementary Table S4).

Nevertheless, NZE scenario offers significant human health benefits compared to the NDC2030 scenario, with co-benefits that become more pronounced over time. For example, under the NZE scenario, premature deaths due to $PM_{2.5}$ are 3 % (approximately 51,000 fewer deaths) lower than under the NDC scenario by 2035, and 15 % (about 260,000 fewer deaths) lower by 2050. At the provincial level, the largest numbers of decreasing premature deaths in 2035 appear in central and eastern China, where both population densities and $PM_{2.5}$ concentrations are highest (Supplementary Figure S7 and Figure S8). This aligns with prior research indicating that the effectiveness of mitigation measures has a greater impact on regional health outcomes in densely populated areas (Xie et al., 2020; Zhang et al., 2021a). By 2050, however, the reductions in mortality are observed from Guangdong province in the south to Liaoning province in the north. It is estimated that approximately 25, 200 (95 % CI, 16,900–32,800), 21,600 (95 % CI, 14,600–27,900), 19, 700 (95 % CI, 13,300–25,200), 17,500 (95 % CI, 11,900–22,400), 17, 400 (95 % CI, 11,800–22,400) and 14,200 (95 % CI, 9570–18,300) premature deaths can be avoided in Guangdong, Shandong, Henan,

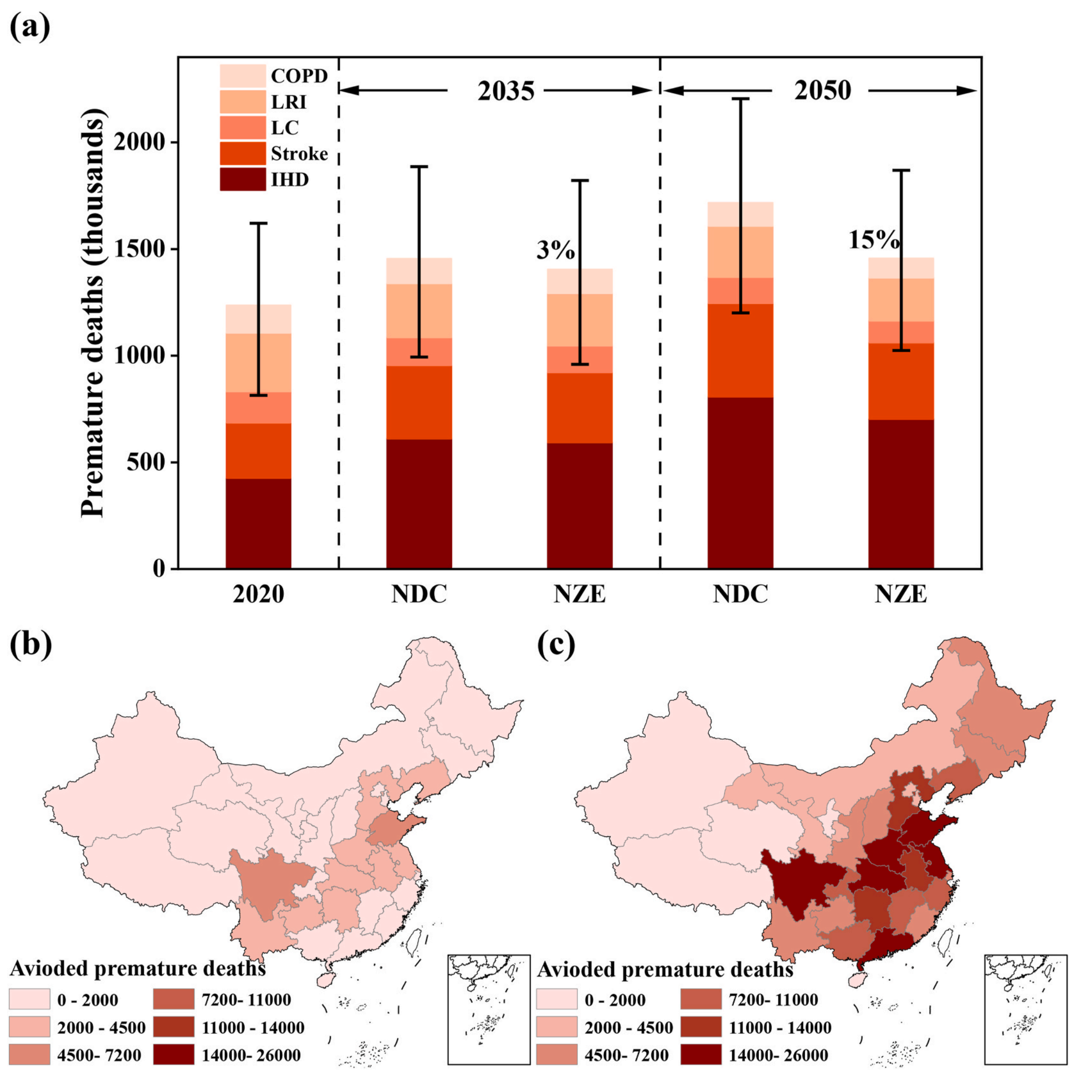

Fig. 4. p.m.$_{2.5}$-attributable mortality and that avoided under different scenarios. (a) National total $PM_{2.5}$-attributable mortality; (b, c) Differences of $PM_{2.5}$-attributable mortality between the NZE scenario and the NDC2030 scenario in 2035 and 2050, respectively.

Sichuan, Jiangsu and Hubei provinces, respectively, which together account for 44 % of the national total.

Fig. 5 shows the avoided $PM_{2.5}$-related premature deaths per million tons of CO_2 abated for each province under the NZE scenario compared to NDC2030. The marginal health benefits of CO_2 reduction are projected to become more pronounced in the long run. In 2035, an average of 57 (95 % CI, 30–70) $PM_{2.5}$-attributable premature deaths per million tons of CO_2 reduced can be avoided nationwide, increasing to 77 (95 % CI, 50–90) by 2050. Regionally, provinces with higher marginal health benefits of CO_2 reduction generally shift eastward from 2035 to 2050. For instance, the number of eastern provinces with benefits greater than 50 avoided deaths per million tons of CO_2 abated rises from 5 in 2035 to 7 in 2050, while the corresponding number in western provinces decrease to 2. This trend aligns with the faster population growth rates observed in eastern China (Supplementary Fig. S9).

Nevertheless, significant spatial heterogeneity exists in the marginal health benefits of CO_2 reduction among the provinces, becoming more evident over the long term. In 2035, a substantial discrepancy of approximately 136-fold is observed across provinces. Beijing exhibits the highest marginal benefits at 273 (95 % CI, 186–353) deaths/Mt CO_2, followed by Hainan with 193 (95 % CI, 132–250), while Xinjiang province records the lowest value at 2 (95 % CI, 1–3). This spatial variability arises from the combined effects of higher health burdens due to dense populations and relatively lower CO_2 emissions in these provinces. For instance, Beijing and Hainan, with their lower CO_2 emissions, exhibits high health benefits from CO_2 reduction, although Hainan bears limited health burdens in 2035 (Supplementary Table S5).

Moreover, we further calculate the coefficient of variation (CV) for avoided $PM_{2.5}$-related early deaths per million tons of CO_2 reduced for years 2035 and 2050. Nationally, the CV increases from 1.12 in 2035 to 1.60 in 2050, indicating a growing disparity in the marginal health benefit of CO_2 reduction among provinces as China progress toward net-zero emissions. This outcome underscores the need for tailored decarbonization strategies to reduce regional disparities and ensure equitable health benefits nationwide.

4. Discussion

4.1. Comparison with previous studies

We compare CO_2 emissions and population-weighted $PM_{2.5}$ concentrations under both less stringent and stringent climate scenarios in China, based on our study and previous research, along with the corresponding reductions in premature deaths associated with these scenarios (Fig. 6). Various decarbonization pathways toward carbon neutrality have been proposed, and we have selected representative pathways that focus on the air quality and health benefits of CO_2 reduction. From Fig. 6a, our estimated CO_2 emissions for base year 2020 are higher than those reported in other studies by 1–37 %. These discrepancies can be attributed to differences in emission factors, emission-source frameworks, scopes of CO_2 emissions, and base years used. For example, Cheng et al. (2023) (Cheng et al., 2023) adopted local emission factors to estimate CO_2 emissions, whereas the GAINS model employed the Intergovernmental Panel on Climate Change (IPCC) recommended emission factors. Ding and Zhang (2022) (Ding and Zhang, 2022) observed that China's CO_2 emissions, calculated using the IPCC emission factor, were approximately 10 %–15 % higher than those derived local emission factors. Most studies including us project that under less stringent climate scenarios–such as the NDC2030, SSP1_REF, and "on time" scenarios–national CO_2 emissions will peak around 2030–2040 before slowly decrease to about 9900–11,900 Mt by 2050, while under stringent climate scenarios–such as the 1.5 °C, SSP1_RCP1.9, and "on time_net zero" scenarios–China is expected to peak its emission before 2030 and see a more rapid decline to 900–5000 Mt by 2050.

Fig. 6b shows that the implementation of stringent climate policies provides additional reductions in $PM_{2.5}$ exposure across studies for the years 2030, 2035 and 2050, compared to scenarios with less stringent climate targets. And the air quality benefits projected in our study are generally lower than those reported in most other studies, with the exception of Conibear et al. (2022) (Conibear et al., 2022). For instance, Cheng et al. (2023) (Cheng et al., 2023), Tang et al. (2022) (Tang et al., 2022), Li et al. (2018) (Li et al., 2018), Liu et al. (2022) (Liu et al., 2022b) and Zhang et al. (2021) (Zhang et al., 2021b) found that stringent climate mitigation scenarios could lower $PM_{2.5}$ exposure by 5.9–9.1 μg/m^3 in 2050 beyond what would be achieved under less stringent climate policies–greater than our estimated reduction of 5.1 μg/m^3, which is 16 %–78 % lower. Additionally, the air quality improvements from climate policies are projected to grow over the longer run. For example, Li et al. (2019) (Li et al., 2019) reported that achieving the "well below 2 °C target" (WBD2) climate target would result in a 7.3 μg/m^3 reduction in $PM_{2.5}$ exposure beyond the NDC pledge in 2050, representing an improvement 304 % greater than the reduction observed in 2030.

In terms of health benefit (Fig. 6c), our estimated avoided premature deaths in 2035 and 2050 associated with less stringent and stringent climate scenarios are lower than those reported in other studies, except for Conibear et al. (2022) (Conibear et al., 2022) and Li et al. (2019) (Li et al., 2019) in 2050. The main reason for the difference can be ascribed to the larger air quality benefits in other studies, leading to greater health benefits. Similar to air quality benefits, more substantial human

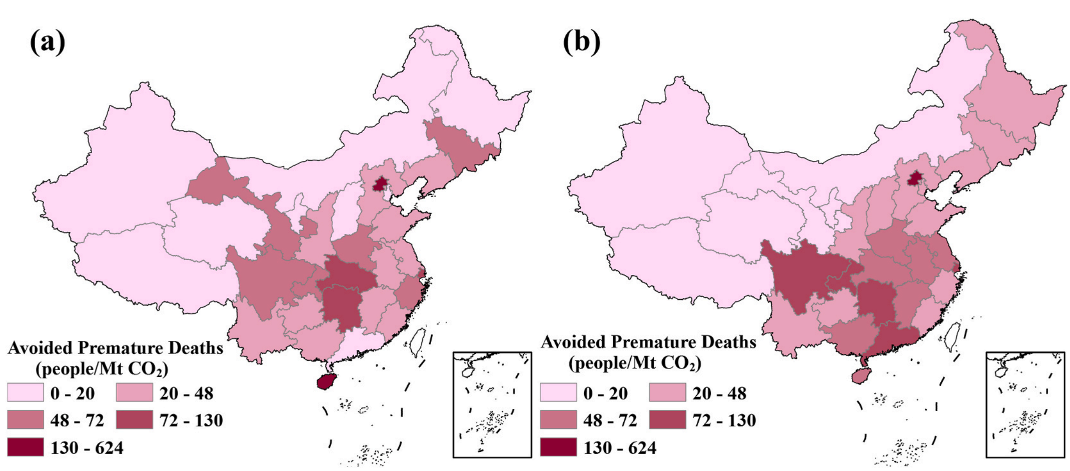

Fig. 5. Avoided $PM_{2.5}$-related premature deaths per million tons of CO_2 abated at each province under the NZE scenario compared to the NDC2030 scenario. (a) 2035, (b) 2050.

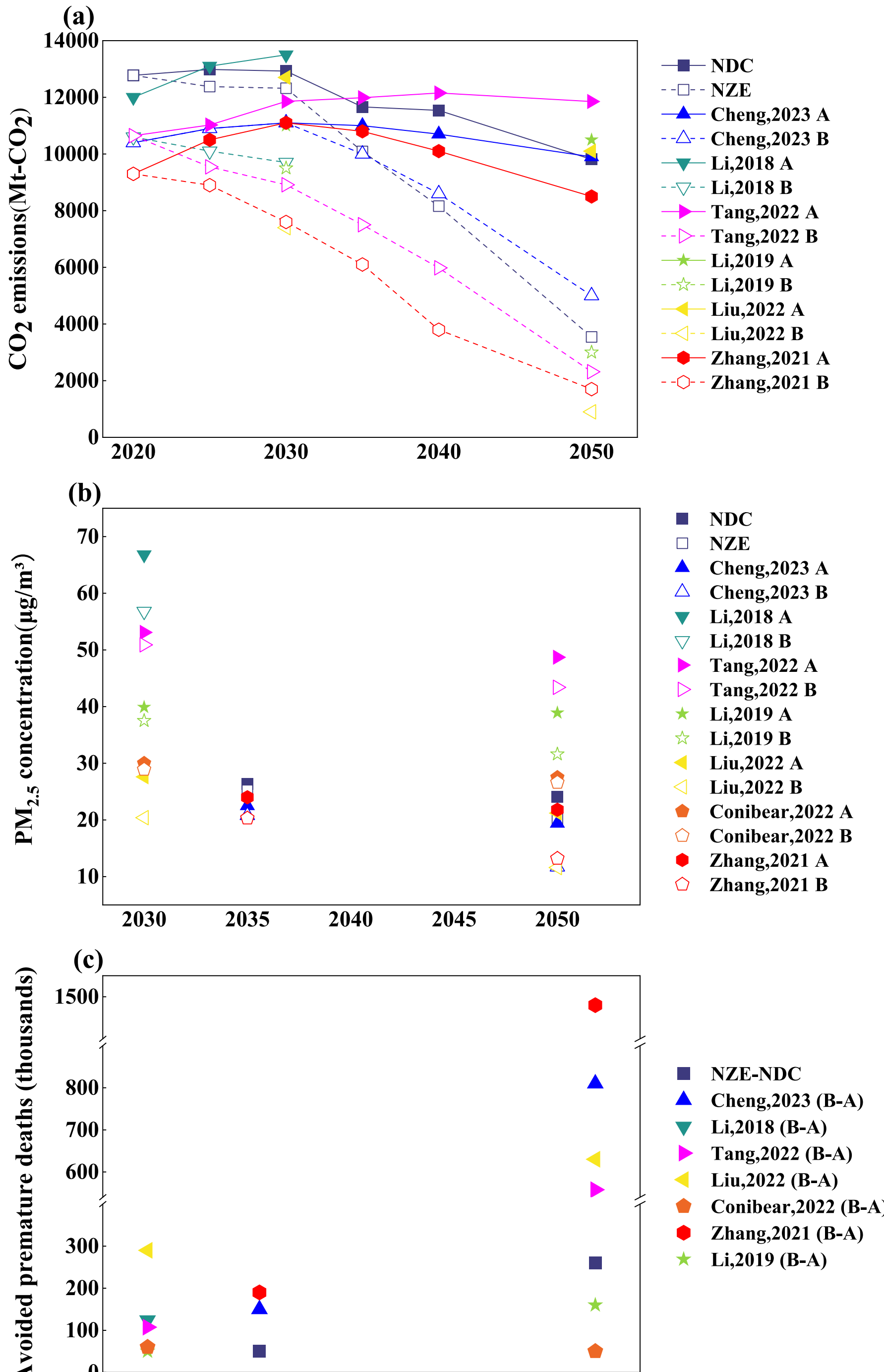

Fig. 6. Comparison with other studies.
Note: Cheng (2023 A: on time + clean; 2023 B: on time_net zero + clean); Li (2018 A: 3 % POL; 2018 B: 5 % POL); Tang (2022 A: SSP1_REF; 2022 B: SSP1_RCP1.9); Li (2019 A: NDC; 2019 B: WBD2); Liu (2022 A: NDC; 2022 B: 1.5 °C); Conibear (2022 A: BASE; 2022 B: SDS); Zhang (2021 A: NDC; 2021 B: Carbon Neutral).

health benefits are observed over time across various studies. For instance, avoided premature deaths range from 50,000 to 290,000 in 2030 and 2035 across different studies, increasing to 160,000–1,210, 000 by 2050. In addition, the variability in health benefits across studies is more pronounced in 2050 than in 2030 and 2035. Apart from scenario design, exposure-response functions (ERFs), and parameter settings, uncertainties related to demographic changes are crucial factors influencing these outcomes.

4.2. Limitations

Our study is subject to several limitations. First, uncertainties associated with net-zero emission pathways are not explicitly discussed, yet they can significantly influence synergistic benefits for air quality and public health. There are multiple pathways to achieve net-zero CO_2 emissions, and the NZE scenario analyzed here represents one possible trajectory, rather than the definitive route to net-zero emissions. The realized co-benefits will depend on various factors, including renewable energy fraction in the power mix, the adoption of emerging technologies, and the extent of behavioral changes (International Energy Agency, 2021; Guo et al., 2023). These aspects warrant further research to better understand how different decarbonization strategies affect air quality and health outcomes. Nevertheless, the co-benefit results derived from the NZE scenario in this work are broadly consistent with other research (Fig. 6), showing aligned trends in CO_2 emissions, $PM_{2.5}$ concentrations and associated health impacts.

Second, in order to isolate the effects of climate measures on air pollution, our scenario analysis does not incorporate dedicated air pollution controls. Emissions of certain air pollutants originating from non-energy sectors–such as NH_3 from agricultural activities and VOCs from solvent use–are not significantly affected by CO_2 mitigation efforts, yet they can have substantial environmental and health implications. For example, Cheng et al. (2021a) discovered that agricultural NH_3 emissions contributed almost 25 % to ambient $PM_{2.5}$ levels in the northern China provinces in 2018. In addition, VOCs play a significant role in the formation of both ozone and secondary $PM_{2.5}$ and are associated with a range of carcinogenic and non-carcinogenic health risks to humans (Zhang et al., 2006).

Third, our air quality modeling relies on a reduced-form source-receptor relationship, which does not explicitly represent primary and secondary organic aerosol formation processes (Kiesewetter et al., 2014; Amann et al., 2011). This simplification can lead to an underestimation of total $PM_{2.5}$ mass, as secondary organic aerosol is recognized as an important component of fine particulate matter in many regions (Singh et al., 2021). To evaluate the magnitude of this potential bias, we compared simulated annual mean $PM_{2.5}$ concentrations with surface observations from 339 cities across China in 2020. The results showed a high degree of agreement ($R^2 = 0.89$) with a modest mean bias of +2.34 $\mu g/m^3$, corresponding to an approximate 5 % deviation at the national scale (Supplement Fig. S1). While this bias indicates that absolute concentrations may be slightly underestimated, its influence on our results is expected to be limited, because the primary focus of this study is on the relative differences across scenarios rather than the exact absolute levels. Nonetheless, future studies should incorporate more comprehensive chemical transport models, such as Weather Research and Forecasting model with Chemistry (WRF-Chem) and the Community Multiscale Air Quality model (CMAQ), to explicitly account for organic aerosol formation and to further refine estimates of $PM_{2.5}$-related health impacts.

Forth, this study is based on national- and provincial-level modeling rather than community-based observations. As such, the findings may not fully capture local variations in exposure, vulnerability, and health impacts at the community level. The results should therefore not be generalized directly to all contexts or specific populations. Future community-based or city-level studies would be valuable for validating our conclusions and for providing more precise evidence to guide localized policy interventions.

Besides, all scenarios used 2015 meteorological fields, which may lead to an overestimation of future air quality benefits from climate policies, as they do not consider the potential adverse effects of future meteorological variations on air quality (Zhang et al., 2019b; Xue et al., 2021). Another important caveat is associated with the health impact. Uncertainties in exposure-response functions and background mortality rates can substantially affect estimates. In this study, background mortality rates are derived from China-specific data reported in the Global Burden of Disease study for the baseline year. These rates were used within the Global Exposure Mortality Model (GEMM) to estimate $PM_{2.5}$-attributable premature deaths. Future changes in mortality rates were also not considered, which may result in an overestimation of $PM_{2.5}$-related premature deaths by 2050 (Rafaj et al., 2021). Furthermore, although $PM_{2.5}$ accounts for a health burden roughly 6 times greater than that of ozone (Westervelt et al., 2019), future research should aim to integrate both $PM_{2.5}$ and O_3-related health impacts into the GAINS model to offer a more thorough evaluation of the public health benefits associated with decarbonization.

4.3. Policy implications

Despite inherent limitations and uncertainties, our results provide several policy implications. First, air quality and human health improvements are a valuable co-benefits of climate policy, which tend to increase over the long term with greater policy stringency. Under the NZE scenario, we project reductions in $PM_{2.5}$-related premature deaths by 3 % in 2035 and 15 % in 2050 compared to the NDC2030 scenario (Fig. 4). These improvements are mainly driven by the increased use of renewable and nuclear energy sources, advancements in energy efficiency, and reduction energy demand across power generation, industrial combustion and process, residential, and transportation sectors. On the supply side, transitioning to zero-carbon energy entails addressing the intermittency and low inertia challenges associated with solar and wind energy and scaling up large-scale nuclear reactors with enhanced safety features. On the demand side, optimizing energy utilization is crucial. This includes electrification of end-use sectors, implementation of process optimization technologies, and utilization of heat or material recycling (Guo et al., 2023). Furthermore, reducing excessive energy consumption through energy-saving practices in households and promoting shifts to more sustainable transport modes, such as cycling, walking, or ridesharing, can significantly contribute to energy efficiency.

Second, the health co-benefits of CO_2 mitigation exhibit substantial regional disparities. Provinces with greater population densities and intensive industrial activities, such as Beijing, Henan, Guangdong, and Hunan, are poised to experience more significant reductions in $PM_{2.5}$-related early deaths per million tons of CO_2 reduced (Fig. 5). Conversely, less densely populated and industrialized regions like Xinjiang, Qinghai, Tibet, and Inner Mongolia may see comparatively modest benefits. To address these disparities, implementing targeted interventions, such as community-focused mitigation measures and sector-specific policies (Yu et al., 2023; Picciano et al., 2023), will be crucial for equitable improvements in air quality and human health throughout China. In fact, Chinese government has initiated measures to promote environmental justice. For instance, in 2016, the National Health and Family Planning Commission launched the 'Implementing the Health and Medical Assistance Program for Poverty Alleviation', emphasizing health-related poverty and alleviation and providing support to economically disadvantaged populations affected by environmental challenges (Material for the press conference of the State Council and Information Office, 2016).

Last but not least, relying solely on decarbonization strategies may be insufficient to achieve desired air quality and health outcomes. Even under the NZE scenario, projections indicate that by 2035, population-weighted $PM_{2.5}$ concentrations in provinces such as Hebei, Henan, and Tianjin may still exceed national air quality standard of 35 $\mu g/m^3$ (Fig. S7). Moreover, considering the aging population, climate policies alone may not effectively reduce national $PM_{2.5}$-related mortality from 2020 to 2050 (Fig. 4). Therefore, it is imperative to implement stringent air pollution control measures to comprehensively safeguard public health. These measures include completing ultra-low emission retrofits in non-electric industries such as steel and cement, enforcing China VII emission standards for on-road mobile sources (e.g., light-/heavy-duty vehicles), implementing China IV standards for non-road machinery, enhancing manure management in livestock, and substitution with low-solvent products in solvent use sector (Xing et al., 2020; Cheng et al., 2021b).

5. Conclusions

This study assessed the air quality and health co-benefits of China's net-zero CO_2 emissions (NZE) pathway, demonstrating substantial co-benefits for energy transition, air quality improvement, and public health. Under the NZE scenario, the share of coal in primary energy use declines from 56 % in 2020 to just 7 % in 2050, while renewables rise to 42 %. These structural changes drive a 72 % reduction in CO_2 emissions relative to 2020 levels, alongside additional cuts of about 3900 kt SO_2, 4500 kt NO_x, and 770 kt $PM_{2.5}$ in 2050 compared with the NDC2030 scenario. As a result, national population-weighted $PM_{2.5}$ concentrations fall to 18.9 μg/m^3, enabling avoidance of about 260,000 premature deaths annually by 2050. At the provincial level, Guangdong, Shandong, Henan, Sichuan, Jiangsu, and Hubei together contribute 44 % of these avoided deaths, underscoring spatial disparities in health gains. Furthermore, the marginal health benefits of CO_2 abatement are projected to increase over time, reaching 77 avoided premature deaths per million tons of CO_2 reduced nationally in 2050, with particularly high values in Beijing and Hainan. However, the coefficient of variation for avoided $PM_{2.5}$-related early deaths per million tons of CO_2 reduced increases from 1.12 in 2035 to 1.60 in 2050, suggesting that while decarbonization delivers large national gains, the distribution of those gains is uneven, raising questions about equity and policy design.

CRediT authorship contribution statement

Yuhang Zhao: Methodology, Formal analysis, Data curation. **Yun Shu:** Writing – review & editing, Writing – original draft, Validation, Supervision. **Hong Sun:** Software, Conceptualization. **Shaohui Zhang:** Project administration, Methodology. **Yinhe Deng:** Validation, Resources.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aeaoa.2025.100374.

Data availability

Data will be made available on request.

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