Engineering 65 (2026) 112–121

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Energy Transition's Technical Pathways, Risks, and Equity—Article

Uncertain Cross-Sector Climate Actions Could Undermine Air Pollution Reduction Co-Benefits in China's Power and Passenger Car Sectors

Hongyi Xie [a], Bin Chen [a,b,c,*], Chen Wang [d], Wei Xie [a], Xinyi Long [a], Dingfan Zhang [a], Min Dai [a], Zhixiu Han [a], Yiru Song [a], Jiashuo Li [d], Yutao Wang [a,e,f,g,*]

[a] Fudan Tyndall Center and Shanghai Key Laboratory of Atmospheric Particle Pollution and Prevention (LAP^3), Department of Environmental Science and Engineering, Fudan University, Shanghai 200438, China
[b] Institute for Big Data, Fudan University, Shanghai 200433, China
[c] MOE Laboratory for National Development and Intelligent Governance, Fudan University, Shanghai 200433, China
[d] Institute of Blue and Green Development, Shandong University, Weihai 264209, China
[e] IRDR International Center of Excellence on Risk Interconnectivity and Governance on Weather/Climate Extremes Impact and Public Health, Fudan University, Shanghai 200438, China
[f] Shanghai Institute for Energy and Carbon Neutrality Strategy, Fudan University, Shanghai 200433, China
[g] Institute of Eco-Chongming (IEC), Shanghai 202151, China

ARTICLE INFO

Article history:
Received 23 August 2024
Revised 24 August 2025
Accepted 11 September 2025
Available online 17 September 2025

Keywords:
Climate action
Energy transition
Passenger car
Air pollutant
Technical pathway
Cross-sector management

ABSTRACT

Sector-specific climate actions are widely recognized for their air pollution co-benefits. However, uncertainties in cross-sector climate action may weaken or reverse these co-benefits. This study quantified the potential negative impacts of uncertain climate actions in the passenger car (PC) and power sectors on air pollutant (AP) emissions by integrating a fleet model with a power plant model under various infrastructure-level transition pathway combinations. Our results show that uncertainties in cross-sector climate actions, particularly when fleet electrification lags behind the car sector's ideal transition pathway across all power sector transition scenarios, are projected to lead to a maximum increase of ~120% in nitrogen oxide emissions and ~635% in particulate matter emissions from the power and PC sectors in 2050, compared to maintaining the 2020 action levels. Additionally, the indirect AP emissions from the electricity use of electric cars are reallocated to provinces that rely heavily on coal-fired power, such as Inner Mongolia, Shanxi, Shandong, and Guizhou, along the power supply chain, thereby leading to significant losses in air pollution reduction co-benefits. We highlight the necessity of shifting from the current single-sector-oriented climate-mitigation policy framework to a cross-sector-integrated perspective. Specifically, it is crucial to reduce car use demand and enhance AP emission control for coal plants in the near term, while accelerating renewable energy transition in the power sector as a long-term strategy to effectively enhance air pollution control co-benefits in response to uncertainties during policy implementation.

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1. Introduction

To achieve China's climate goal, accelerating renewable energy expansion in power production and electrification of power consumption are imperative measures [1]. On the production side, China is working towards constructing a renewable energy power system while phasing out fossil fuel power plants [2,3]. On the consumption side, China has promoted electric vehicles (EVs) as alternatives to gasoline passenger cars (PCs) [4–7]. The associated air pollutant (AP) reduction benefits from these climate actions are vital for controlling AP in China in the future [8,9]. Previous studies show that a full transition to EVs in China leads to a significant reduction in particulate matter lower than 2.5 μm ($PM_{2.5}$) and NO_2 by 30%–70% and 30%–80%, respectively [10]. Meanwhile, climate actions from China's power sector are projected to further reduce emissions of SO_2, NO_x, and primary $PM_{2.5}$ emissions [11]. Thus, multiple pieces of evidence have highlighted the co-benefits of AP reductions from climate mitigation policies targeted at either the PCs sector or the power sector [12–15]. However, the net AP reduction co-benefits of EVs are diminished when

* Corresponding authors.
E-mail addresses: chen_bin@fudan.edu.cn (B. Chen), yutaowang@fudan.edu.cn (Y. Wang).

https://doi.org/10.1016/j.eng.2025.09.006
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considering the extended system boundary that includes power plants [16], as coal-fired power plants (CFPPs) are the dominant power infrastructure in China and remain major contributors to APs emissions [17,18]. This trade-off between vehicle electrification and upstream power sector emissions has been widely observed in previous studies [19–24]. However, net APs reduction co-benefits from the coupling of both power and car sectors can still be observed only under the condition of the most ideal carbon neutrality pathway in China, that is, the simultaneous rapid decarbonization of the power sector and large-scale deployment of EVs [25–29]. Examining this interaction under various electrification and power decarbonization pathways would support more integrated and effective policymaking in China.

Previous studies have not fully addressed how these co-benefits under the ideal pathway may be affected by real-world uncertainties (supporting evidence is detailed in Note S1 in Appendix A), especially because of the challenges of synchronizing the pace of climate actions between sectors. In China's current climate policy regime [30], climate actions in both sectors may be implemented in sub-optimal cross-sector combinations [31–33], because the penetration of intra-sector climate actions in both sectors involves uncertainties. For example, in the PCs sector, factors such as battery limitations (e.g., range constraints, supply risks, and cost), power challenges (e.g., multi-sector power competition, volatility of renewable electricity), infrastructure gaps (e.g., lack of charging facilities), and policy incentives may impede the penetration of EVs [34–40]. In the CFPPs sector, factors such as key metal shortages, waste recycling challenges in renewable energy, and energy security concerns may hinder climate actions on the power generation side [41–43]. Consequently, these uncertain intra-sector climate actions and cross-sector combinations potentially result in adverse air pollution from a system-wide perspective, which remains unknown. Although a few studies [28] have explored the uncertainties in cross-sector actions, they have primarily focused on the penetration rates of vehicle electrification and renewable energy in the grid. However, there are other factors in the vehicle and power sectors that contribute to the uncertainties in cross-sector actions; for example, car use management indirectly affects CFPPs emissions. Moreover, the heterogeneity of infrastructure attributes affects the emission reduction potential of these climate actions [15,44,45]. Therefore, there is an urgent need to explore the net emission changes of the coupled PC–CFPP system in the context of infrastructure heterogeneity and the uncertainty of cross-sector climate action combinations in China.

To address this knowledge gap, we developed an integrated fleet- and infrastructure-level CO_2 and AP emission accounting system covering PCs and CFPPs across China (Fig. S1 in Appendix A). Various scenario combinations were designed based on gradient implementation strategies in both the PCs and CFPPs sectors, resulting in nine combinations of cross-sector climate actions with three action levels for both sectors: Maintaining the 2020 implementation trend as the business-as-usual (BAU) scenario, enhancing policy with an implementation process hindered by uncertainties (enhanced policy scenario (EPS)), and achieving carbon neutrality with a strong climate ambition (carbon neutrality scenario (CNS)). Details and further elaboration on the parameters and scenarios can be found in the Section 2 and Supplemental data in Appendix A. We project future CO_2 and AP emission trends in the coupled PCs–CFPPs system, investigate the contributions of cross-sector actions to emission reductions, and explore provincial variations. Our results on the emission pathways and reduction potentials of China's coupled PCs–CFPPs system can inform tailored mitigation strategies and facilitate the development of cross-sectoral management policies.

2. Materials and methods

2.1. Integrated model framework

We developed an infrastructure-level accounting model based on power linkages between the PCs and CFPPs sectors (Note S2 in Appendix A). The accounting boundary considered only on-site emissions from PCs and CFPPs. This model consists of three main modules: the PCs module, power grid, and CFPPs modules. The PCs module simulated the electricity consumption demand. The electricity demand is then converted into coal consumption by individual CFPPs within the grid module. Finally, CO_2 and APs emissions were calculated for both the PCs and CFPPs modules. Due to the lack of data, Taiwan Province, Hong Kong, and Macao were not included in our study.

For the PC module (Note S3.1 in Appendix A), we developed a bottom-up fleet dynamics module based primarily on previous studies [5,46]. The fleet consisted of a cross-section of four car types and four power types, totaling 16 categories. The car types included sedans, sports utility cars, multiple-purpose cars, and crossover cars. Power types include internal combustion engine cars, hybrid electric cars, plug-in hybrid electric cars, and battery electric cars. The emission standards for AP (except for SO_2) are determined by the sales year of new cars. SO_2 emission standards are based on the modeling year rather than the sales year, using China's national standard for motor gasoline standards [47].

We developed a grid-scale conversion module that converts the electricity consumption of the PCs module to the amount of coal burned in each coal plant within the CFPPs module (Note S3.2 in Appendix A). We assume that the generation and consumption of electricity occur only within each of China's six regional grids, following a previous study [26], and exclude the cross-grid area electricity used by the PCs. The CFPP-to-EV process power losses were considered within our accounting boundary. The coal-fired power generation was then identified through the power mix of each grid. We predicted the future energy mix of six power grids in China using the Global Change Analysis Model (GCAM). Based on the installed capacity, the total coal-fired power generation is allocated to surviving CFPPs, which are determined by phaseout sequencing [45].

For the CFPPs module (Note S3.3 in Appendix A), we consolidated power plant-level data for CFPPs in China based on the Global Coal Plant Tracker, Global Power Plant Database, and compilation of statistics from the electric power industry [48]. Plant-level data were summarized and matched to the provincial capacity reported in the Electricity Statistics Yearbook [49]. The database contains detailed information on each power plant, including the province, plant name, date of establishment, geographic coordinates, installed capacity, generation capacity, generation hours, coal consumption, boiler type, and tail gas treatment equipment (desulfurization, denitrification, and dedusting). The AP and CO_2 emissions accounting methods were based on previous studies [50,51]. The carbon capture and storage (CCS) system is considered only at the CNS level, and the source-sink matching relationship follows the approach in a previous study [52].

2.2. Cross-scenario groups settings for coupled PCs–CFPPs system

To explore CO_2 and AP emissions from coupled PCs–CFPPs system under future uncertain climate actions, we designed a scenario set for PCs and CFPPs. As shown in Fig. 1, we develop a PCs–CFPPs coupled scenario group based on the cross-combination of scenario sets for PCs (V1–V9) and CFPPs (P1–P9) to capture the uncertainties of intra-sector climate action penetration as well as the resulting inter-sector spillover effects. Specifically, we set up two dimensions in each scenario based on the implementation degree

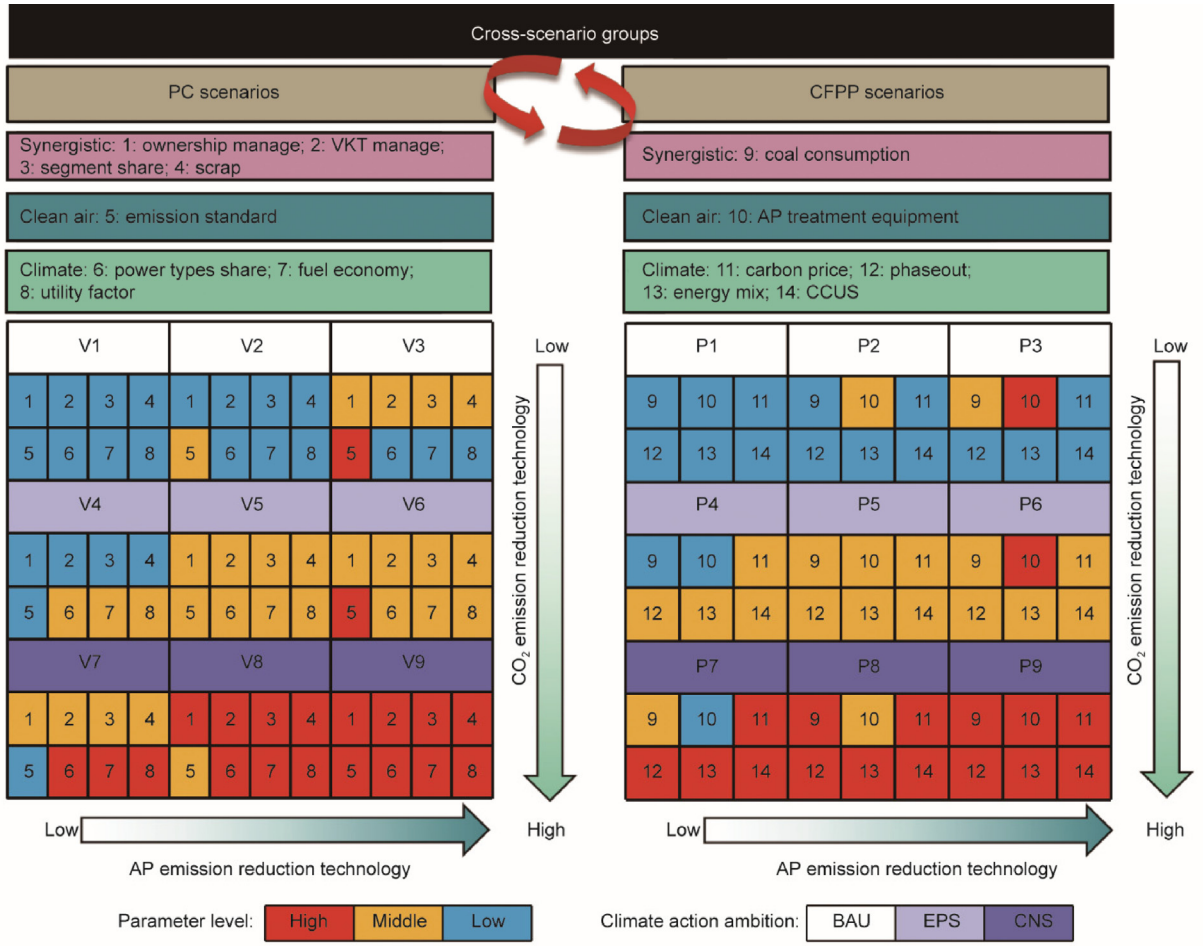


Fig. 1. Cross-scenario groups settings: BAU, EPS, CNS, PC sector, and CFPP sector scenarios. The numbers in the table represent technical parameters, which can be matched with the corresponding descriptions in the boxes above the tables. VKT: vehicle annual kilometrage; CCUS: carbon capture, utilization, and storage.

of AP emission reduction technology and CO_2 emission reduction technology. Based on the level of ambition for climate action, V1–V3 and P1–P3 are BAU scenarios, V4–V6 and P4–P6 are EPS scenarios, and V7–V9 and P7–P9 are the CNS scenarios. Consequently, the cross-combination of the PC and CFPP sector scenario sets forms the cross-scenario group for this study (i.e., a total of 81 scenario combinations). An overview of the scenario narratives and parameter assumptions can be found in Note S4 in Appendix A.

The parameters, which are key selections based on relevant policies in China's passenger vehicle and power sectors, are classified into three types: climate, clean air, and synergistic actions. Considering the potential gap between policy targets and actual implementation, we selected representative values for these parameters that reflect their uncertainties. Each parameter has three levels—high, middle, and low—based mainly on historical trends in China and future projections, considering different socioeconomic development scenarios, as derived from relevant research papers, industry reports, government plans, and statistical yearbooks (details of parameters and sources can be found in Note S5 in Appendix A). For example, the benchmark (i.e., V1–P1) used in our study is the combination of the PCs sector's V1 scenario and CFPPs sector's P1 scenario of the CFPP sector. Specifically, the V1 scenario represents that the synergistic actions of the PC sector (ownership management, annual kilometrage, segment share, and scrap), clean air actions (updates to AP emission standards), and climate actions (management of power type share, fuel economy, and utility factor of plug-in hybrid electric cars) are all at low levels. The P1 scenario represents that the CFPPs sector's synergistic actions (management of CFPPs coal consumption rates), clean air actions (updates to AP treatment equipment), and climate actions (carbon price, CFPPs phase-out, energy mix adjustments for China's six power grids, and the implementation of CCS for CFPPs) are all at low levels.

We selected 81 representative scenarios to encompass a wide range of potential outcomes, including both upper and lower limits, and a sufficient number of intermediate scenarios. While real-world situations may differ, decision makers can closely approximate these scenarios to anticipate possible outcomes. Our macro-level assessment underscores the need for a more detailed investigation in the future, with a focus on specific policies and their system-wide impact mechanisms to address the complexities of real-world applications.

3. Results

3.1. Future emissions from coupled PCs–CFPPs system under uncertain climate actions

We explored the impact of uncertain cross-sector climate actions on CO_2 and APs emissions, assuming that clean air actions will remain at the 2020 level to isolate the effects of climate actions. Fig. 2 reveals that different combinations of cross-sector climate actions have significant and varying impacts on emissions from the coupled PCs–CFPPs system up to 2050. As shown in Fig. 2(a), adopting more climate-ambitious actions in both sectors leads to a maximum 90.55% reduction in carbon emissions by

2050 compared to the benchmark scenario (i.e., climate actions of both sectors at the BAU levels). Notably, we found that CO_2 emission reductions would primarily depend on the climate actions of the PCs sector, while climate actions in the CFPPs sector could achieve further emission reductions, albeit to a lesser extent than those in the PCs sector.

Different APs exhibited varying characteristics of synergistic emission reductions in the coupled PCs–CFPPs system. CO, volatile organic compounds (VOCs), and SO_2 emissions can be synergistically reduced alongside CO_2 emissions, compared to the benchmark (Figs. 2(b)–(d)), with the PCs sector's climate actions dominating the reduction co-benefits. SO_2 emissions (Fig. 2(d)) are reduced in absolute terms compared to maintaining the 2020 action levels when the PCs sector reaches the CNS level. However, NO_x, $PM_{2.5}$, and PM_{10} emission reduction co-benefits are undermined, as the PCs sector enhances its climate ambitions and may even generate adverse air pollution compared to the benchmark (Figs. 2(e)–(g)). For example, when climate actions in both sectors are elevated to the EPS level (V4–P4 scenario), these three APs exceed the benchmark by 4.30%, 31.72%, and 110.92%, respectively, in 2050. Although there are some scenarios in which APs emission reduction co-benefits exist in 2050, emissions in excess of the benchmark can still be observed between 2020 and 2050. For instance, when both sectors reach the CNS level (V7–P7 scenario), there are still adverse emissions of $PM_{2.5}$ in 2020–2037 and PM_{10} in 2020–2049 compared to the benchmark. Notably, when the PCs sector's climate actions are at EPS levels, adverse air pollution is more severe than at the BAU and CNS levels. For $PM_{2.5}$, when the CFPPs sector is at the BAU, EPS, and CNS levels, the PCs sectors at the EPS level emit 119.31%, 54.22%, and 22.34% more than at the BAU level by 2050, respectively. This leads to a maximum increase of ~120% in nitrogen oxide emissions and ~635% in particulate matter emissions by 2050 compared to maintaining the 2020 action levels.

3.2. Uncovering the contribution of various actions to emission reductions

Progressively enhanced CO_2 emission reductions can be observed from 2020 to 2050 (Fig. 3(a)) when climate actions in the PCs sector are implemented at the EPS (V4–V6) and CNS (V7–V9) levels. The emission changes compared to the benchmark in the synergistic group (CO, VOC, and SO_2) closely aligned with the CO_2 trends from 2020 to 2050. Adverse emissions compared with the benchmark can be observed in the non-synergistic group (NO_x, $PM_{2.5}$, and PM_{10}). These adverse emissions mainly occur when the CFPPs sector air actions are at the 2020 levels (i.e., P1, P4, and P7).

We then analyzed the sectoral contributions to emission changes (Fig. 3(b)). CO_2 emissions gradually shifted from the PCs sector to the CFPPs sector when climate actions in the CFPPs sector were carried out at the BAU (P1–P3) and EPS (P4–P6) levels. However, the PCs sector remains the dominant contributor to CO_2 emissions. The CO and VOC emissions originate almost entirely from the PCs sector. As for SO_2 emissions, a significant shift in the main contributing sector from the PCs to the CFPPs sectors can be observed. The SO_2 emission contribution of the CFPPs sector

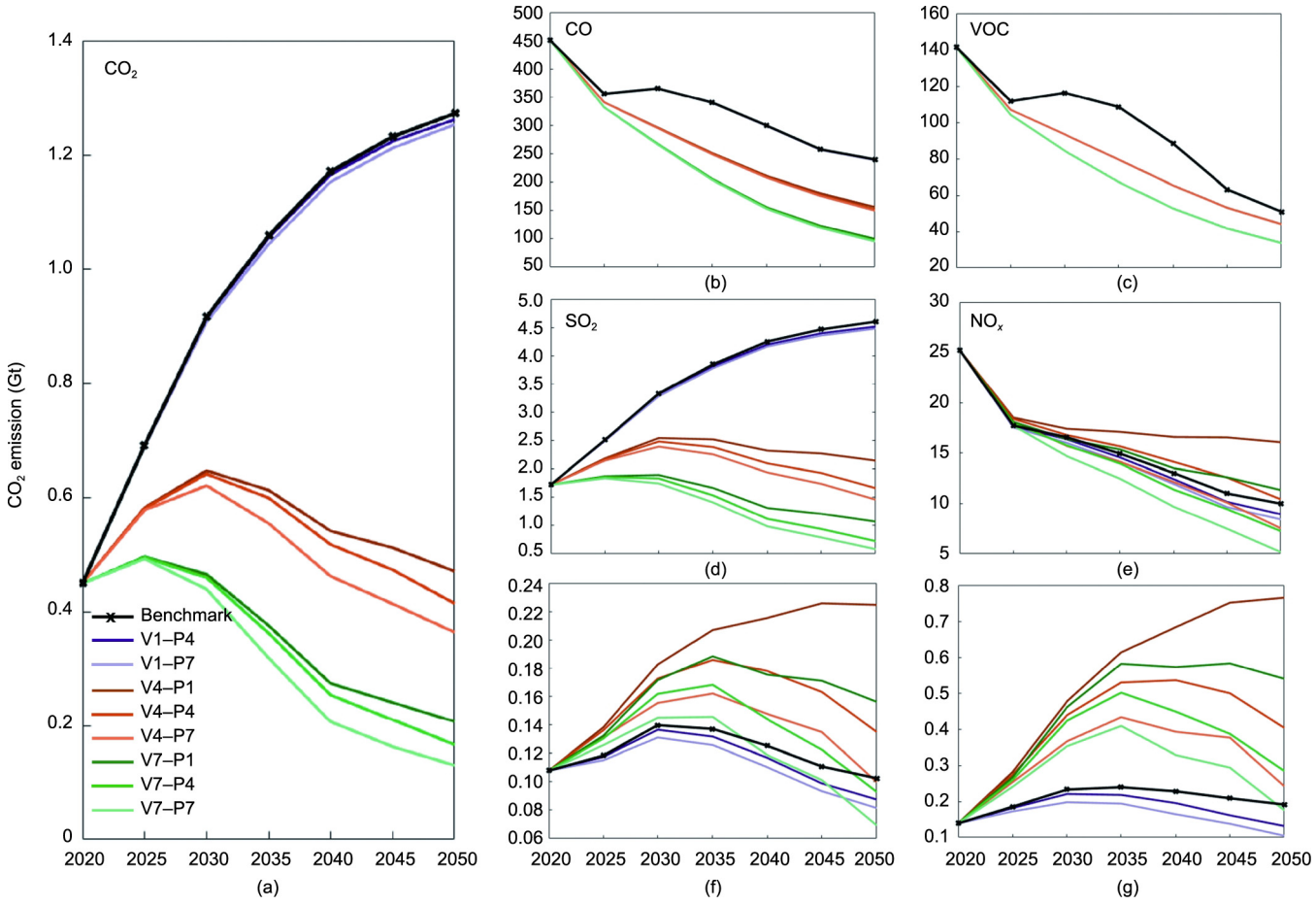


Fig. 2. Future emission trends of (a) CO_2, (b) CO, (c) VOC, (d) SO_2, (e) NO_x, (f) $PM_{2.5}$, and (g) PM_{10} from coupled PCs–CFPPs system. To identify the synergistic co-benefits from climate actions, the clean air actions in both sectors are controlled at the 2020 levels. The black line represents the V1–P1 cross-scenario group, which is the benchmark for our study and represents both sectors' climate actions at the BAU.

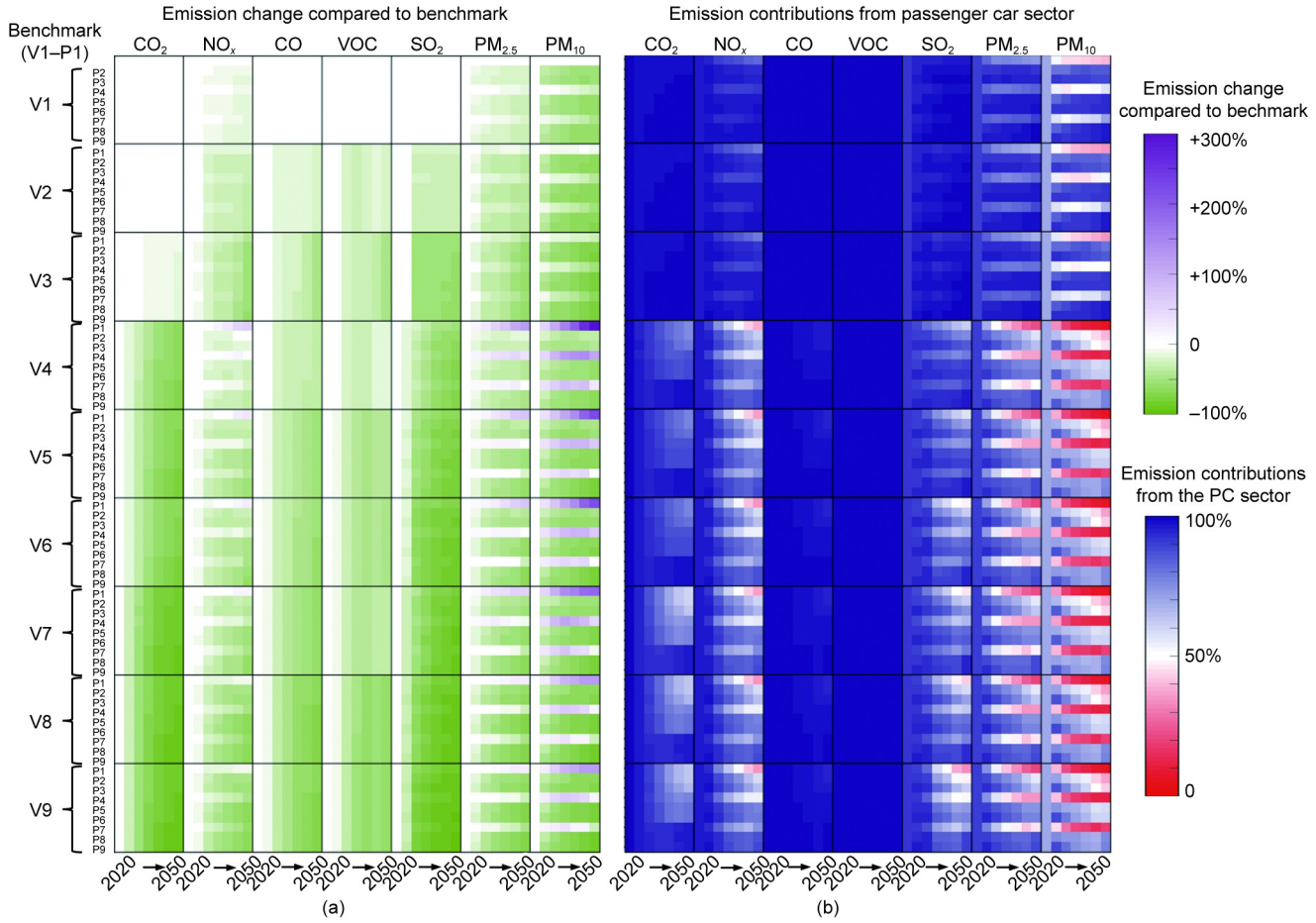


Fig. 3. The results of (a) CO_2 and AP emission changes in 2050 compared to benchmark (V1–P1) and (b) contributions of emission sources. The vertical coordinate represents the combination of scenarios, for a total of 81 combinations. V1–V9 are PC sector scenarios, P1–P9 are CFPP sector scenarios. The horizontal coordinates are categorized as emission types (above) and further categorized from 2020 to 2050 (below), with a time interval of five years.

reaches a maximum of 66.31% by 2050. The emission contribution of the CFPPs sector to NO_x, $PM_{2.5}$, and PM_{10} in 2050 reached a maximum of 65.01%, 78.68%, and 93.67%, respectively.

We accounted for the contribution of actions in both sectors to CO_2 and AP emission reductions (Fig. 4). The calculation process is detailed in Note S6 in Appendix A. CO_2 emissions from the coupled PCs–CFPPs system decrease from 1.27 Gt (benchmark pathway, i.e., V1–P1) to 0.12 Gt (integrated pathway, i.e., V9–P9) by 2050 (Fig. 4(a)), based on the gradual implementation of six categories of future actions (i.e., climate actions, clean air actions, and synergistic actions in both sectors). CO_2 emission reductions mainly result from synergistic actions and climate actions in the PCs sector, which accounts for a total reduction of 85.75% compared to the benchmark in 2050. The PCs sector's actions dominate CO and SO_2 emission reductions by 2030 and 2050, respectively (Figs. 4(b)–(e)).

PCs sector climate actions lead to an increase in NO_x and $PM_{2.5}$ emissions in the future (Figs. 4(f)–(i)). In 2030, the most effective emission reduction measures are synergistic actions in the PCs sector (reducing 2.69×10^4 t NO_x and about 300 t $PM_{2.5}$) and clean air actions in the CFPPs sector (reducing 1.87×10^4 t NO_x and about 400 t $PM_{2.5}$). By 2050, the most effective measures come from the CFPPs sector's climate actions which reduce 4.08×10^4 t NO_x and about 500 t $PM_{2.5}$. Notably, compared to the increase in NO_x and $PM_{2.5}$ emissions due to PCs sector climate actions, climate actions in the CFPPs sector offset 95.6% and 62.5% in these emissions, respectively, by 2050. Further emission reductions rely on additional measures. Therefore, we suggest developing a strategy that focuses on reducing car use demand and enhancing CFPPs tailpipe management in the near term while promoting the climate transition of the power sector in the long term.

3.3. Regional heterogeneity in synergistic effects of CO_2 and NO_x emission reductions

We further examined the synergy between CO_2 and NO_x emission reductions across the provinces. The results for China are consistent with those found earlier in this study; however, provincial heterogeneity in emission changes is evident (Fig. 5). CO_2 and NO_x emissions can be synergistically reduced in some regions (e.g., Beijing, Xizang, Qinghai, Yunnan, and Sichuan), where CFPPs have smaller installed capacities in the power grid and are phased out earlier in the future. These regions experience less pressure for coal-based power generation within their respective power grids. However, indirect NO_x emissions are shifted to other regions (e.g., Inner Mongolia and Shanxi) in the same grid, where the installed capacities are larger or where CFPPs are being phased out more slowly. This redistribution of indirect NO_x emissions due to the coal power generation structure within the grid exacerbates the loss of reduction co-benefits losses for central coal-power-generating provinces. Inner Mongolia faces significant challenges in achieving synergistic emissions reductions from 2020 to 2050, with emissions peaking at over 150% of the benchmark, indicating that more robust local policies than the most effective actions in this study are required to achieve synergistic emissions reductions. The ban on new gasoline-powered car sales in Hainan

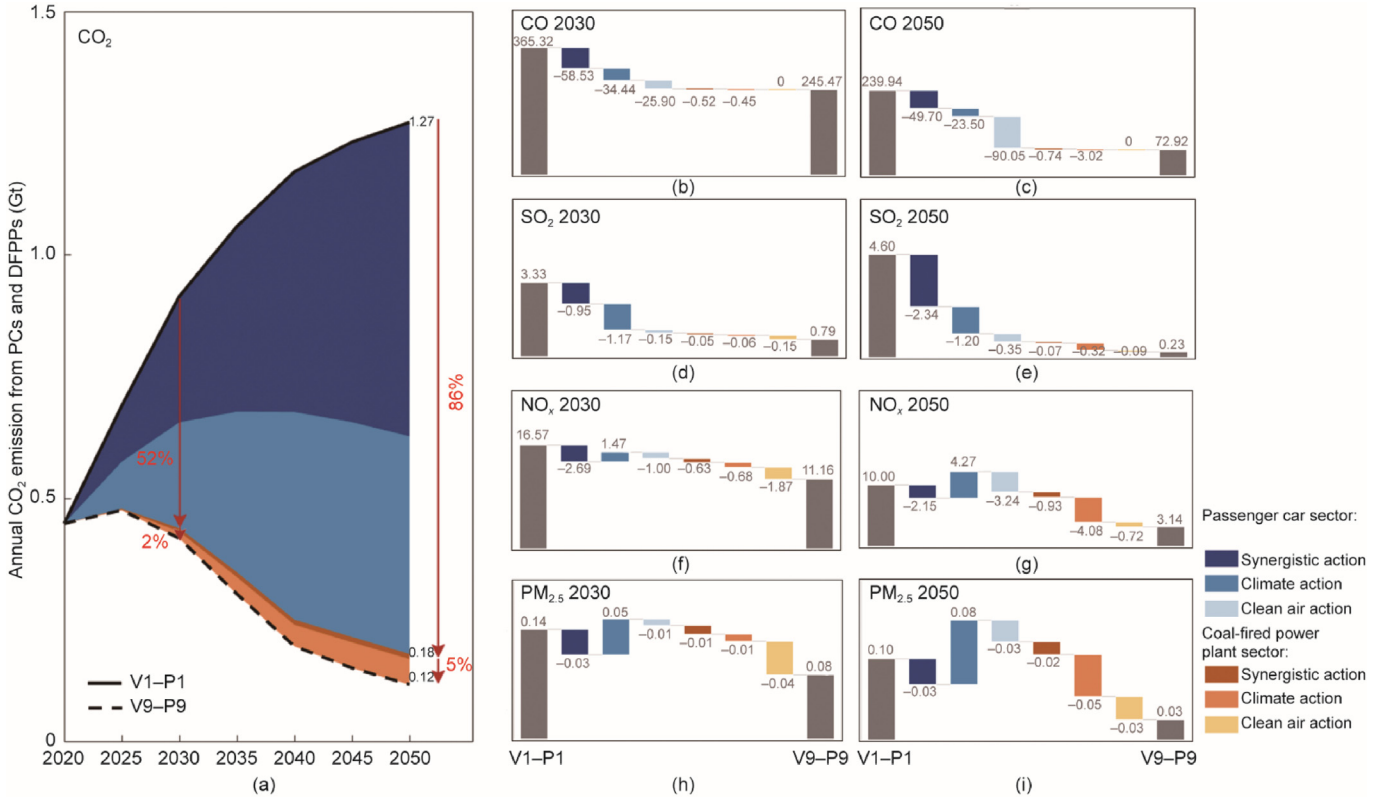


Fig. 4. Actions' emission reduction potential of (a) CO_2 from 2020 to 2050, CO in (b) 2030 and (c) 2050, SO_2 in (d) 2030 and (e) 2050, NO_x in (f) 2030 and (g) 2050, and $PM_{2.5}$ in (h) 2030 and (i) 2050 compared to benchmark (V1–P1). The optimal CO_2 and AP emission pathway under both sectors' various partially and fully combined strategies (V9–P9) is regarded as the integrated pathway.

Province after 2030 [47] represents China's strongest EVs promotion policy. A clear shift in the emission pathway (dotted line) toward the upper-right direction in Hainan after 2030 indicates that the uncertainties from cross-sector climate actions lead to more severe adverse NO_x emissions and less CO_2 reduction compared to the benchmark. However, the optimal strategy (solid line) shifts in the opposite direction after 2030, demonstrating a further enhancement of synergistic CO_2 and NO_x emission reductions.

4. Discussion

Our results demonstrate the necessity of developing a strategy to offset adverse AP emissions caused by uncertainties in cross-sector climate actions while maximizing the synergistic effects of CO_2 and AP emission reductions associated with China's PCs and CFPPs transition in the coming decades. These findings can inform policymakers and industry decision-makers on the timing and effectiveness of various cross-sector climate and clean air strategies to reduce the potential adverse impacts of the entire coupled PCs–CFPPs system.

4.1. Breaking down sectoral regulation boundaries is necessary for maximizing co-benefits

Breaking down sectoral regulation boundaries can help achieve balanced actions, facilitating synergistic AP emission reductions. Although the Chinese government has developed numerous climate action plans for each sector within the carbon peaking and carbon neutrality 1 + *N* policy framework [30] and has set requirements for cross-sector cooperation, specific implementation plans and safeguard measures remain inadequate. We propose a policy strategy that aims to reduce car use demand and enhance CFPPs' tailpipe management in the near term while focusing on the climate transition of the power sector in the long term. However, policy measures are managed by different administrations in China, creating a barrier to the development of an effective cross-sector strategy. A previous study [28] suggests that China should accelerate vehicle electrification and rapidly achieve decarbonization in the power sector. We find that strengthening vehicle demand management and further improving AP emission management in CFPPs in the near term may have a more effective impact. A previous study [5] also highlighted the importance of short-term demand management through public engagement in the PCs sector for carbon reduction, and we found that it is also important for environmental authorities to upgrade PCs emission standards. The tailpipe management of CFPPs still holds further potential for APs emission reduction, but entails high investment and operational costs, necessitating careful consideration of these trade-offs by managers. Long-term emission reductions require better coordination between transportation and power administration in climate action planning, as the current policy framework is fragmented.

It is crucial to develop specific tools, such as the evaluation framework developed in our study, for cross-sector policy assessments to identify and address potential synergies and conflicts between sectors. While the power and transportation sectors continue to set their own policies within their respective domains, having a tool in place to assess and guide interactions between these sectors is essential for ensuring coordinated and effective climate actions. Additionally, a cross-departmental coordination mechanism should be introduced during policy design, such as establishing coordination groups at higher levels.

4.2. Wary of emission risks from hindered EVs large-scale promotion

Promoting EVs is not only a cornerstone of China's climate policy, but is also deeply embedded in its energy and industrial strate-

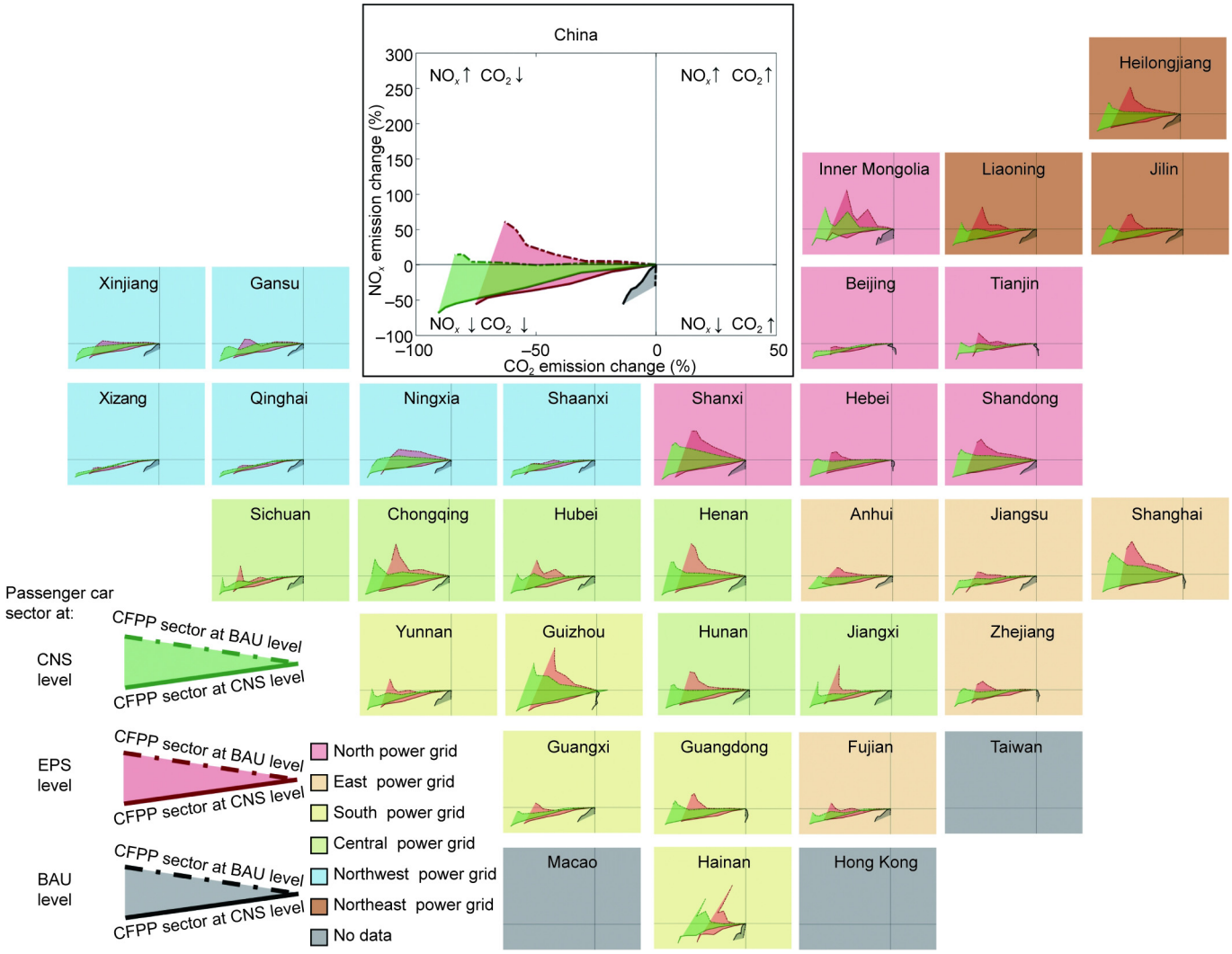


Fig. 5. The coupled PCs–CFPPs system provincial CO_2 and NO_x emissions changes under cross-sector climate actions compared to benchmark (V1–P1) from 2020 to 2050. Emissions change pathways are plotted for each cross-scenario group from 2020 to 2050. The starting point is the origin of the coordinates (representing 2020). The time step is five years. For the synergistic/antagonistic relationship between CO_2 and NO_x emissions, the first quadrant represents antagonism, the second quadrant represents CO_2 emission reduction but NO_x emission increase, the third quadrant represents synergy, and the fourth quadrant represents CO_2 emission increase but NO_x emission decrease.

gies [6,7]. However, when the large-scale promotion of EVs is hindered by uncertainty factors, the climate actions at the PCs EPS level may generate more serious adverse emissions from the non-synergistic group of AP than the actions at the PCs BAU and CNS levels (Figs. 2(e)–(g)). This is because although electrification is hindered, there is still an increase in demand for electricity, leading to higher emissions from CFPPs. Moreover, the entry of new gasoline cars into the fleet, driven by blocked EV promotion, contributed to increased APs emissions. To safeguard the large-scale promotion of EVs and meet CNS-level requirements, several measures can be considered, such as material recycling, technical innovation in battery chemistry, and the introduction of purchase tax incentives [35,53–57]. Previous studies [12,19] have revealed that upgrading the PCs emission standards in the hindered electrification process can help offset adverse APs emissions. Our results confirm that upgrading the PCs emission standards remains effective even for the coupled PCs–CFPPs system, but further emission offsets require additional climate actions and enhanced clean air actions in the power sector. Therefore, the adoption of electric cars and the next phase of gasoline cars' AP emission control standards should be actively promoted.

4.3. Power grid-level management need to be emphasized

Regional administrators should develop specific policies that consider regional policy and infrastructure heterogeneity. Our results identify provinces that play a greater role in power generation by CFPPs are more likely to face more serious adverse emission situations than others (Fig. 5). For provincial managers, updating more efficient APs control facilities in CFPPs, implementing power mix optimization, and retiring coal plants while safeguarding power demand can help reduce APs emissions. Moreover, managing the relationship between electricity generation and consumption requires increased consideration of indirect emission transfers between provinces along the power supply chain. We suggest fostering collaboration between provinces, which can ensure alignment of strategies, balancing energy security with carbon neutrality, and clean air goals.

Owing to the limited availability of infrastructure-level data, our analysis focuses exclusively on CFPPs' emissions. However, gas-fired power plants are also sources of NO_x emissions. Considering the ~50% reduction in the NO_x emission factors for natural gas versus coal power generation, our current NO_x emission estimates

for the coupled system may represent an upper-bound case. Future studies should integrate gas-fired power generation by enhancing the data availability and refining emission accounting methodologies to provide a more comprehensive assessment of its impact on NO_x emissions and strategies for emission control policies.

4.4. Challenges and Outlook

AP emissions from gasoline-powered cars are typically dispersed across urban areas, whereas the shift to electric cars concentrates emissions at power plants. This transition can improve air quality and reduce health risks in urban areas [26], particularly in densely populated cities, but may also increase the risk for communities near power plants [25]. We found that future AP emissions will shift toward provinces that are major coal-fired power providers (Fig. 5). For example, the widespread adoption of EVs in Beijing significantly improves local air quality. However, the electricity used for these EVs leads to increased power sector emissions in other provinces, primarily from CFPPs in Inner Mongolia, Shaanxi, and Shandong, resulting in increased health risks to the populations exposed to these power plants. The redistribution of coal-fired power generation through electricity supply chains will lead to increasingly unequal health risks across the provinces of China. The co-benefits of air pollution mitigation in climate policies require a more systematic evaluation, in which the benefits of urban air quality improvements are balanced against the disproportionate health burdens imposed on rural and industrial communities. Encouraging the adoption of cleaner energy sources and enhancing emission control measures at power plants can help mitigate these regional inequalities. Future research can further explore air quality issues and population health risks caused by the redistribution of AP between sectors using model tools (e.g., the WRF-CMAQ model, concentration–response function, and Global InMAP model). Moreover, as electric cars tend to be heavier than gasoline cars, this could exacerbate non-exhaust emissions [58,59], which may further increase health risks [60]. Future research should emphasize addressing this issue.

Our study offers insights for other sectors pursuing emission reduction through electrification, emphasizing that life-cycle emissions should be a key focus for future research, such as emissions from car manufacturing [61,62], charging infrastructure [63], power transmission, and energy storage facilities [64]. We conducted a preliminary estimation of future emissions from vehicle manufacturing (Note S7 in Appendix A for details). We found that under the current clean production level in EVs' manufacturing processes, upstream SO_2 emissions will increase significantly. According to Sharma et al. [61], cleaner manufacturing in steel production, copper refining, and nickel refining is critical for controlling upstream SO_2 emissions. Therefore, large-scale adoption of electric vehicles must be synchronized with the advancement of cleaner manufacturing technologies to effectively mitigate upstream SO_2 emissions. Variations in the EV charging timing and behavior can alter the associated emission impacts [65], representing a critical consideration for future research. In addition to the climate actions and clean air actions considered in this study, more factors (e.g., energy security, electricity competition, and costs) may be explored in the context of future inter-sector synergistic emissions reduction. These aspects deserve more profound and quantitative investigation to better inform global strategies for sustainable development.

5. Conclusions and implications

We found that well-matched cross-sector climate actions can achieve a maximum of 1.15 Gt CO_2 emission reductions and deliver significant synergistic reductions in AP emissions by 2050. In contrast, uncertainties during policy implementation pose a risk of diminishing these co-benefits, particularly when obstacles hinder electrification efforts in the PC sector. Provinces heavily dependent on coal power production are especially vulnerable to co-benefit losses. We recommend strategies aimed at breaking down the regulatory boundaries between sectors to address adverse emissions and amplify co-benefits. Policymakers need to prioritize the development of a unified cross-sector climate action plan, which is essential for aligning efforts and maximizing the effectiveness of climate actions across different sectors.

China is currently in the early stages of climate transition and is one of the largest emitters of carbon and pollutants globally. Uncertainties surrounding future climate change actions are a common challenge faced by countries worldwide. Our findings from China can provide insights for other developing countries that are in the early stages of their own transitions or are planning transformation strategies, especially for countries that mainly rely on coal power (e.g., India, Indonesia, and South Africa).

Data and code availability

All data are available in the main text or supplementary material. Bottom-up car data and coal-fired plant database are available upon reasonable request. The code used in this study is available at GitHub (https://github.com/XieEco/Engineering.git).

CRediT authorship contribution statement

Hongyi Xie: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bin Chen:** Writing – review & editing, Funding acquisition, Conceptualization. **Chen Wang:** Methodology, Formal analysis, Data curation. **Wei Xie:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Xinyi Long:** Writing – review & editing, Methodology. **Dingfan Zhang:** Writing – review & editing, Visualization. **Min Dai:** Writing – review & editing. **Zhixiu Han:** Writing – review & editing. **Yiru Song:** Writing – review & editing, Visualization, Methodology. **Jiashuo Li:** Methodology, Conceptualization. **Yutao Wang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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.

Acknowledgments

We are grateful to the National Natural Science Foundation of China (52022023, 52100210, and the 72121002) and the Shanghai Municipal Education Commission (24KXZNA15).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eng.2025.09.006.

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