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Original Research

Optimizing air quality and health Co-benefits of mitigation technologies in China: An integrated assessment

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ABSTRACT

Carbon mitigation technologies lead to air quality improvement and health co-benefits, while the practical effects of the technologies are dependent on the energy composition, technological advancements, and economic development. In China, mitigation technologies such as end-of-pipe treatment, renewable energy adoption, carbon capture and storage (CCS), and sector electrification demonstrate significant promise in meeting carbon reduction targets. However, the optimization of these technologies for maximum co-benefits remains unclear. Here, we employ an integrated assessment model (AIM/enduse, CAM-chem, IMED|HEL) to analyze air quality shifts and their corresponding health and economic impacts at the provincial level in China within the two-degree target. Our findings reveal that a combination of end-of-pipe technology, renewable energy utilization, and electrification yields the most promising results in air quality improvement, with a reduction of fine particulate matter ($PM_{2.5}$) by −34.6 μg m^{-3} and ozone by −18.3 ppb in 2050 compared to the reference scenario. In contrast, CCS technology demonstrates comparatively modest improvements in air quality (−9.4 μg m^{-3} for $PM_{2.5}$ and −2.4 ppb for ozone) and cumulative premature deaths reduction (−3.4 million from 2010 to 2050) compared to the end-of-pipe scenario. Notably, densely populated regions such as Henan, Hebei, Shandong, and Sichuan experience the most health and economic benefits. This study aims to project effective future mitigation technologies and climate policies on air quality improvement and carbon mitigation. Furthermore, it seeks to delineate detailed provincial-level air pollution control strategies, offering valuable guidance for policymakers and stakeholders in pursuing sustainable and health-conscious environmental management.

1. Introduction

The need to confront the escalating societal issues arising from global climate change, such as those associated with extreme heat, flooding, and drought, is attracting widespread attention and proving a cause for concern [1]. In response to this and shouldering the responsibilities of a major country, China announced the ambitious goals of achieving a carbon peak by 2030 and carbon neutrality by 2060. In line with these goals, commendable progress has been made in reducing carbon intensity, with a notable decrease of 48.4% observed from 2005 to 2020 [2]. Numerous studies have investigated the synergistic effects of global and national climate policies on air quality improvement and the associated health and economic impacts [3–8]. Implementing optimal climate policies has demonstrated the potential for co-benefits that offset the mitigation costs [9]. For instance, ambitious clean-air policies and climate goals are projected to significantly reduce fine particulate matter ($PM_{2.5}$)-related deaths by 0.32–0.55 million by 2050, in line with the National Determined Contributions (NDC) goal [10]. As this demonstrates, China's substantial efforts toward

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air quality improvement have not only led to a reduction in air pollutant concentrations but also yielded considerable co-benefits in health [11], and achieving the climate goal of capping global warming at two degrees will deliver further co-benefits by corresponding to an improving air quality [12]. The efforts to date have also yielded considerable economic co-benefits [11], and it is estimated that China could avoid USD 400 billion and USD 1.2 trillion in economic costs in the 2030s and 2050s, respectively, through an improvement in the ambient $PM_{2.5}$ concentration. If China reaches a carbon peak in 2030, this could ultimately lead to a maximum saving of USD 3.0 trillion, far offsetting the carbon mitigation cost [13].

Previous studies primarily focused on the health co-benefits of carbon reduction and clean air under different climate policies. Some studies quantified the benefits of historical policies [14], such as the Blue Sky Protection Campaign (BSPC, 2018) [15], while others provided in-depth modeling and assessments of future policy scenarios [10,16,17]. More recently, as research has expanded on climate policy's health and economic benefits, attention has shifted toward investigating regional and sectoral differences among climate mitigation technologies [12,18–20]. For instance, banning new sales of internal combustion engine vehicles could prevent 18,600 premature deaths by 2050 under the best-case scenario [19]. Three-quarters of the avoided deaths are based on end-of-pipe control measures. However, those benefits will be exhausted by 2030, rendering such measures insufficient to meet the World Health Organization (WHO) $PM_{2.5}$ standards set for 2060.

More ambitious mitigation efforts are required to achieve long-term climate goals, and the transport, residential, and building sectors are key areas for carbon reduction [21]. In these sectors, switching to electricity instead of coal and biomass in rural regions could yield economic benefits of 0.09% of the national gross domestic product (GDP), and there will be related health benefits. For instance, in Japan, end-of-pipe (EoP) and electrification technologies are forecast to reduce $PM_{2.5}$- and ozone-induced premature deaths by 65,500 annually in the residential, building, and transportation sectors in 2050 compared to 2010 [12]. However, in the extant research into such possibilities, most studies were designed to analyze the effects of individual mitigation technologies in specific sectors, with few exploring multi-sector combinations in China.

To address this research gap, in our study, we employed an integrated assessment model to evaluate the spatial distribution of future health and economic benefits in China under different technological pathways. The results revealed variations in the co-benefits of different combinations of climate mitigation technologies, and we identified the sensitivity levels of 31 provinces (excluding Hong Kong, Macao, and Taiwan due to missing data) to these technologies. The technology portfolio includes EoP, carbon capture and storage (CCS), renewables (RE), and electrification in the building (BLD) and transport (TRT) sectors. When considering how these technological portfolios will perform in China and which key technologies will achieve the maximum synergistic benefits, our results provide a reference that may aid in formulating diverse climate policies and contributing to future climate mitigation and air pollution reduction in China.

2. Methods

2.1. Methodological framework

This study employed an integrated assessment model comprising the AIM/enduse model, CAM-chem model, and IMED|HEL model. The AIM/enduse model assesses end-of-pipe measures and the carbon reduction potential, providing primary emissions of various air pollutants (SO_2, NO_x, $PM_{2.5}$, PM_{10}, OC, CO, Non-Methane Volatile Organic Compounds (NMVOCs), and NH_3). These emissions are then used in the CAM-chem model to simulate air quality, specifically focusing on $PM_{2.5}$ and ozone pollution and their associated co-benefits. The CAM-chem model outputs, including $PM_{2.5}$ and ozone concentrations, are integrated into the IMED|HEL model to generate health and economic results. Detailed descriptions of these models follow in the subsequent sections.

2.2. AIM/enduse model

The AIM/enduse model is a dynamic optimization model that achieves a partial equilibrium by minimizing system costs across regions, sectors, energy types, and air pollutants. It is a bottom-up technological model with a detailed technology selection framework. The constraints that it includes are energy and material supply, service demand, technology deployment, and emissions. The total system costs, meanwhile, encompass the initial and operating technology costs, energy expenses, taxes, and subsidies. The model performs multi-year computations, assessing scenarios that include policy effects such as new and revised regulations. The AIM/enduse model covers various sectors, such as building and transport, considering both long-lived greenhouse gases (GHGs) and short-lived climate pollutants, along with air pollutants and ozone-depleting substances [22]. For more detailed information about the AIM/enduse model, please refer to the Supplementary Methods.

2.3. CAM-chem model

This study employed the advanced air quality model CAM-Chem, based on the global Community Atmosphere Model (CAM) version 4 within the Community Earth System Model (CESM, v1.2.2). CAM-chem features a $2.5^\circ \times 1.9^\circ$ horizontal grid, 56 vertical levels, and an 1800 s timestep. Utilizing high-resolution GEOS-5 meteorology from NASA, its simulations span six years (2012–2017), with the initial year as a spin-up. Stratospheric gases follow climatology from the Whole Atmospheric Community Climate Model simulations [23,24]. Anthropogenic air pollutant variations use emission factors from a RETRO analysis of the TRO chemical composition. NMVOCs are categorized based on CAM-Chem speciation [25,26], as modeled by CAM-chem [27]. Biogenic emissions are simulated by MEGAN-v2.1 [28] (MEGAN-v2.1) within CAM-chem, and lightning NO_x emissions are calculated. Natural emissions (soil, ocean, volcano) from standard CAM-Chem files remain constant across all simulations [29].

2.4. IMED|HEL model

The IMED|HEL model evaluates the health impacts of $PM_{2.5}$ and ozone exposure, including mortality, morbidity, work-loss days (WLDs), health expenditures, and the value of statistical life (VSL). Population data are sourced from publicly available grids for the Chinese provinces [30]. The pollutant–health association follows a concentration–response function (CRF) [31,32]. $PM_{2.5}$-related mortality is determined by employing nonlinear exposure–response functions and the Global Exposure Mortality Model (GEMM) [33,34], while ozone-related mortality is based on linear exposure–response functions [35]. $PM_{2.5}$-induced medical expenditures are calculated by employing linear concentration–response functions and health service costs in China [36]. Annual WLDs combine morbidity and cumulative mortality-related WLDs for the working-age population (15–65 years). The IMED|HEL settings were described in previous studies [15,37,38]. The economic loss of premature deaths in China is estimated using the willingness-to-pay method, with the VSL in China obtained from the study of Jin et al., at RMB 5.54 million (USD 1.58 million) [39]. Further principles are detailed elsewhere [37,40].

2.5. Scenario setting

This study explored five scenarios based on climate goals and EoP technology combinations. The climate target was the two degrees outlined in the Paris Agreement, assuming a broad application of carbon mitigation measures and a carbon price of USD 400 per t CO_2 by 2050 [22]. These scenarios, outlined in Table 1, were as follows.

- Reference (REF): A benchmark, excluding considerations of the two-degree climate target.
- EoP only: A scenario incorporating middle-grade EoP technologies, excluding the two-degree climate target considerations.
- Thermal power electrification with CCS (TES): Aligned with the two-degree target, this scenario emphasizes coal and biomass energy with CCS technology while bolstering electrification in the building sector.
- Primary electrification (PES): Aligned with the two-degree target, this scenario prioritizes renewable energy adoption and advances electrification in the transport sector.
- Enhanced electrification (EES): Aligned with the two-degree target, this scenario intensifies efforts toward renewable energy adoption and enhances electrification across the building and transport sectors.

Note that these scenarios are independent, and their benefits also vary due to variations in the combinations of mitigation technologies. Further elaboration on the settings for these scenarios and the implemented mitigation technologies can be found in the Supplementary Methods section of the appendix.Table. 2

3. Results

3.1. $PM_{2.5}$ and ozone concentrations

End-of-pipe technology and climate mitigation policies in China are projected to enhance air quality and yield health benefits by 2050. Fig. 1 illustrates the concentration reductions in $PM_{2.5}$ and ozone under the EES compared with the REF scenario in 2050. The most significant improvements in air quality are concentrated in central China, especially in the Henan, Hebei, and Sichuan provinces. In the REF scenario, without additional reduction measures, China experiences a continual rise in the annual average $PM_{2.5}$ concentration and daily maximum 8-h average (MDA8) ozone concentration. Specifically, the $PM_{2.5}$ concentration is expected to increase by 17.0 μg m^{-3} in the short term (2010–2030) and by 22.8 μg m^{-3} in the long term (2010–2050) in the REF scenario. The ozone concentration is projected to increase marginally by 6.6 ppb in the short term and by 11.8 ppb in the long term (Supplementary Material Table S3).

Utilizing different mitigation technologies results in varying degrees of improvement in air quality across China (Supplementary Material Table S2). Compared to the REF scenario, implementing end-of-pipe mitigation measures can reduce $PM_{2.5}$ concentrations by 16.5 μg m^{-3} and ozone concentrations by 10 ppb by 2050. Alternatively, incorporating CCS technology, coupled with the enhancement of electrification in the building sector, leads to a concentration decrease compared to the EoP scenario, with $PM_{2.5}$ declining by 9.4 μg m^{-3} and ozone by 2.4 ppb in 2050. Moreover, $PM_{2.5}$ and ozone concentrations further reduce by 7.7 μg m^{-3} and 5.7 ppb compared to the TES in the PES by 2050. Compared to the PES, the additional implementation of electrification in the building sector in the EES is observed to yield only a limited reduction in 2050 (−1.0 μg m^{-3} for $PM_{2.5}$ and −0.2 ppb for ozone).

Table 2
Area averaged $PM_{2.5}$ and ozone concentrations of China among different scenarios in 2030 and 2050, respectively. Data in parentheses represent the difference in concentration from the upper scenario.

Scenario	$PM_{2.5}$ (μg m^{-3})		Ozone (ppb)	
	2030	2050	2030	2050
REF	51.8	57.6	68.9	74.0
EoP	47.0 (−4.8)	41.1 (−16.5)	62.0 (−6.9)	64.0 (−10.0)
TES	39.6 (−7.4)	31.7 (−9.4)	62.9 (−0.9)	61.6 (−2.4)
PES	38.8 (−0.8)	24.0 (−7.7)	62.3 (−0.6)	55.9 (−5.7)
EES	38.2 (−0.6)	23.0 (−1.0)	62.1 (−0.2)	55.7 (−0.2)

We found significant regional disparities in $PM_{2.5}$ and ozone concentration reductions among the 31 provinces studied in China (Supplementary Material Fig. S2). In the absence of mitigation technologies in the REF scenario, Henan, Hebei, and Tianjin were found to be the top three in terms of severe air pollution issues, with their $PM_{2.5}$ and ozone concentrations increasing by 109.2 μg m^{-3} and 30.1 ppb (Henan), 95.2 μg m^{-3} and 29.9 ppb (Hebei), and 86.9 μg m^{-3} and 27.6 ppb (Tianjin) during 2010–2050. In the EES, Henan, Hebei, and Tianjin were then the key provinces for reducing $PM_{2.5}$ pollution. Moreover, the $PM_{2.5}$ concentrations in these three provinces decreased by 64.2, 58.2, and 58.1 μg m^{-3} in the EoP scenario compared to the REF, and further reduced by 61.5, 55.9, and 54.1 μg m^{-3} in the PES in 2050. Compared to the use of only end-of-pipe technology, when applying other mitigation technologies, Sichuan enters the arena as a region with a high potential for ozone concentration reduction, registering the second-highest potential (after Henan). In the EES in 2050, the ozone concentrations in Henan and Sichuan are reduced by 29.6 and 29.1 ppb compared to the REF, respectively (15.6 and 20.6 ppb in EoP, 18.0 and 19.4 ppb in TES, 28.5 and 28.7 ppb in PES).

3.2. Health impacts with regional variations

When dividing the 31 provinces into seven major regions geographically (Fig. 2), the regional differences in mortality between scenarios become pronounced. The efficacy of advanced mitigation technologies is underscored by the substantial decreases in premature deaths. However, the extent of the health benefits varies significantly with the differing levels of effectiveness of air

Table 1
Scenario settings and brief descriptions.

Scenario	Two-degree target	End-of-pipe measures	Energy preference	Electrification sector
Reference (REF)	No	No	–	–
End-of-pipe mitigation (EoP)	No	Yes	–	–
Thermal power electrification (TES)	Yes	Yes	Thermal power with CCS	Building sector
Primary electrification (PES)	Yes	Yes	Renewables	Transport sector
Enhanced electrification (EES)	Yes	Yes	Renewables	Transport & building sector

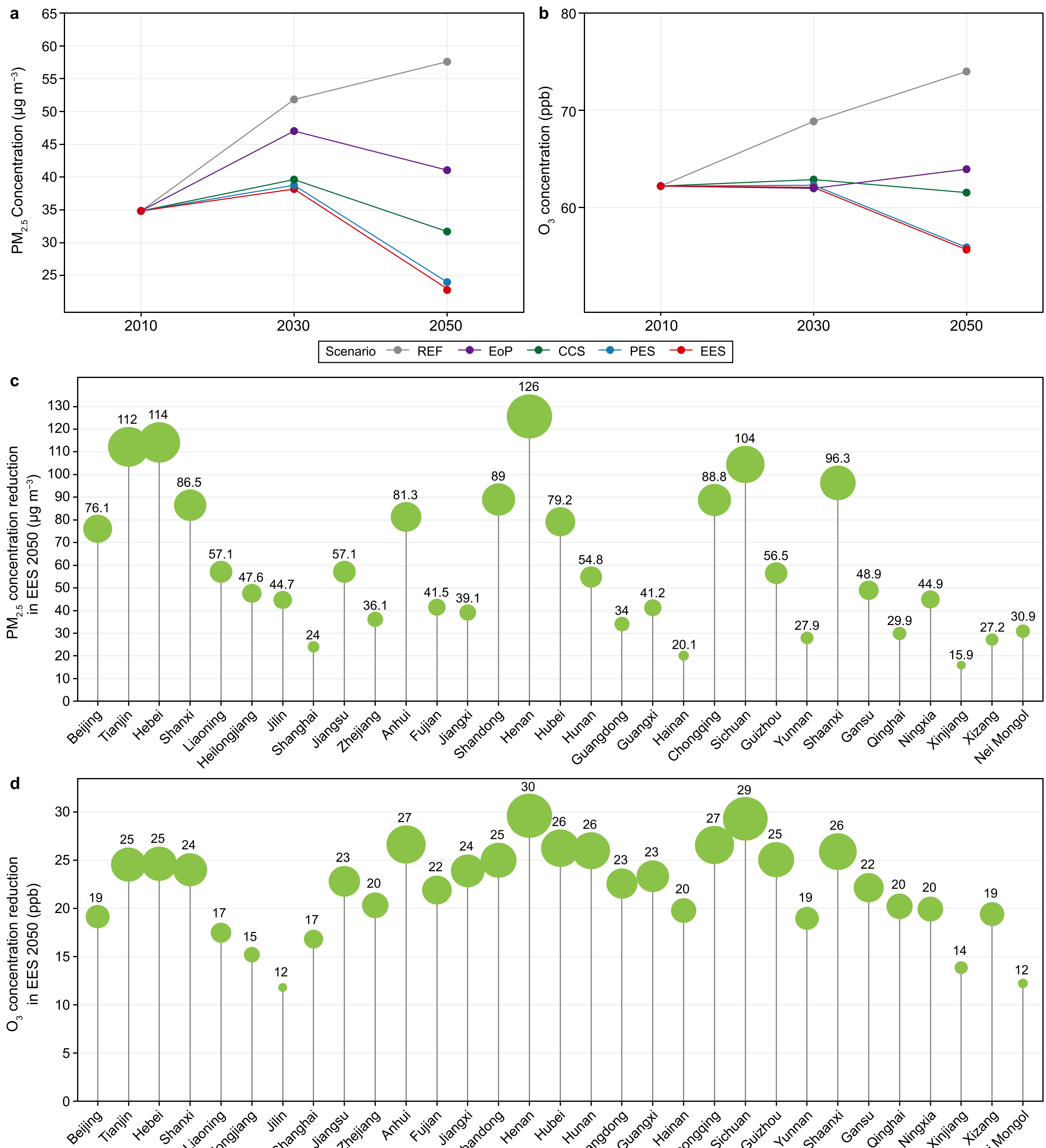

Fig. 1. **a**–**b**, China's $PM_{2.5}$ (**a**) and ozone (**b**) concentrations in different scenarios from 2010 to 2050. **c**–**d**, $PM_{2.5}$ (**c**) and ozone (**d**) reduction in the enhanced electrification scenario (EES) scenario compared to the reference (REF) scenario in 2050.

pollution control technologies. Notably, the exclusive adoption of EoP technology is the most impactful, leading to substantial health benefits. For instance, in central and eastern China, the EoP scenario anticipates averting 55 thousand and 76 thousand premature deaths in 2050, constituting 27% and 28% reductions, respectively, compared to the REF. Beyond end-of-pipe technologies, renewables and electrification also exhibit promising contributions. Transitioning from TES to PES yields additional health benefits of 29 thousand and 41 thousand avoided deaths in central and eastern China. However, adding extra electrification in the building sector to the PES brings only a marginal mortality reduction (from −0.3 to −3.3 thousand avoided deaths), though with generally positive effects observed across all regions. Meanwhile, CCS technology yields limited benefits in Northeast China (−0.7 thousand deaths) and, unexpectedly, leads to a slight increase in premature deaths in northern (5.7 thousand deaths), central (4.3 thousand deaths), and

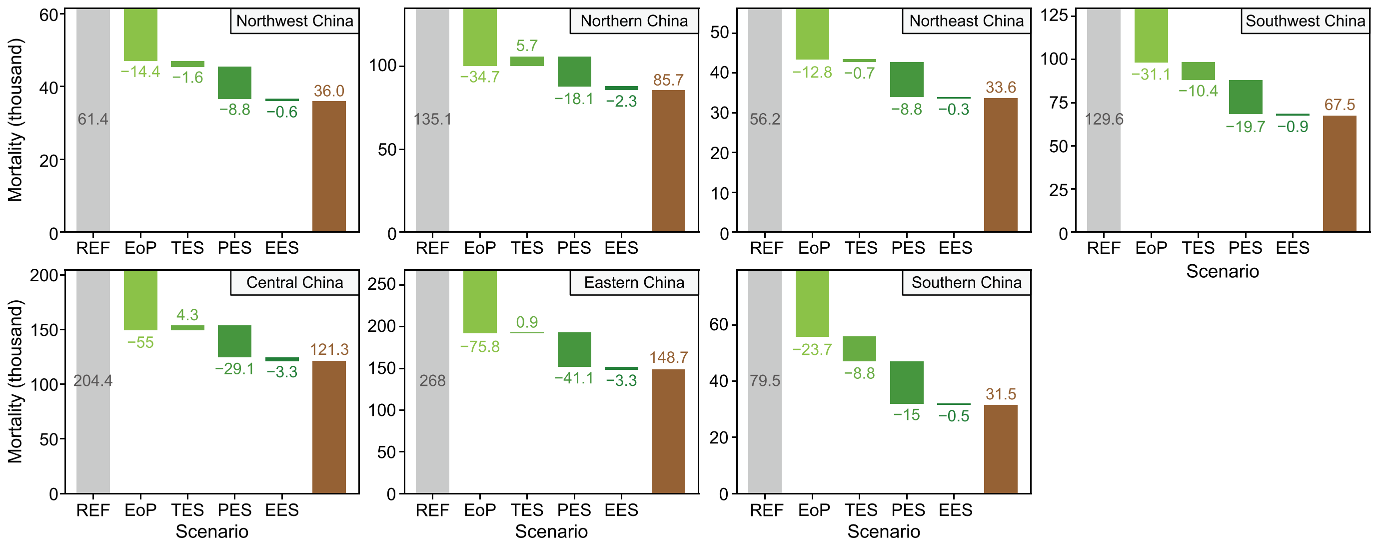

Fig. 2. Changes in $PM_{2.5}$ and ozone-related mortality in 2050 for different scenarios in seven regions of China. The first bar in grey represents the premature deaths of the reference (REF) scenario, and the last bar in brown represents the values of the enhanced electrification scenario (EES) scenario, while the middle four green bars indicate the change in premature deaths between the two adjacent scenarios. The classification of the seven regions of China is shown in Table S6 (Supplementary Materials).

eastern China (0.9 thousand deaths). Remarkably, while CCS technology is confirmed to yield positive effects in terms of air pollution reduction, our results suggest that it averts fewer deaths than the other scenarios in certain areas.

Across the seven regions, the number of premature deaths aligns roughly with the size of the total regional population. For instance, central and eastern China, which represent approximately 46% of the total population, account for 50.5% of the total national mortality (472 thousand out of 934 thousand) in the REF scenario. However, southern China emerges as the most sensitive to each mitigation technology, with the EES achieving the highest proportion of averted deaths at 60% (48 thousand). In comparison, northern China exhibits the lowest at 37% (49 thousand). This reveals that, for each mitigation technology, southern China appears more sensitive to reducing premature mortality.

In terms of cumulative avoided deaths, the EES outperforms the EoP scenario, particularly in $PM_{2.5}$-related deaths (Fig. 3). Compared to the REF scenario, cumulative avoided $PM_{2.5}$-related deaths amount to 4.5 million in the EoP and triple to 13.5 million in the EES. Conversely, ozone-related deaths show less variation between scenarios, with 6.8 million avoided deaths in the EoP and 7.1 million in the EES. Regionally, $PM_{2.5}$-related deaths exhibit a more even distribution, while ozone-related deaths concentrate in central and southern China. Fig. 3 highlights that provinces such as Guangdong (1.3 million) and Shandong (0.9 million) experience the most significant $PM_{2.5}$-related avoided deaths in the EES, owing to their large population bases. Surprisingly, northern and eastern Chinese provinces, such as Hebei, Shandong, and Henan, achieve higher ozone-related health benefits in the EoP scenario than in the EES. These regional nuances underscore the complexity of the health impacts associated with diverse air pollution mitigation strategies.

3.3. Economic impact assessment

Economic impact assessment demonstrates that implementing climate mitigation technologies across various scenarios will yield substantial economic benefits through multiple channels (Fig. 4). One notable economic impact is the significant reduction in the VSL, representing the economic loss associated with premature deaths, quantified through the willingness-to-pay method. In 2010, China's VSL economic loss stood at USD 1.4 trillion. With the integration of mitigation technologies, particularly end-of-pipe technologies in the EoP scenario, the average value is reduced by 25% across the 31 provinces. Moreover, applying end-of-pipe, renewable energy, and electrification technologies will result in a 50% reduction in VSL losses in the EES (USD 5.0 trillion) compared to the REF (USD 10.3 trillion) nationwide by 2050. At the provincial level, in 2050, Shandong and Henan experience the highest avoided VSL economic losses in the EES, amounting to USD 793.6 and 580.6 billion, respectively, with 49% and 42% reduction rates compared to the REF. In fact, it can be found that the top four provinces (Shandong, Henan, Jiangsu, and Hebei) collectively account for 51% (USD 2.6 trillion) of the total national economic loss of VSL in the EES by 2050, indicating a concentration of potential economic losses in northern China.

Our results reveal a consistent increase in health expenditure savings from each province of China from 2010 to 2030 (Supplementary Material Fig. S5), followed by a decrease in EoP, PES, and EES by 2050 (Fig. 4b). In the short term (2010–2030), total national expenditures on $PM_{2.5}$- and ozone-related diseases increase by 36.8% in the REF scenario, 14.4% in PES, and 12.2% in EES compared to REF (USD 16.89 billion). In the long term (2010–2050), the EES further reduces medical expenditures by USD 11.7 billion (a 46.6% decline compared with REF in 2050), with the most significant cost reduction occurring between 2030 and 2050. Among all provinces, Henan, Shandong, Sichuan, and Hebei benefit the most from mitigation measures, with Henan experiencing the highest savings of USD −1.15 billion in 2050. Notably, in 2050, Sichuan and Guangdong derive relatively greater benefits from renewable energy and electrification in the EES than the other provinces, with avoided expenditure costs of USD 0.43 billion (30% reduction rate) and USD 0.44 billion (45% reduction rate), respectively, compared to the EoP scenario.

The economic impact assessment also considered work time loss, and our findings aligned with the trends observed in VSL and expenditures. By 2050, the EES could potentially avoid economic losses of USD 330.9 billion nationwide. Henan, Shandong, Sichuan, and Hebei continue to lead in economic benefits, with the four provinces accounting for 41.4% of the country's total economic

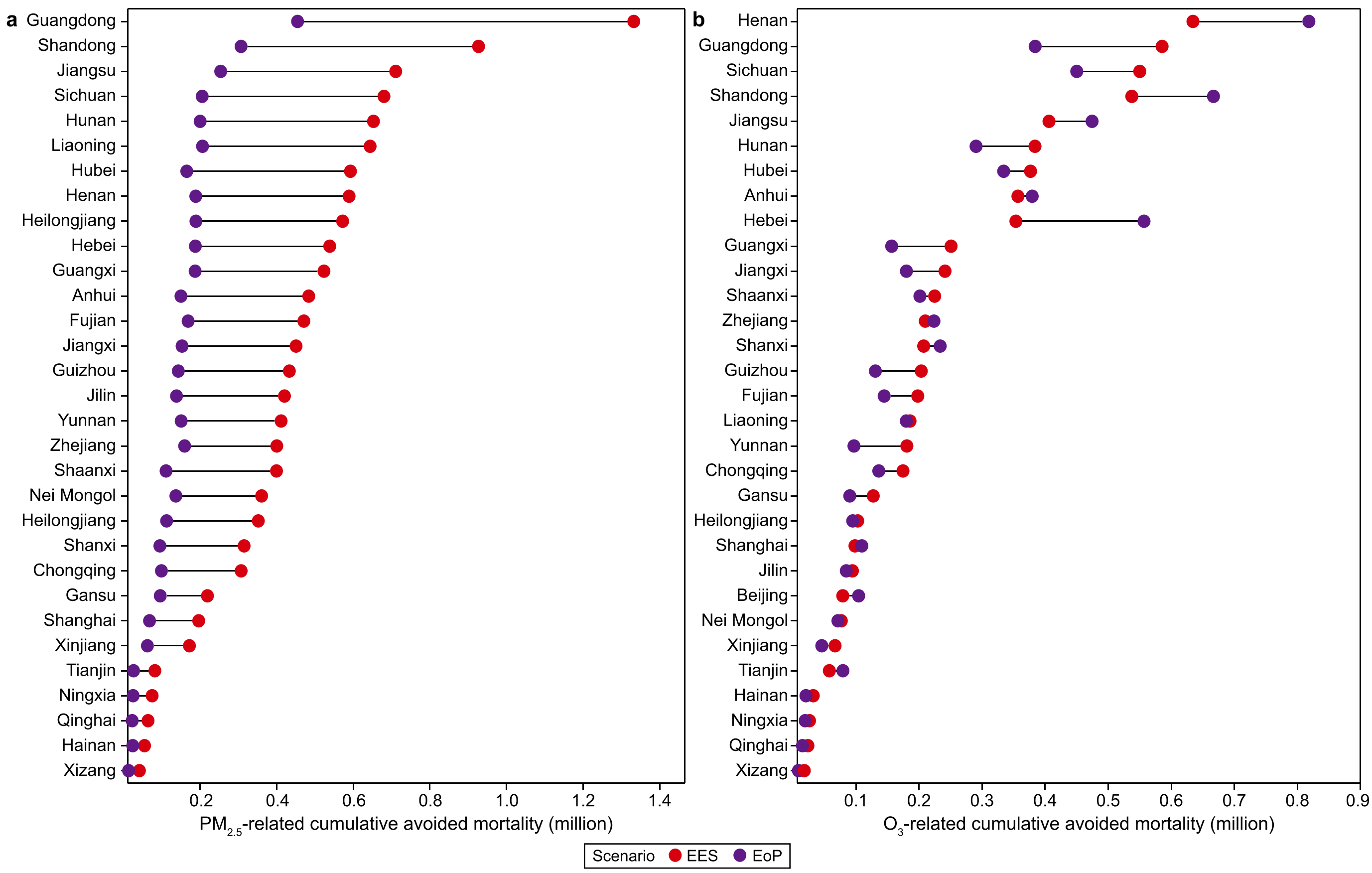

Fig. 3. Provincial Cumulative avoided deaths caused by $PM_{2.5}$ (**a**) and ozone (**b**) in end-of-pipe (EoP) scenario and enhanced electrification scenario (EES) compared with reference (REF) scenario during 2010–2050.

benefits, highlighting regional disparities in economic losses due to air pollution in China (Fig. 4c).

4. Discussion and conclusion

In this study, we employed an integrated assessment model to analyze the co-benefits of various air pollution and climate mitigation measures, shedding light on these technologies' effectiveness and revealing notable regional disparities. Our findings underscore the need for China to adopt climate policies and mitigation technologies to address the impending air pollution challenges. In the REF scenario, our results highlighted the severity of air pollution in 2050, surpassing the desired climate change consequences. Without heeding the two-degree target, China's $PM_{2.5}$ concentration is projected to be more than triple (57.6 μg m^{-3}) the WHO AQG2021 standard (15 μg m^{-3}) in 2050, with a total economic loss of USD 10.9 trillion across 31 of its provinces.

Our research demonstrated that deploying mitigation technologies in China will yield substantial health and economic benefits, particularly for provinces with well-developed economies and large populations. Likewise, Zhang et al. found that Sichuan could see its $PM_{2.5}$ concentration reduced by 5.9 μg m^{-3} in 2035 and receive USD 23 billion in health co-benefits with stringent end-of-pipe control under a carbon mitigation scenario [5]. Our findings went further, indicating that the economic loss that could be avoided in Sichuan totals USD 46.7 billion by 2035 and that provinces such as Sichuan would enjoy benefits in the long term, such as an avoided loss of USD 156.5 billion by 2050. Another finding in our study was that the abatement benefits were mainly concentrated in the Henan, Shandong, Hebei, and Sichuan provinces, which have large populations or are heavily polluted. In the literature, Yang et al. likewise noted that provinces in heavily polluted and densely populated regions will benefit the most from carbon and pollution control strategies, consistent with our conclusions [4].

Among the mitigation technologies evaluated in this study, EoP treatment stood out with significant improvements. It was also revealed that electrification across sectors will be crucial in further reducing pollutant concentrations and economic losses. In the literature, Geng et al. demonstrated that end-of-pipe control techniques prevented 0.87 million deaths in China from 2012 to 2017 [41], and consistent with this finding, our research confirmed the substantial health benefits that may be derived from end-of-pipe technology and the two-degree climate target, with 24.3 million premature deaths avoided in the EoP scenario from 2010 to 2050. Meanwhile, the prospect of applying CCS and renewable technologies has been widely discussed in climate mitigation. It is estimated that low-cost renewables could reduce the value of CCS by 15–96% across different energy sectors [42], which means that CCS technology will be less competitive for future applications due to the additional air pollutant emissions and cost. Likewise, while our results suggest that the electrification pathway under conventional fossil energy with CCS technologies may bring significant health benefits, those are not as large as the benefits of an energy transformation to renewables. However, given the complexity of power system transformation and the volatility of renewable technologies, CCS technology is not likely to become obsolete in the short term.

Finally, our research also revealed the particular importance of

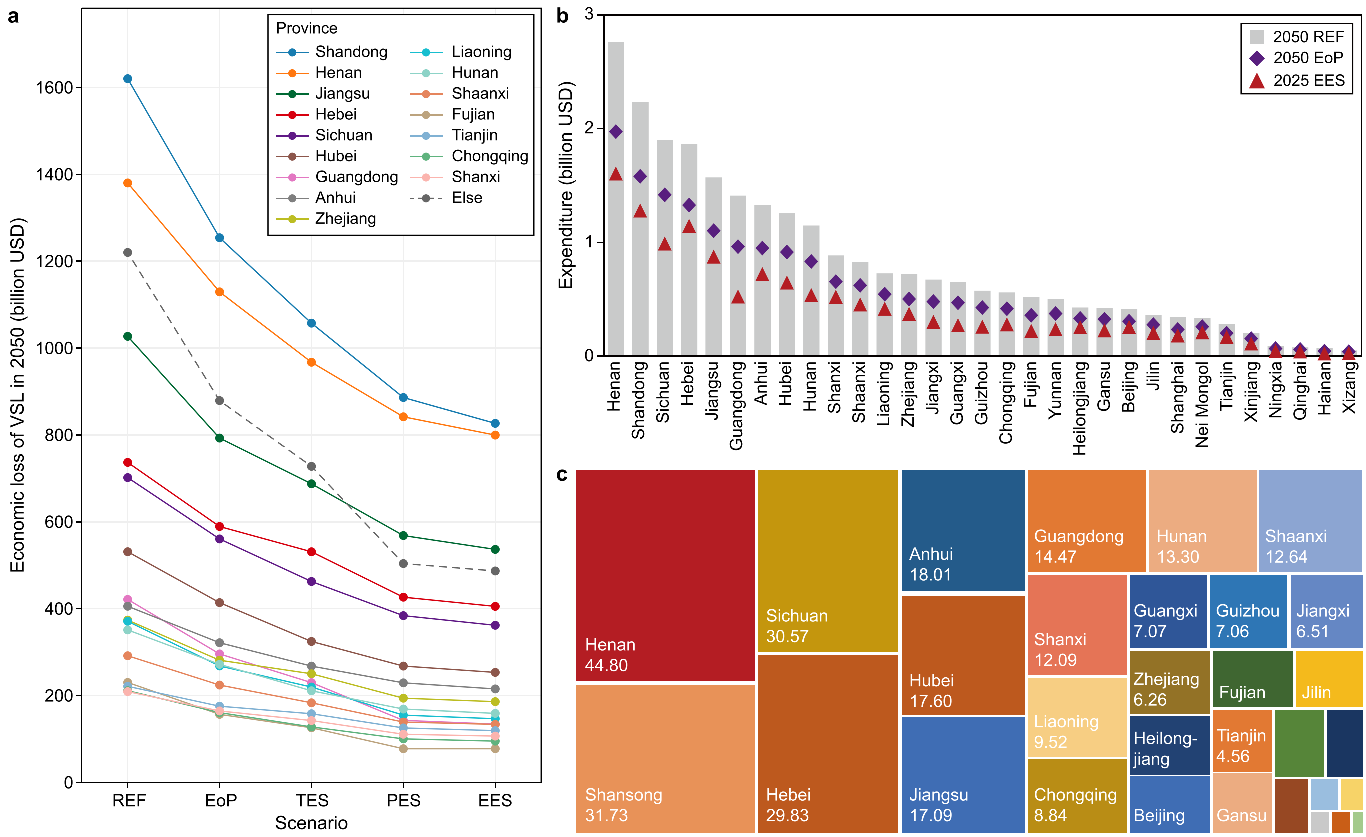

Fig. 4. Economic impacts due to $PM_{2.5}$ and ozone pollution in 2050. **a**, National sub-provincial economic loss of value of statistical life (VSL) under different scenarios in 2050. **b**, Medical expenditures of 31 provinces in reference (REF), end-of-pipe (EoP), and enhanced electrification scenario (EES) scenarios in 2050. **c**, The value of avoided economic loss of work time loss in enhanced electrification scenario (EES) 2050 compared with reference (REF) scenario in different provinces (Unit: billion USD).

emission reductions in the transport and building sectors. We found that electrification and the use of renewable energy in the transport sector will result in the avoidance of 0.16 million premature deaths by 2050. Likewise, in a previous study, Wang et al. indicated that vehicular emissions during 1998–2015 would have been two to three times as large as they were if mitigation measures were not implemented, causing around 0.51 million premature deaths [43]. The study by Huan et al. also identifies electrification as a critical approach in building sector's low carbon transition, by 2050, the share of electricity in final energy consumption is expected to reach 44%, 54% and 59% in reference, 2-degree and 1.5-degree scenarios respectively [44].

In summary, our study explores the air quality and health economic benefits associated with different combinations of mitigation technologies in a quantitative approach. Our findings reveal that EoP technologies and sector electrification technologies are critical to achieving carbon reduction and air quality goals as well as improving public health. Therefore, our quantitative findings can effectively assist governments in formulating future climate policies at the technical level. Meanwhile, our study also further refines the direction of related research from the perspective of mitigation technologies. Future studies could place more emphasis on quantifying the medium- and long-term impacts of different mitigation technologies.

However, this study also had limitations and uncertainties. For a start, we considered that there will be the same technological progress in all the provinces of China, which is an inadequate hypothesis as it does not match the actual situation forecast. Specifically, ignoring the heterogeneity among regions may have led us to overestimate western China and underestimate eastern China due to their different technical advancements. Furthermore, we made conservative estimates based on the currently available technologies and did not consider the rapid technological advancements that may be made, which could, for instance, reduce the cost of CCS technology. There were also limitations of our input data and models in their capacity to accurately quantify uncertainties and project future scenarios. Nonetheless, our study, to some extent, sheds light on the important implications of future mitigation technologies.

CRediT authorship contribution statement

Mengdan Zhao: Writing - Review & Editing, Writing - Original Draft, Visualization, Software, Investigation, Formal analysis, Conceptualization. **Yang Xie:** Writing - Review & Editing, Supervision, Resources, Methodology, Conceptualization. **Meng Xu:** Writing - Review & Editing, Visualization, Supervision, Investigation. **Zhixiong Weng:** Supervision. **Tatsuya Hanaoka:** Supervision. **Yuqiang Zhang:** Supervision. **Dan Tong:** Supervision.

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.ese.2024.100454.

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