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Original Research

Provincial-level analysis of electrification feasibility and climate policy interactions

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ABSTRACT

Improving electrification feasibility is essential for reducing emissions from non-electric energy sources, thereby enhancing air quality and public health. Concurrently, climate mitigation actions, such as carbon pricing policies, have significant potential to alleviate increasing carbon dioxide (CO_2) and other co-emitted air pollutants. However, the interactions between climate policy and the improvement of electrification feasibility at the provincial level remain unclear, collectively impacting the net-zero transition of energy-intensive sectors. Here we combine a technologically rich economic-energy-environment model with air quality modeling across China to examine the health, climate, and economic implications of large-scale upgrades in electrification feasibility and climate policies from 2017 to 2030. The results indicate that advancing electrification feasibility, coupled with adopting carbon pricing policies, is likely to facilitate a transition towards electricity-dominant energy systems. Improved electrification feasibility is projected to yield a 7–25% increase in nationwide climate benefits and a 5–14% increase in health benefits by 2030. These incremental benefits, coupled with reduced economic costs, result in a 22–68% increase in net benefits. However, regionally, improvements in electrification feasibility will lead to heightened power demand and unintended emissions from electric energy production in certain provinces (e.g., Nei Mongol) due to the coal-dominated power system. Additionally, in major coal-producing provinces like Shanxi and Shaanxi, enhanced electrification feasibility exacerbates the negative economic impacts of climate policies. This study provides quantitative insights into how improving electrification feasibility reshapes energy evolution and the benefit-cost profile of climate policy at the provincial level. The findings underscore the necessity of a well-designed compensation scheme between affected and unaffected provinces and coordinated emission mitigation across the power and other end-use sectors.

1. Introduction

Recent reports have decisively shown that climate-sensitive emissions from fossil energy use have unequivocally caused global warming [1]. Theoretically, there are a range of options available to abate the emissions from fossil energy, including the adoption of electric end-use technologies instead of fossil-fueled alternatives (known as electrification) [2], decreasing the intensity of carbon emissions via biomass and carbon capture and storage (CCS), and compensating for emissions through carbon dioxide removal. However, bioenergy and CCS are associated with greater resource and sustainability limitations than zero-carbon power energy, rendering the end-use electrification option increasingly important [3,4].

Economists use the "substitutability" between fossil fuels and electricity to quantify the difficulty of electrification (i.e., the extent to which fossil energy can be replaced with electricity), which is hereafter referred to as the electrification feasibility. Technological

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advancements, consumer behavior, and policies designed to mitigate carbon emissions all affect the feasibility of such a substitution [5,6]. When an energy system exhibits greater substitutability, it is more likely to achieve electrification at a relatively lower cost, meaning that fossil fuels (i.e., coal and oil) are more likely to be phased out [6,7]. Improving the electrification feasibility—a critical method of accelerating end-use electrification—promises to reduce fossil energy demand and curb fossil energy-related emissions, including greenhouse gases (GHGs) and local air pollutants. These reductions in local air pollutant emissions will improve the air quality, potentially providing substantial health benefits.

In particular, improving the electrification feasibility is essential in the industry and transportation sectors [8,9], which account for almost half of all annual carbon dioxide (CO_2) emissions in China [10]. To achieve the carbon neutrality target, electricity is supposed to provide at least 61–73% of the energy supply in these two sectors [11,12]. Electric energy is, however, still primarily provided via fossil fuel generation in China, which has given rise to a concern about overcapacity in the coal-fired power industry due to the increased electricity demand. In other words, while undoubtedly important, some measures intended to improve the electrification feasibility could potentially offset the gains derived from the improved air quality stemming from reduced fossil energy in other sectors, thus negatively affecting human health unless additional measures are adopted. Such complementary measures include, but are not limited to, implementing carbon pricing, restricting the coal-fired capacity, and/or investing in renewable energy, such as solar photovoltaic (PV) and wind power.

Despite considerable attention having been paid to policies and measures designed to tackle climate change [13,14], to the best of our knowledge, no research has examined how improving the electrification feasibility reshapes the cost-benefit profile of these climate policies. Here, we focus on this interaction at the provincial level in China. Due to its high reliance on coal during rapid industrialization, China has substantially contributed to global GHG emissions and caused severe local air pollution [15,16]. Still, China committed to peaking its carbon emissions by around 2030, including its best efforts to peak early and achieve 20% non-fossil energy as a primary energy supply by 2030 [17]. The pace of both electrification and energy technology innovation is rapidly increasing, and the rapid development of decarbonizing technology will inevitably have consequences for the electrification feasibility [18], making it essential to perform an analysis beyond purely focusing on climate policies.

This study examines the impacts of a range of policy portfolios—complementing a carbon-pricing policy with electrification feasibility improvement—that go far beyond the current electrification feasibility level but align with calls for concerted efforts to profoundly improve the electrification feasibility [19]. We employ China's economic–energy–environment model and air quality framework (CEEEM-AIR) to analyze energy consumption, CO_2 emissions, and air quality health in diverse scenarios by combining electrification feasibility improvements with carbon pricing and coal-fired power limitation policies. By examining the implications of such combinations' costs and benefits (including for climate and human health), our study sheds new light on how increased electrification feasibility can contribute to enhanced decarbonization and improved human health.

2. Materials and methods

2.1. CEEEM-AIR model

The CEEEM-AIR model integrates a multi-sector and multi-region computable general dynamic equilibrium (CGE) model [20,21], power dispatching model, air quality model (CHEER-AIR) [22], and health impact model (CHEER-HA) [22,23]. The comprehensive framework models the production, intermediate input flows, consumption, interprovincial trade, and energy in China based on the Carbon Emission Accounts and Datasets (CEADs) the Chinese mainland Provincial Multi-Regional Input–Output (MRIO) Table for 31 Provinces (42 sectors, 2017) [24] and the Energy Inventory for Chinese Provinces (https://www.ceads.net.cn/) [25,26]. The CEEEM-AIR model reports the energy- and non-energy-related (i.e., production processing) CO_2, sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3), organic carbon (OC), black carbon (BC), and carbon monoxide (CO) emissions from 2017 to 2030. Moreover, we perform the calibration and validation of our modeling results against real outcomes grounded in historical data via certain economic, energy, and environmental metrics, such as the gross domestic product (GDP) (see Ref. [27]), industrial structure (see Ref. [27]), $PM_{2.5}$ concentration, and electricity production, as illustrated in Supplementary Material Figs. S7 and S8. More modeling details concerning the CEEEM-AIR are available in Ref. [27].

2.2. Calculating the net benefits

We select three indicators to calculate the net benefits (NB_r) of climate policies: economic losses (EL_r), climate benefits (CB_r), and health benefits (CB_r). Equation (1) calculates the net benefits. Economic losses refer to the adverse impacts on the industrial structure, social employment, and other related aspects that may arise from the implementation of climate policies. Such losses are measured in terms of the GDP. Climate benefits refer to the monetary benefits to society stemming from reduced extreme weather events caused by decreased unit CO_2 emissions. To account for these climate benefits, we utilize the calculation method reported by Yang et al. [28] and Dong et al. [29], and we incorporate the social cost of carbon (SCC) estimated by Ricke et al. [30] (equation (2)). The SCC value used in this study is simulated using the damage function (Burke, Hsiang and Miguel, 2015 [31] (BHM) Long-run model within the Shared Socioeconomic Pathway (SSP) 2 and Representative Concentration Pathway (RCP) 6.0. Here, $\Delta Carbon_r$ is the CO_2 emissions reduction of a specific policy portfolio, as given in the unit of ton of CO_2. The health benefits consider the synergistic effects of climate policies on improving air quality, where $\Delta Mort_r$ is the premature mortality avoided as a result of climate mitigation efforts, which is calculated using the CHEER-AIR and CHEER-HA modules in the CEEEM-AIR model. The $\Delta Mort_r$ valuations (equation (3)) are based on Jin et al. [32] and the value of a statistical life (VSL_{base}) estimates, with a suggested value of RMB 5.54 million in China. We derive the provincial VSL for China using equation (4), following the procedure outlined in Wang et al. [33]. Here, β represents the income ($\frac{YT}{YB}$) elasticity of the VSL_r, while $(1+\%AP)$ is the inflation factor, which follows the World Bank (https://www.worldbank.org/en/home).

$$NB_r = CB_r + HB_r - EL_r \tag{1}$$

$$CB_r = SCC \times \Delta Carbon_r \tag{2}$$

$$HB_r = VSL \times \Delta Mort_r \tag{3}$$

$$VSL_r = VSL_{base} \times \left(\frac{YT}{YB}\right)^{\beta} \times (1+\%AP) \tag{4}$$

2.3. Scenario settings

We first design a baseline scenario (No-policy scenario) to represent the situation without any climate policy. We then employ a uniformly consistent climate policy across all the policy scenarios (Abbreviated as CP in the scenario name, i.e., CP-δ, CP-1.5δ, CP-2.0δ, and CP-2.5δ), which entails a carbon pricing policy and a restriction on the newly built coal-fired power capacity. The carbon price is determined by forecasting the future carbon prices in China [34,35]. The electrification feasibility (hereafter simply referred to as δ in the scenario name) is commonly measured by economists using a metric known as substitution elasticity [36,37]. In this context, a high substitution elasticity indicates a high capacity for substituting the two (i.e., fossil energy and electricity). Theoretically, the electrification feasibility is conditional upon factors such as the availability and cost of alternative energy sources, the infrastructure and technology required for both electricity production and distribution, the specific end-use application, and government policies and incentives [37–40]. The CP-δ scenario merely considers the climate policy without improving the electrification feasibility. The substitution elasticity of electricity across various industries in China (Supplementary Material Fig. S1), as estimated by Cao et al. using firm-level data [5], is used in the No-policy and CP-δ scenarios. Next, we develop three electrification feasibility scenarios—namely, CP-1.5δ, CP-2.0δ, and CP-2.5δ—to represent future paths for electrification feasibility improvements, which are grounded in the potential electrification feasibility improvements for a typical industry according to the National Grid Company's planning [19]. In the CP-1.5δ, CP-2.0δ, and CP-2.5δ scenarios, we allow for 50%, 100%, and 150% electrification feasibility increases, respectively, when compared with the CP-δ scenario in all industries.

3. Results

3.1. Energy consumption and associated emissions

Fig. 1a presents China's projected fossil energy consumption, including coal, gas, and oil, from 2017 to 2030. The effect of improving the electrification feasibility on reducing fossil energy consumption is evident: fossil energy consumption in the three electrification feasibility scenarios (i.e., CP-1.5δ, CP-2.0δ, and CP-2.5δ) will be 2%, 5%, and 8% lower, respectively, than in the CP-δ scenario—that is, merely implementing a carbon-pricing policy without considering further progress in terms of the electrification feasibility. More specifically, when compared with the No-policy scenario, in 2030, the CP-2.5δ scenario will lead to a nationwide reduction in fossil energy consumption of 36%, while the CP-1.5δ and CP-2.0δ scenarios will lead to a 32% and 34% reduction, respectively. By contrast, the CP-δ scenario will merely result in a 31% reduction in fossil energy consumption in 2030.

Regarding power generation, Fig. 1b shows the corresponding power generation by technology in China from 2017 to 2030. When the electrification feasibility is improved by 50%, 100%, and 150%, the electricity generation in 2030 will increase to 11.3, 12.8, and 14.3 PWh, respectively, driven by the increased economy-wide electricity demand, thus leading to a slight expansion of coal-fired power. For example, the generation of coal-fired power in the CP-1.5δ scenario is 12% higher than that in the CP-δ scenario, partially explaining the increase in coal consumption (Fig. 1a). This finding implies that improving the electrification feasibility further couples end-use sectors to the grid, yet the former and the latter might be largely uncoordinated. As a consequence, avoiding the overcapacity of fossil-fuel-based generation is critical.

Still, the evolution of the end-use energy and power generation systems leads to lower total net emissions (Fig. 1c). The CO_2 emissions in the CP-δ scenario will be lower by 29% compared with the emissions in the No-policy scenario in 2030, primarily contributed by the power and heavy industries, which collectively account for over 60% of the total reduction. Moreover, the CO_2 emissions in the CP-2.0δ and CP-2.5δ scenarios will be 34% and 36% lower than the No-policy scenario in 2030. These further emission reductions can be attributed to the potential emission savings from energy-intensive industries. More specifically, a 50%, 100% and 150% improvement in the electrification feasibility will further lead to 375, 764, and 1143 Mton CO_2 emission reductions, respectively, in energy-intensive industries in 2030, which will be partially offset by additional emissions from the power industry (e.g., offsetting 45%, 41%, and 36% of the reduced CO_2 emissions contributed by energy-intensive industries in the CP-1.5δ, CP-2.0δ, and CP-2.5δ scenarios, respectively; Fig. 2). Additionally, we observe further emission reductions in the electrification feasibility scenarios for nearly all the non-CO_2 air pollutants that we examine, except for $PM_{2.5}$, driven by the decreased consumption of oil and gas (e.g., a 12% decline in oil and a 28% decline in natural gas in the CP-2.5δ scenario when compared with the CP-δ scenario; Fig. 1a). These findings imply that while there is a trade-off in the emission reduction between the electric and the non-electric sectors, climate policies and electrification feasibility policies might be nationally complementary on the net as they together result in more emission reductions.

Next, we examine the sectoral emission reduction in different provinces to explore the provincial disparity in the mitigation outcomes of complementing electrification feasibility improvement with climate policies. Despite the further reduction observed nationally, not all the provinces consistently show a decline in emissions. Instead, an electrification feasibility improvement will increase society's electricity demand, leading to the expansion of coal-fired or coal-fired CCS power and consequently higher pollutant/CO_2 emissions. This case is particularly evident for pollutant emissions in certain provinces dominated by fossil-fuel-based generation, as adopting CCS technology to meet the growing electricity demand can partially mitigate CO_2 emissions, yet it does not reduce the alternative air pollutant emissions associated with the coal-fired power expansion. For example, the emissions of CO_2, NO_x, and SO_2 in Nei Mongol in the CP-2.5δ scenario are 2%, 18%, and 30% higher, respectively, than those in the CP-δ scenario (Supplementary Material Fig. S2). Therefore, a carbon pricing policy put in place to steer the energy transition might prove insufficient to achieve deep decarbonization. As a result, the mandatory co-control of fossil-energy-based power generation technologies, including coal-fired power, will likely prove necessary.

3.2. Changes in climate and health benefits

Building on the projected emission reductions, we estimate the effect of electrification feasibility improvements on monetized human health and climate mitigation via the avoided premature deaths and the social cost of carbon (Fig. 3). However, it is noteworthy that the results only represent a central estimate of the health and climate benefits associated with electrification feasibility upgrades, as the diverse portfolio of VSL and SCC values might affect their corresponding outcomes (see our previous work involving 5000 Monte Carlo simulations based on the distribution of the VSL and SCC values [27]). For this reason, we pay attention to the relative values of the benefits across space and diverse electrification feasibility improving scenarios instead of the specific values of the generated climate and health benefits (including the net benefits mentioned later).

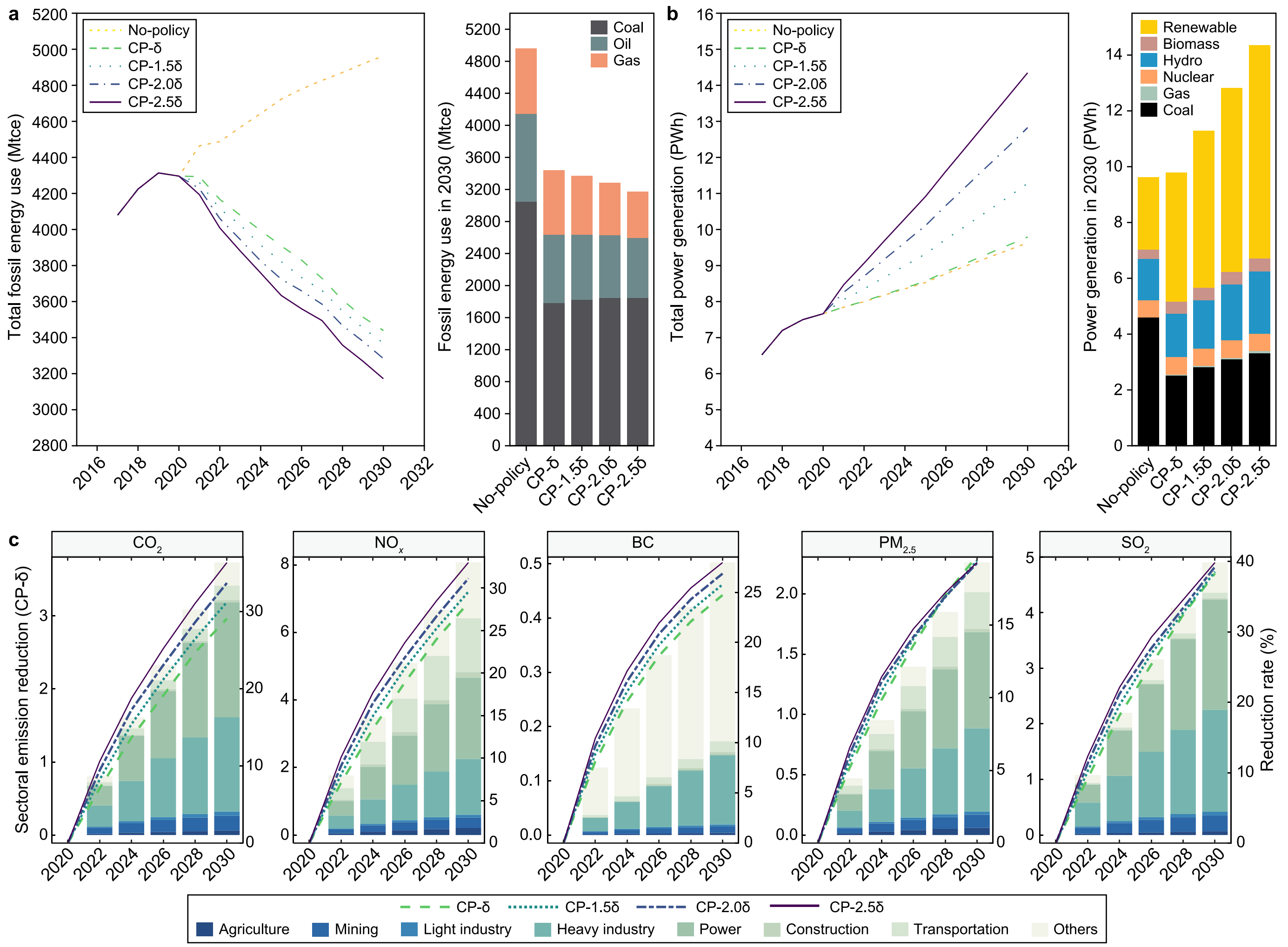

Fig. 1. Projected energy consumption and associated emission reductions from our scenarios. **a**, Projected fossil energy use. The right panel illustrates the composition of fossil energy under different scenarios in 2030. **b**, Projected power generation. The right panel displays the composition of the power system under different scenarios in 2030. **c**, Projected emission reductions across diverse policy scenarios (compared to the No-policy scenario) of different pollutant specifics (i.e., CO_2, NO_x, BC, $PM_{2.5}$, and SO_2). The bars represent the sectoral emission reduction of the CP-δ scenario. The unit in CO_2 emission is gigaton (Gt), and the others are megaton (Mton). The lines represent the reduction rates of total sectoral emissions under the corresponding policy scenarios in the unit of %.

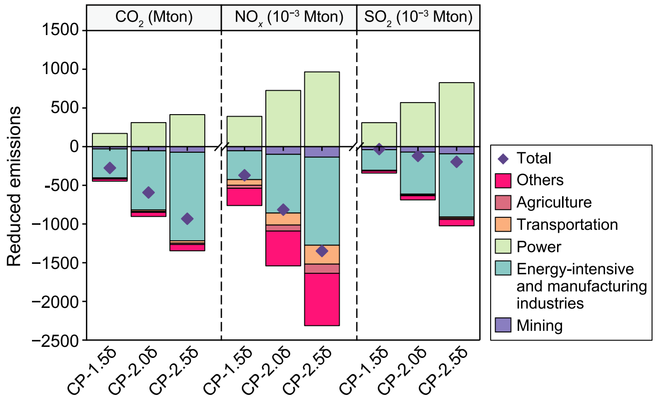

Fig. 2. Sectoral CO_2, NO_x, and SO_2 emission reduction due to electrification feasibility improvement at the national level in 2030. The emission under the electrification feasibility improving scenarios (CP-1.5δ, CP-2.0δ, and CP-2.5δ, as presented in the horizontal axis) minus the corresponding emission under the CP-δ scenario. We further aggregate light, heavy, and construction industries, as presented in Fig. 1, into energy-intensive and manufacturing industries. The scatters in the figure represent the total emission reduction of different scenarios.

Nationwide, electrification feasibility improvement (50–150%) will lead to 7–25% and 5–14% increases in the climate and health benefits, respectively, in 2030. However, due to the provincially differentiated evolution of the energy system and emission reductions, the climate and health benefits that result from electrification feasibility improvement might vary across provinces. Thus, we first focus on how climate and health benefits spread across provinces in the reference case (i.e., the CP-δ scenario). The provinces with the most climate benefits do not necessarily gain the most health benefits. Indeed, health benefits are especially pertinent to the local air quality, which depends on local emissions reduction and geographically close provinces or provinces in the dominant wind direction [37]. The greatest health benefits occur in densely inhabited and economically developed provinces, such as Jiangsu, Shandong, and Guangdong provinces, which amount to RMB 185 billion, RMB 127 billion, and RMB 93 billion in 2030, respectively, in the CP-δ scenario. Unlike the health benefits, Hebei, Nei Mongol, and Jiangsu have the highest climate benefits, reaching RMB 163 billion, RMB 155 billion, and RMB 143 billion in 2030, respectively.

As a result, the extent of the variation in the climate and health

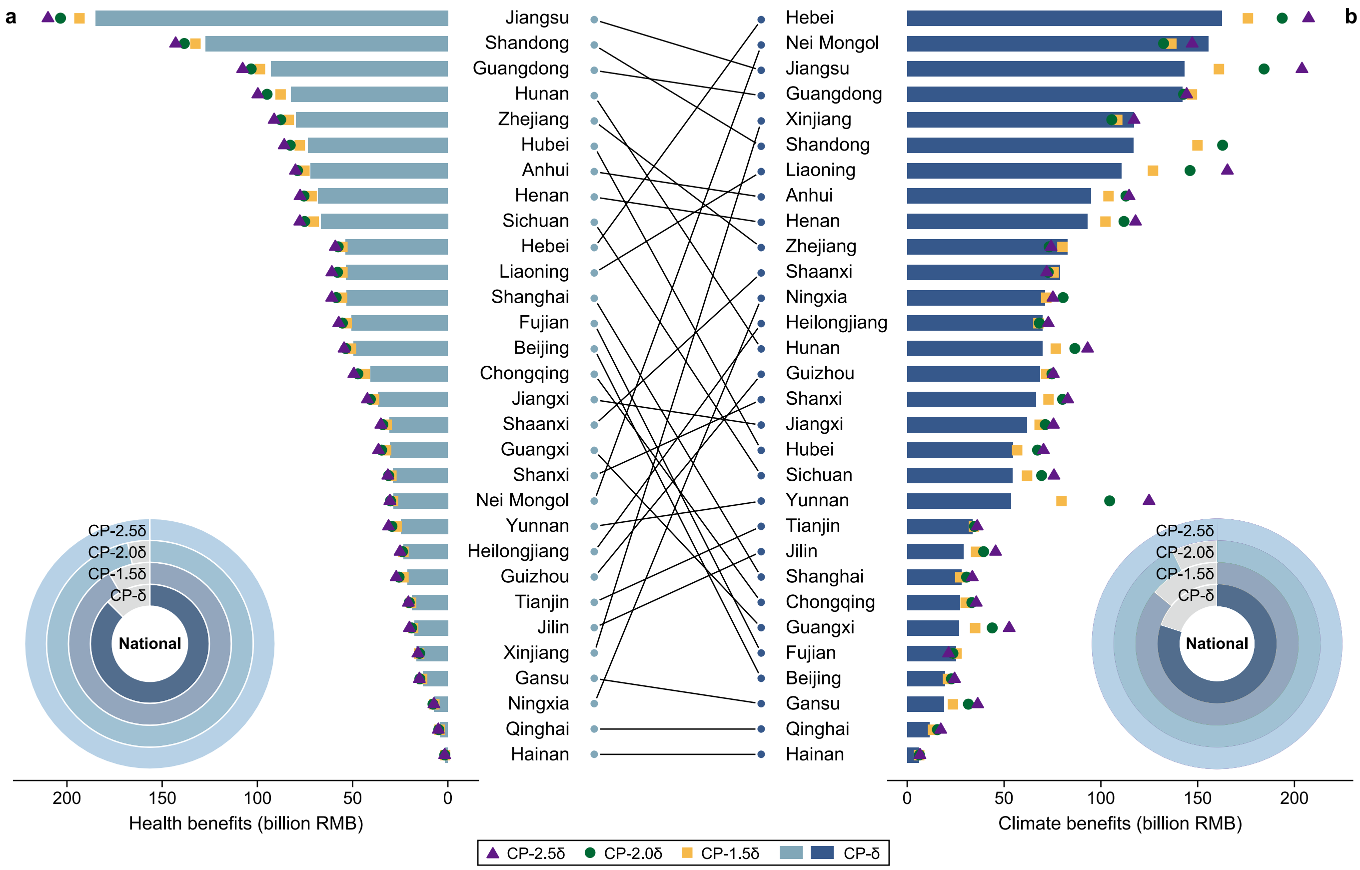

Fig. 3. Projected climate and health benefits from our scenarios in 2030. a, The ranking of provinces based on health benefits. **b**, The order grounded in climate benefits under the CP-δ scenario. The effect of improving electrification feasibility (CP-1.5δ, CP-2.0δ, and CP-2.5δ) on climate and health benefits of climate policy is presented in scatters. The line between panels **a** and **b** represents the discrepancy in provincial ranking between health and climate benefits under the CP-δ scenario. The circles in **a** and **b** represent nation-level health benefits and climate benefits, respectively.

benefits due to the increased electrification feasibility also exhibits a differentiated pattern. Regarding the health benefits, there is a positive correlation between the level of health benefits observed in the CP-δ scenario and the extent to which the regional health benefits improve with increased substitutability (Supplementary Material Fig. S3). In Jiangsu, for example, adopting climate policies leads to greater health benefits in the CP-δ scenario and consequently a more evident incremental increase in the health benefits associated with the electrification feasibility improvement. By contrast, improving the electrification feasibility has a negligible effect in Hainan, Qinghai, and other provinces that inherently gain less health benefits in the CP-δ scenario. Improving health benefits is especially pertinent to province-specific factors, such as population density, baseline mortality rate, and weather conditions, which are partially involved in the reference case (i.e., the CP-δ scenario). These locally inherent meteorological and demographic characteristics will weaken the spatial redistribution of additional emission reductions across provinces. For instance, in more populated regions, while numerically small, further emission reductions can lead to greater health benefits due to the larger number of people affected. This causes a stronger correlation between the improved health benefits and the values observed in the CP-δ scenario. Conversely, the extent of the increases in the climate benefits is comparatively independent of the corresponding values in the CP-δ scenario (Supplementary Material Fig. S3). For instance, in Yunnan, the climate benefits amount to only RMB 53 billion in the CP-δ scenario, whereas the benefits almost double in the CP-2.5δ scenario.

3.3. Changes in net benefits

Exploring the economic impacts of a policy portfolio is equally important, given that they affect the net benefits in combination with the climate and health benefits. Fig. 4 presents the estimated economic costs and net benefits in our diverse scenarios. The provincial distributions of the net benefits in the CP-δ scenario are also provided in Supplementary Material Fig. S4.

Improving the electrification feasibility helps lower the mitigation cost of CO_2 reduction, particularly during the deep-decarbonizing phase (Fig. 4a). Nationwide, the climate policies in the CP-δ scenario will result in a GDP loss of RMB 2.29 trillion in 2030. For comparison, in the electrification feasibility improvement scenarios wherein the substitutability between fossil energy and electricity is improved by 50–150%—that is, corresponding to the CP-1.5δ, CP-2.0δ, and CP-2.5δ scenarios—the GDP loss will decline to RMB 2.24 trillion, RMB 2.19 trillion, RMB 2.16 trillion, respectively (Fig. 4b). This is also the case for the cross-province average of the economic costs, which decreases from RMB 76.2 billion in the CP-δ scenario to RMB 71.9 billion in the CP-2.5δ scenario.

The net benefits across the different scenarios incorporate the economic costs, climate benefits, and health benefits (Fig. 4c). Despite the substantial costs associated with climate policies in China, the potential air quality and climate co-benefits are sufficient to provide net gains (RMB 1.26 trillion), even in the absence of improved electrification feasibility (i.e., in the CP-δ scenario). The impacts of improving the electrification feasibility on promoting the net benefits of climate policies are evident: the nationwide net

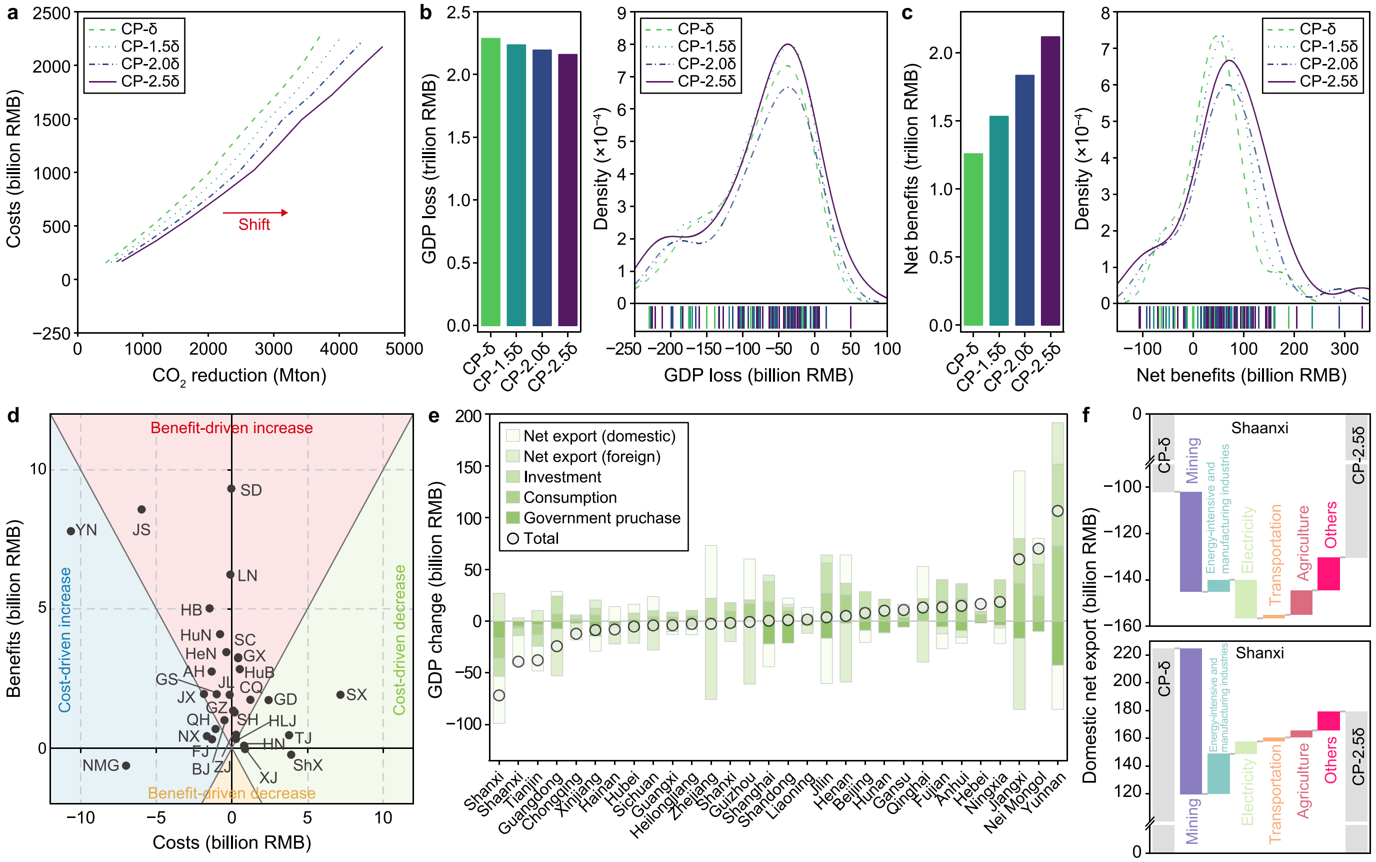

Fig. 4. The net benefits integrating economic costs, climate benefits, and health benefits from our scenarios. **a**, Emission abatement cost curve. The red colored arrows indicate the movement from the CP-δ scenario to the CP-2.5δ scenario. **b**, Total (left) and distributions (right) of economic costs from our scenarios in 2030. **c**, Total (left) and distributions (right) of net benefits from our scenarios in 2030. **d**, Cost-benefit analysis of provincial net benefit changes (the value under the CP-2.5δ scenario minus the corresponding provincial value under the CP-δ scenario). See Supplementary Material Table S1 for the full provincial names corresponding to the abbreviations on the figure. **e**, Economic cost changes in 2030 (the value under the CP-2.5δ scenario minus the corresponding provincial value under the CP-δ scenario) disaggregated by economic variables at the provincial level. **f**, Domestic net export change disaggregated by sectors in 2030 (the value under the CP-2.5δ scenario minus the corresponding value under the CP-δ scenario) in Shaanxi and Shanxi provinces.

benefits in the CP-2.5δ scenario are 68% higher than that in the CP-δ scenario, as is also the case concerning the cross-province average of the net benefits. Nevertheless, the distribution of net benefits across the provinces will be more widespread. In other words, improving the electricity feasibility may disproportionally affect the regional net benefits, inevitably creating new and perpetuating pre-existing winners and losers concerning climate policies (Supplementary Material Figs. S5 and S6).

Motivated by the spatially unequal impacts, we conduct a province-specific analysis between scenarios CP-δ and CP-2.5δ (Fig. 4d–f). The increments in the provincial net benefits are primarily driven by the increased benefits—namely, the sum of the climate and health benefits—whereas the decrements are predominantly impacted by the increase in economic costs (Fig. 4d). In particular, the most pronounced increases in economic costs occur in Shanxi and Shaanxi provinces, which can be partially explained by the shrinking net domestic exports (Fig. 4e). Fig. 4f further zooms into the sectorally disaggregated export outcomes in Shanxi and Shaanxi provinces, revealing a substantial decrease in exports within the mining sector, particularly coal mining. Shanxi and Shaanxi provinces occupy a pivotal position in the supply chain of fossil-based energy, and coal production accounts for a relatively higher share of the GDP in these provinces. Improving the electrification feasibility will lead to a decline in fossil energy consumption in non-electricity-producing industries and, consequently, to a recession in the upstream fossil-energy-extracting sectors. These adverse impacts will be propagated along the fossil fuel supply chain, along with the increased production costs for local industries due to climate policies, hindering economic growth. At the same time, compared to the highly local economic costs, most of the benefits associated with climate and air quality will be reaped nationally rather than locally. These two aspects collectively contribute to the detrimental effect on the net benefits of Shanxi and Shaanxi provinces, partially explaining the postponed mitigation efforts.

4. Discussion and conclusions

Limiting global warming in line with the climate targets of the Paris Agreement requires a profound and rapid energy transformation. Against this background, a climate mitigation strategy centered on renewables-based electrification is increasingly important [12]. This paper analyzes the effects of electrification feasibility improvement that extend substantially beyond current policies on the health benefits, climate benefits, and economic costs of climate policies at the provincial level in China. The scenarios modeled in this study are deliberately simple, enabling comparison of the potential benefits across the level of electrification feasibility rather than attempting to predict the future. In reality, the exact trajectory of upcoming technological developments, policy intensities, etc., remains highly uncertain. In this sense, our scenarios provide quantitative insights rather than exact estimates of specific outcome variables.

Complementing climate policies by improving electrification feasibility (the CP-1.5δ, CP-2.0δ, and CP-2.5δ scenarios) will lead to a 29–36% decrease in CO_2 emissions, a 28–33% decrease in NO_x emissions, and a 25–28% decrease in BC emissions in 2030. These CO_2 and non-CO_2 emissions reductions will bring about considerable climate and health benefits, amounting to around RMB 2.61 trillion and RMB 1.66 trillion in 2030 in the CP-2.5δ scenario. Moreover, improving the electrification feasibility will lower the economic costs associated with climate policies, leading to higher net benefits. Nationwide, improving the electrification feasibility by 50–150%, for instance, will lead to a 2–6% decline in the GDP loss and a 21–68% increment in the net benefits. These results are highly relevant for policy purposes, as they suggest that apart from directly investing in renewable energy [41], improving the electrification feasibility in end-use sectors can also offer a pragmatic and straightforward entry point to enhance the net benefits of climate policies. Another important policy implication is that the co-control of emissions in the power sector matters. Economic-wide carbon pricing, while important, is insufficient to guard against the risk of the overcapacity of coal-fired power that accompanies more stringent electrification in energy systems. One essential solution is coal-fired capacity restrictions, as explored in this study, to overcome the overdevelopment of coal power because of the rapidly increased electricity demand stemming from electricity feasibility improvement.

Despite the considerable improvement in the net benefits, improving the electricity feasibility may disproportionally affect the provincial net benefits. Previous studies on climate policies in China have especially focused on their regionally differential impacts on the economy [42]. Similarly, we find that the climate policies will prove particularly burdensome for coal-supplying provinces such as Shanxi and Shaanxi. Furthermore, improving the electricity feasibility will inevitably create new and perpetuate pre-existing winners and losers concerning climate policies, thereby exacerbating the inequities of the net benefits' distribution across provinces. This a novel and important finding. The consistent patterns of winners and losers across our modeled scenarios give rise to policy recommendations concerning compensation schemes between unaffected and affected provinces. Future analyses should pay close attention to investigating policy mechanisms for redressing these persistent inequalities.

However, there are some noteworthy caveats and limitations across our analysis. While we address the potential benefits and economic losses associated with electrification feasibility improvement, we do not examine the potential costs associated with technical solutions to improve the electrification feasibility. These solutions are diverse and potentially costly [43,44], including but not limited to upgrading the electricity-related infrastructure and promoting technological electric-use innovation. Moreover, our analysis represents only the minimum health benefits (i.e., $PM_{2.5}$-related health outcomes), as fossil fuel energy withdrawal not only reduces exposure to $PM_{2.5}$ pollution but also decreases exposure to other co-emitted toxic pollutants [14]. The latter, however, is not fully reflected in this study. Thus, future research should explore the cost outlays concerning technical solutions and other benefits excluded from this study to provide policymakers with a more holistic picture of the cost–benefit profile of electrification feasibility improvement.

Another consequential extension worthy of pursuit pertains to the feedback loop between climate policy and electrification feasibility improvement, which remains absent from the analysis. Indeed, overwhelming evidence has shown the positive effects of carbon-pricing policies on technological progress [45,46], for example, electric vehicles, which promote the feasibility of end-use electrification. The feasibility of real-world electrification is undergoing a dynamic evolution that is partially affected by climate policies. At the same time, the cost–benefit profiles of climate policies are also influenced by the electrification feasibility. In short, there may be a positive feedback loop: climate policy increases electrification substitutability, and such increased substitutability, in turn, strengthens climate policy gains. This implies that existing studies focusing on the costs of climate policies may offer inflated estimates, as they mostly ignore this positive feedback loop.

CRediT authorship contribution statement

Huihuang Wu: Writing - Original Draft, Methodology, Investigation, Formal Analysis, Conceptualization. **Haozhe Yang:** Writing - Review & Editing, Methodology, Conceptualization. **Xiurong Hu:** Writing - Review & Editing, Methodology, Conceptualization. **Yuhan Zhou:** Writing - Review & Editing, Methodology. **Xian Wang:** Writing - Review & Editing, Methodology. **Junfeng Liu:** Writing - Review & Editing, Methodology, Conceptualization. **Ying Liu:** Writing - Review & Editing, Methodology. **Shu Tao:** Writing - Review & Editing, Methodology.

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.2024.100474.

References

[1] IPCC, Energy systems, in: IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, 2022. Cambridge, UK and New York, NY, USA (2022).

[2] J.E.T. Bistline, G. Blanford, J. Grant, E. Knipping, D.L. McCollum, U. Nopmongcol, H. Scarth, T. Shah, G. Yarwood, Economy-wide evaluation of CO2 and air quality impacts of electrification in the United States, Nat. Commun. 13 (1) (2022) 6693.

[3] V. Heck, D. Gerten, W. Lucht, A. Popp, Biomass-based negative emissions difficult to reconcile with planetary boundaries, Nat. Clim. Change 8 (2) (2018) 151.

[4] F. Humpenöder, A. Popp, B.L. Bodirsky, I. Weindl, A. Biewald, H. Lotze-Campen, J.P. Dietrich, D. Klein, U. Kreidenweis, C. Müller, S. Rolinski, M. Stevanovic, Large-scale bioenergy production: how to resolve sustainability trade-offs? Environ. Res. Lett. 13 (2) (2018) 15.

[5] J. Cao, M.S. Ho, R. Ma, Analyzing carbon pricing policies using a general equilibrium model with production parameters estimated using firm data, Energy Econ. 92 (2020) 12.

[6] E. Malikov, K. Sun, S.C. Kumbhakar, Nonparametric estimates of the clean and dirty energy substitutability, Econ. Lett. 168 (2018) 118–122.

[7] C. Papageorgiou, M. Saam, P. Schulte, Substitution between clean and dirty energy inputs: a macroeconomic perspective, Rev. Econ. Stat. 99 (2) (2017) 281–290.

[8] Z.J. Schiffer, K. Manthiram, Electrification and decarbonization of the chemical industry, Joule 1 (1) (2017) 10–14.

[9] M. Yuan, J.Z. Thellufsen, H. Lund, Y.T. Liang, The electrification of transportation in energy transition, Energy 236 (2021) 14.

[10] H.Q. Qian, S.D. Xu, J. Cao, F.Z. Ren, W.D. Wei, J. Meng, L.B. Wu, Air pollution reduction and climate co-benefits in China's industries, Nat. Sustain. 4 (5) (2021) 417.

[11] S. Yu, S. Fu, J. Behrendt, Q. Chai, L. Chen, W. Chen, X. Cheng, L. Clarke, D. Du,

F. Guo, N. Hultman, N. Khanna, V. Krey, M. Li, J. Liu, H. Lu, J. Lou, C. Mei, X. Qin, K. Wang, Y. Wu, Z. Yang, S. Zhang, N. Zhou, China Carbon Neutrality Report 2022: Deep Electrification Facilitates Carbon Neutrality, The Energy Foundation, Beijing, China, 2022.

[12] G. Luderer, S. Madeddu, L. Merfort, F. Ueckerdt, M. Pehl, R. Pietzcker, M. Rottoli, F. Schreyer, N. Bauer, L. Baumstark, C. Bertram, A. Dirnaichner, F. Humpenöder, A. Levesque, A. Popp, R. Rodrigues, J. Strefler, E. Kriegler, Impact of declining renewable energy costs on electrification in low-emission scenarios, Nat. Energy 7 (1) (2022) 32–42.

[13] F. Wang, J.D. Harindintwali, K. Wei, Y. Shan, Z. Mi, M.J. Costello, S. Grunwald, Z. Feng, F. Wang, Y. Guo, X. Wu, P. Kumar, M. Kästner, X. Feng, S. Kang, Z. Liu, Y. Fu, W. Zhao, C. Ouyang, J. Shen, H. Wang, S.X. Chang, D.L. Evans, R. Wang, C. Zhu, L. Xiang, J. Rinklebe, M. Du, L. Huang, Z. Bai, S. Li, R. Lal, M. Elsner, J.-P. Wigneron, F. Florindo, X. Jiang, S.M. Shaheen, X. Zhong, R. Bol, G.M. Vasques, X. Li, S. Pfautsch, M. Wang, X. He, E. Agathokleous, H. Du, H. Yan, F.O. Kengara, F. Brahushi, X.-E. Long, P. Pereira, Y.S. Ok, M.C. Rillig, E. Jeppesen, D. Barceló, X. Yan, N. Jiao, B. Han, A. Schäffer, J.M. Chen, Y. Zhu, H. Cheng, W. Amelung, C. Spötl, J. Zhu, J.M. Tiedje, Climate change: strategies for mitigation and adaptation, The Innovation Geoscience 1 (1) (2023) 100015.

[14] M.W. Li, D. Zhang, C.T. Li, K.M. Mulvaney, N.E. Selin, V.J. Karplus, Air quality co-benefits of carbon pricing in China, Nat. Clim. Change 8 (5) (2018) 398.

[15] H. Fan, C.F. Zhao, Y.K. Yang, A comprehensive analysis of the spatio-temporal variation of urban air pollution in China during 2014-2018, Atmos. Environ. 220 (2020) 12.

[16] Y.L. Shan, D.B. Guan, H.R. Zheng, J.M. Ou, Y. Li, J. Meng, Z.F. Mi, Z. Liu, Q. Zhang, Data Descriptor: China CO2 emission accounts 1997-2015, Sci. Data 5 (2018) 14.

[17] K.S. Gallagher, F. Zhang, R. Orvis, J. Rissman, Q. Liu, Assessing the Policy gaps for achieving China's climate targets in the Paris Agreement, Nat. Commun. 10 (1) (2019) 1256.

[18] K. Zheng, J. Zhang, J. Liu, J. Feng, G. Fu, J. Li, Quantitative analysis of China's electrification process based on the 3E optimization model, Electr. power 52 (4) (2019) 18–24.

[19] M.J. Jiang, M.Y. Ren, S.X. Chen, Y.F. Son, Z.W. Jiang, S.B. Li, Research status and potential analysis of electricity substitution based on the "dual-carbon" goal, The Electrical Age No 484 (1) (2022) 69–72, in Chinese.

[20] X.R. Hu, J.F. Liu, H.Z. Yang, J. Meng, X.J. Wang, J.M. Ma, S. Tao, Impacts of potential China's environmental protection tax reforms on provincial air pollution emissions and economy, Earth Future 8 (4) (2020) 11.

[21] X. Hu, H. Wu, W. Ni, Q. Wang, D. Zhou, J. Liu, Quantifying the dynamical interactions between carbon pricing and environmental protection tax in China, Energy Econ. 126 (2023) 106912.

[22] S. Zhang, K. An, J. Li, Y. Weng, S. Zhang, S. Wang, W. Cai, C. Wang, P. Gong, Incorporating health co-benefits into technology pathways to achieve China's 2060 carbon neutrality goal: a modelling study, Lancet Planet. Health 5 (11) (2021) e808–e817.

[23] R. Burnett, H. Chen, M. Szyszkowicz, N. Fann, B. Hubbell, C.A. Pope, J.S. Apte, M. Brauer, A. Cohen, S. Weichenthal, J. Coggins, Q. Di, B. Brunekreef, J. Frostad, S.S. Lim, H.D. Kan, K.D. Walker, G.D. Thurston, R.B. Hayes, C.C. Lim, M.C. Turner, M. Jerrett, D. Krewski, S.M. Gapstur, W.R. Diver, B. Ostro, D. Goldberg, D.L. Crouse, R.V. Martin, P. Peters, L. Pinault, M. Tjepkema, A. Donkelaar, P.J. Villeneuve, A.B. Miller, P. Yin, M.G. Zhou, L.J. Wang, N.A.H. Janssen, M. Marra, R.W. Atkinson, H. Tsang, Q. Thach, J.B. Cannon, R.T. Allen, J.E. Hart, F. Laden, G. Cesaroni, F. Forastiere, G. Weinmayr, A. Jaensch, G. Nagel, H. Concin, J.V. Spadaro, Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter, Proc. Natl. Acad. Sci. U. S. A 115 (38) (2018) 9592–9597.

[24] H.R. Zheng, Y.C. Bai, W.D. Wei, J. Meng, Z.K. Zhang, M.L. Song, D.B. Guan, Chinese provincial multi-regional input-output database for 2012, 2015, and 2017, Sci. Data 8 (1) (2021) 13.

[25] Y.R. Guan, Y.L. Shan, Q. Huang, H.L. Chen, D. Wang, K. Hubacek, Assessment to China's recent emission pattern shifts, Earth Future 9 (11) (2021) 13.

[26] Y.L. Shan, Q. Huang, D.B. Guan, K. Hubacek, China CO2 emission accounts 2016-2017, Sci. Data 7 (1) (2020) 9.

[27] H. Wu, Y. Zhou, X. Wang, X. Hu, S. Zhang, Y. Ren, J. Liu, Y. Liu, S. Tao, The climate, health, and economic outcomes across different carbon pricing policies to achieve China's climate goals, Appl. Energy 368 (2024) 123498.

[28] J. Yang, X. Li, W. Peng, F. Wagner, D.L. Mauzerall, Climate, air quality and human health benefits of various solar photovoltaic deployment scenarios in China in 2030, Environ. Res. Lett. 13 (6) (2018) 064002.

[29] J. Dong, B. Cai, S. Zhang, J. Wang, H. Yue, C. Wang, X. Mao, J. Cong, F. Guo, Closing the gap between carbon neutrality targets and action: technology solutions for China's key energy-intensive sectors, Environ. Sci. Technol. 57 (11) (2023) 4396–4405.

[30] K. Ricke, L. Drouet, K. Caldeira, M. Tavoni, Country-level social cost of carbon, Nat. Clim. Change 8 (10) (2018) 895–900.

[31] M. Burke, S.M. Hsiang, E. Miguel, Global non-linear effect of temperature on economic production, Nature 527 (7577) (2015) 235–239.

[32] Y. Jin, H. Andersson, S.Q. Zhang, Do preferences to reduce health risks related to air pollution depend on illness type? Evidence from a choice experiment in Beijing, China, J.Environ.Econ.Manage. 103 (2020) 17.

[33] Y. Wang, Y. Jin, S. Zhang, Valuing mortality risk reductions in fast-developing societies: a meta-analysis of stated preference studies in China from 1998 to 2019, in: The Society for Benefit-Cost Analysis 2023 Annual Conference, 2023.

[34] S.Z. Qi, S.H. Cheng, X.J. Tan, S.H. Feng, Q. Zhou, Predicting China's carbon price based on a multi-scale integrated model, Appl. Energy 324 (2022) 15.

[35] Y.Y. Weng, D. Zhang, L.L. Lu, X.L. Zhang, A general equilibrium analysis of floor prices for China's national carbon emissions trading system, Clim. Pol. 18 (2018) 60–70.

[36] A. Serletis, G.R. Timilsina, O. Vasetsky, International evidence on sectoral interfuel substitution, Energy J. 31 (4) (2010) 1–29.

[37] C.P. Xie, A.D. Hawkes, Estimation of inter-fuel substitution possibilities in China's transport industry using ridge regression, Energy 88 (2015) 260–267.

[38] J.L. Li, B.Q. Lin, Inter-factor/inter-fuel substitution, carbon intensity, and energy-related CO2 reduction: empirical evidence from China, Energy Econ. 56 (2016) 483–494.

[39] J. Steinbuks, Interfuel substitution and energy use in the UK manufacturing sector, Energy J. 33 (1) (2012) 1–29.

[40] F. Wang, X.Y. Liu, D.M. Reiner, R.Q. Wang, Impacts of energy intensity target constraint on elasticity of substitution between production factors in China, Energy Effic 14 (3) (2021) 26.

[41] H. Wu, H. Yang, X. Hu, L. Zheng, J. Li, Y. Li, X. Wang, W. Ge, Y. Zhou, Y. Liu, J. Liu, Y. Wang, J. Ma, S. Tao, Complementing carbon tax with renewable energy investment to decarbonize the energy system in China, Renew. Sustain. Energy Rev. 189 (2024) 113997.

[42] H.J. Dong, H.C. Dai, Y. Geng, T. Fujita, Z. Liu, Y. Xie, R. Wu, M. Fujii, T. Masui, L. Tang, Exploring impact of carbon tax on China's CO2 reductions and provincial disparities, Renew. Sustain. Energy Rev. 77 (2017) 596–603.

[43] H. Son, M. Kim, J.K. Kim, Sustainable process integration of electrification technologies with industrial energy systems, Energy 239 (2022) 14.

[44] X.Z. Zhang, Z.H. Lin, C. Crawford, S.X. Li, Techno-economic comparison of electrification for heavy-duty trucks in China by 2040. Transport. Res. Part D-Transport, Environ. Times 102 (2022) 19.

[45] W. Zhang, G.X. Li, F.Y. Guo, Does carbon emissions trading promote green technology innovation in China? Appl. Energy 315 (2022) 12.

[46] P. Aghion, A. Dechezleprêtre, D. Hémous, R. Martin, J. Van Reenen Carbon Taxes, Path dependency, and directed technical change: evidence from the auto industry, J. Polit. Econ. 124 (1) (2016) 1–51.