Assessing distributional impacts of synergetic air pollution reductions under different power system decarbonisation policies in China

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Abstract

Decarbonising the power system contributes to carbon emission reductions and synergetic air pollution reductions, but these co-benefits may be unevenly distributed across regions. These distributional consequences from national policies may lead to conflict of interests at subnational levels, which has often been overlooked. This study assesses provincial economic impacts and synergetic air pollutant reductions of power system decarbonisation in China, achieved by two different national policies, namely a mandatory phaseout policy and an Emissions Trading System (ETS). To this end, a multi-regional dynamic Computable General Equilibrium (CGE) model is developed and adopted. The scenario analysis shows that the mandatory phaseout policy is more effective in reducing air pollutant emissions from the power sector, while leading to greater GDP losses at the national level. At provincial levels, the ETS mitigates the trade-off between economic growth and air pollutant reductions, but the mandatory phaseout policy would be more favourable to the majority of provinces no matter whether the GDP growth or air pollution reduction is prioritised.

Keywords: ETS; Coal power phaseout; Co-benefit; provincial disparity; General equilibrium

1 Introduction

Greenhouse Gas (GHG) emission reductions can lead to substantial co-benefits, such as air pollution reductions and public health improvement (Gao et al., 2018; Watts et al., 2015). An intuitive explanation is that fossil fuel combustion releases GHG emissions and air pollutants at the same time. In this regard, GHG mitigation would provide considerable local health benefits from air pollution reduction (Cifuentes et al., 2001; Shi et al., 2022), which would further lead to economic benefit due to the avoidance of working time losses and medical expenditure (Xie et al., 2016).

However, GHG emission is a global issue, while air pollution is a local one. GHG emissions last long in the atmosphere. They contribute equally to radiative forcing and global warming after diffusion wherever they were initially released. In contrast, the damage of air pollution is usually limited to a certain range, close to where it is generated (Chen et al., 2020). This makes the air pollution a location-specific problem. Such difference of GHG emissions and their synergetic air pollutants becomes especially important when it comes to climate policies that cover a large range of regions, because these regions may experience gains and losses unevenly under one universal policy, which is known as the distributional impact (Mendelsohn et al., 2006).

China has pledged to peak carbon emissions in 2030 and achieve carbon neutrality by 2060. Power system decarbonisation is a crucial step towards this ambitious pledge (IEA, 2021). Mandatory regulations such as shutting down out-dated coal power units have been a widely-used policy instrument in China (Tan et al., 2021), while China's nationwide emissions trading system (ETS) has also been operated since 2021, covering both coal and gas power generation. Both policies aim at phasing out fossil fuel (mainly coal) in China's power system, but they may lead to diverse impacts at provincial levels. In this case, even if ETSs are economically more efficient than mandatory policies (Tietenberg, 1985), the theoretically optimal distribution of carbon emission permits may not lead to the ideal mitigation of air pollutants because air pollutants are still not internalised in the ETS. Thus, provinces may purchase carbon emission permits and consequently suffer from more air pollutants in a poorly designed ETS (Lejano et al., 2020). Given the large provincial disparities in population and economic development levels in China, such distributional impacts may lead to equity concerns. Therefore, it is crucial to assess the distributional impacts of synergetic air pollution under different carbon abatement policies in China.

Extensive studies have been focusing on air pollution and health co-benefits of GHG emission reductions (Deng et al., 2017; Gao et al., 2018). Most of these studies were simulations and estimations, following a typical research framework that is summarised as below.

(i) Design scenarios of potential mitigation policies, such as environmental mandates and standards, renewable energy subsidies, environmental taxes, etc.

(ii) Apply economic models to simulate the impacts of exogenous policy interventions to the economic system.

(iii) Link the carbon emissions and air pollutants to the production activities and consumptions by emission factors. Calculate the changes of emissions according to the economic model results.

(iv) Apply chemical transport models to simulate the changes of air pollutants concentrations induced by the emission changes from the previous step.

(v) Evaluate the impacts on human mortalities and morbidities induced by pollution exposure using exposure-response functions, thus assessing the health impacts of mitigation policies.

(vi) Monetise health damages using approaches such as cost of illness, human capital, and willingness to pay. Such monetised damage can be looped back into the economic model. In this regard, the economic impact of these damages can be assessed, thus closing the loop of the assessment.

These studies drew a similar conclusion that there would be significant air pollution co-benefits brought by carbon abatement policies. These conclusions were made by comparing a no policy scenario with a policy scenario where specific policies were implemented. For example, Cifuentes et al. (2001) estimated that the implementation of GHG mitigation technologies would avoid 64,000 premature deaths, 65,000 chronic bronchitis cases, and 37 million person-days of restricted activity or work loss in four major cities in Mexico, USA, Chile, and Brazil. Rao et al. (2016) conducted a comparative study with multiple IAMs evaluating the potential air pollution and health co-benefits of global climate change mitigation. Their results indicated that collaborative policies on air pollution control and climate change mitigation would lead to 40% of global population exposed to PM levels below the World Health Organisation (WHO) air quality guideline. Li et al. (2018a) linked a CGE model with the GEOS-Chem model and found that the health co-benefits measured by a value of statistical life (VSL) would partially or fully offset the policy costs of achieving China's National Determined Contribution (NDC). Similar results were obtained in other studies that combined economics models with air pollution models and health impact models (Dong et al., 2015; Liu et al., 2014; Tang et al., 2022). However, these previous studies only focused on the significant co-benefits by the comparison with a no policy scenario but ignored the comparisons among different policy instruments.

There were also empirical studies on synergetic effects between carbon emission and air pollution reductions, but these studies mainly focused on finding evidence that carbon emissions and air pollution decrease simultaneously (Li et al., 2017; Nie and Lee, 2023) or finding correlations between carbon abatement policies and air pollution reductions (Cai et al., 2016; Li et al., 2022). Their focus was not to evaluate the distributional consequences across provinces under different policies.

Furthermore, although the distributional impact has been an important topic in climate policy assessments, these previous studies mostly focused on the inequal distribution of economic losses across different regions or income groups (Fragkos et al., 2021; Zhang et al., 2023). In contrast, only a few studies considered regional disparities of the synergetic effects in air pollution reductions (Bielen et al., 2020). Huang et al. (2023) assessed the unequally distributed air quality and health impacts of climate mitigation policies across countries. They found a carbon pricing policy would lead to unintended mortality risk increases in certain regions through complex interactions among different systems, namely bioenergy and land use. At the regional level, the cap-and-trade system (one type of ETSs) in California has been a typical case for co-benefit and environmental equity studies (Shonkoff et al., 2011). Similarly, Cushing et al. (2018) focused on the potential social disparities in GHG emission and its co-pollutants with regard to the disadvantaged communities. They found that facilities that are regulated under California's cap-and-trade system, as well as facilities that increased their GHG emission and its co-pollutants after the ETS, are disproportionately located in disadvantaged neighbourhoods. In addition, Anderson et al. (2018) found that the California's cap-and-trade system only leads to limited air pollution reductions in the neighbourhoods of disadvantaged communities. However, these studies only emphasised that the synergetic impacts of one specific carbon abatement policy (mainly ETSs) are not evenly distributed across regions, while they did not assess the distributional impacts under different policies.

In summary, these previous studies focused on the overall air pollution co-benefits brought by carbon abatement policies, while they overlooked that the distribution of these co-benefits across regions may be uneven. In addition, it has also been overlooked that such distributional consequences of national level policies at subnational levels may lead to potential barriers to the implementation of carbon abatement policies.

To fill these research gaps, this study assesses provincial economic and environmental impacts of a mandatory coal power phaseout policy and a nationwide ETS aiming at decarbonising China's power system through 2030. We emphasise the different distributional consequences across provinces under the two policy instruments that aim at a same carbon emission abatement goal. To this end, a multi-regional dynamic CGE model is developed, which features disaggregated power sectors, built-in mandatory coal power phaseout and ETS modules, and an air pollutants accounting module including sulphur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matters (PM) from the power sectors. We expect that this study contributes to the existing literature by (a) improving the CGE model to enable the exogenous control of emission cap in a rate-based ETS specification, (b) evaluating distributional impacts on economic growth and synergetic air pollution reductions of mandatory and market-based policies, and (c) identifying potential barriers when national scale decarbonisation polices are implemented at the regional scale.

The reminder of this study is organised as follows. Section 2 introduces the development of the CGE model and the data sources. Section 3 presents economic and environmental impacts at both national and provincial levels under a mandatory coal power phaseout policy and a nationwide ETS in China's power system. Section 4 discusses policy implications. Section 5 concludes the main findings of this study.

2 Methods and data

This study adopted a Computable General Equilibrium (CGE) model to simulate the cross-regional and cross-sectoral impacts from different power system decarbonising policies. The basic CGE model is originally developed by the previous work from Yu et al. (2023). The original model is modified and improved for the purpose of this study. These modifications include the development of an ETS module with output-based allocation and an air pollutant emission accounting module. These modifications enable the modelers to exogenously control the carbon emission cap of a rate-based ETS, which use to be difficult due to the flexibility of the rate-based ETS. The following subsections provide a brief introduction about the original CGE model, and a detailed description of the modifications that have been made in this study.

2.1 Brief introduction about the original CGE model

The original model is a China-based multi-regional recursive dynamic CGE model. The original model covers 30 Chinese provinces and 13 sectors (Appendix, Table S1). Hongkong, Macao, Taiwan, and Tibet are not included due to data unavailability. The production, consumption, and regional trade activities are described by nested Constant Elasticity of Substitution (CES) functions. The economic growth is driven by the population growth and capital accumulation. The model reaches general equilibrium by minimising the cost of production sectors and maximising the welfare of the household. The base year of this model is 2015. The development from 2015 to 2019 of this model is calibrated so that the baseline GDP, energy use, carbon emissions and air pollutant emissions match the historical data.

The original model contains specifications in the power generation sector. First, the fossil fuel and renewable energy sources in the power generation sector are disaggregated. The corresponding power generation technologies and their abbreviations are listed in Table 1. The products from different power technologies are homogeneous, thus power technologies with lower costs will substitute the ones with higher costs during model simulation. In addition to this price-driven mechanism, the maximum growth rate of each power technology is subject to exogenous fixed factors that are calibrated according to NDRC's estimation (National Development and Reform Commission, 2015) through 2030. Second, the original model contains a mandatory coal power phaseout module. This module simulates a non-market-based policy that mandatorily shuts down coal power units according to certain phaseout standards. The phaseout standards are based on the age and capacity of the coal power units. This mandatory policy is realised by setting an exogenous upper limit to the growth rate of coal power generation in each province. Third, the original model contains an ETS module that covers the coal and gas power sectors, which is consistent with the coverage of China's current nationwide ETS. For further information, Yu et al. (2023) provides a more detailed description of these specifications.

The original model is written in the General Algebraic Modelling System (GAMS) using its subsystem called MPSGE - Mathematical Programming System for General Equilibrium (Rutherford, 1999). The model is solved by the PATH (Ferris and Munson, 2000) solver. All the monetary values in this model are calculated based on the 2015 price, with a CNY/USD exchange rate of 6.23.

Table 1 Abbreviations of the disaggregated subsectors from the power generation sector

Subsector code	Description
ELE_col	Coal power
ELE_gas	Gas power
ELE_ofu	Other fuel
ELE_bio	Biomass
ELE_hyd	Hydro
ELE_nuc	Nuclear
ELE_wnd	Wind
ELE_slr	Solar
ELE_grd	Power grid

2.2 Emissions trading module

The current stage of China's nationwide emissions trading only includes coal and gas power. The initial permits are freely allocated. In this model, the free allocation of permits is realised indirectly by recycling the revenue of permit auction (Wu et al., 2016). Specifically, we first assume that a full permit auction takes place, and the revenue of the permit auction is collected by the government. Then the revenue is recycled back to the sectors based on the corresponding allocation rules.

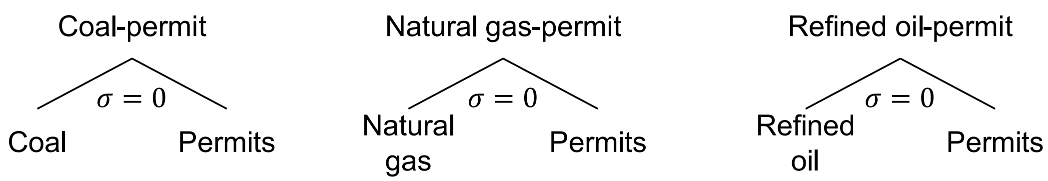

Figure 1 CES structure of carbon permits

The emissions trading in this CGE model is realised by adding permits into the nesting structure of the CES functions. As shown in Figure 1, if a certain producer is covered in the emissions trading, its fossil fuel input will be first nested with emission permits with an elasticity of zero. This specification simulates the reality that the producers are required to surrender the same number of emission permits when they release emissions. A dummy production block is activated to produce the fuel-permit bundle. The scarcity of carbon permits will rise the cost of producing the fuel-permit bundle, creating incentives for the producer to reduce their use of fossil fuels. The carbon permits can be freely traded among provinces and sectors.

China's current nationwide ETS is a rate-based system (ICAP, 2021). The total emission cap in a rate-based ETS is not fixed and is calculated by multiplying the output of the participants with a benchmark rate – usually an intensity-based rate reflecting emissions per unit of output. Therefore, the total emission under a rate-based ETS is unknown because it can be dynamically adjusted according to the output of the participants. This feature makes it difficult to compare the impacts of the ETS with other policies achieving the same emission reduction goal.

To solve this problem, an Output-Based Allocation (OBA) method is applied in this study. The OBA method is an alternative initial allocation method. The initial permits are allocated to the participants according to their shares of output among the total output. The permit is calculated by Equation 2. This method enables an exogenously given emission cap, which equals the total emission under the mandatory coal power phaseout policy given by the model in this study. Meanwhile, the OBA method is able to keep the feature of a rate-based system, because the total emission cap divided by total output is equivalent to an intensity-based benchmark rate. In this way, the OBA method enables the comparison between a mandatory coal power phaseout policy and an ETS under the same emission abatement goal.

$$permit_{r,elet,t} = \overline{CAP_t} \times \frac{Y_{r,elet,t}}{\sum_{r,elet} Y_{r,elet,t}} \tag{2}$$

$$elet \in \{col, gas\}$$

Where:

$elet$ refers to the power generation technologies that are covered by the ETS, namely the coal power and gas power in this study.

$permit_{r,elet,t}$ refers to the permit of power technology $elet$ in region r in year t, measured in Mt.

$\overline{CAP_t}$ refers to the total emission cap in year t, which is exogenously given.

$Y_{r,elet,t}$ refers to the output of power technology $elet$ in region r in year t, measured in USD.

2.3 Air pollution module

2.3.1 Air pollutant accounting

This model was extended to incorporate air pollution in order to evaluate the synergetic effects of ETS and air pollutants. Three main air pollutants are covered in this model, namely SO_2, NO_x, and particulate matters (PM). Only primary PM is included in this model because the main precursor of secondary PM is Volatile Organic Compound (VOC), which is hardly affected by the climate policies that are discussed in this study. In addition, secondary organic aerosols only account for about 5% of the total $PM_{2.5}$ emission in China (Fu et al., 2012). Other air pollutants, such as CO, Black Carbon (BC) or Organic Carbon (OC) are not considered in this study because coal-fired power plants only contributed a small fraction to the national total emissions of the above pollutants (Liu et al., 2015).

The air pollution inventory is derived from the CEAP database, which covers 96.2% of China's thermal power capacity for 2014-2017 (Tang et al., 2019). Only the inventory of the base year 2015 is used in this study. The air pollution inventories of coal, gas, and other fuel power are used in this study. The air pollution quantities are divided by the energy input for each of the thermal power technology to derive the pollution factors.

$$\overline{pol_{r,ele,air}} = \frac{\overline{POL_{r,ele,air,2015}}}{\overline{ENERGY_{r,ele,2015}}} \tag{3}$$

$$ele \in \{col, gas, ofu\}$$

$$air \in \{SO_2, NO_x, PM\}$$

Where:

$\overline{pol_{r,ele,air}}$ refers to the pollution factor of air pollutant air for power technology ele in region r, measured in tonnes per tce.

$\overline{POL_{r,ele,air,2015}}$ refers to the base year air pollutant air from power technology ele in region r, measured in tonnes.

$\overline{ENERGY_{r,ele,2015}}$ refers to the base year energy input for technology ele in region r, measured in tce.

In the simulation, these pollution factors are then used to calculate the air pollution of each thermal power technology for 2016-2030.

$$POL_{r,ele,air,t} = \overline{pol_{r,ele,air}} \times ENERGY_{r,ele,t} \tag{4}$$

$$ele \in \{col, gas, ofu\}$$

$$air \in \{SO_2, NO_x, PM\}$$

Where:

$POL_{r,ele,air,t}$ refers to the air pollutant air from power technology ele in region r in year t, measured in tonnes.

$ENERGY_{r,ele,t}$ refers to the energy input for technology ele in region r in year t, measured in tce.

The energy input of each thermal power technology is subject to the Annual Energy Efficiency Improvement (AEEI) parameters, which controls the energy efficiency, i.e., energy inputs needed per unit of output. The AEEI will autonomously reduce the energy input per unit of power generation, thus reduce the carbon emission and air pollution per unit of power generation. This mechanism already leads to a reasonable decay of air pollution intensities (Appendix Figure S5). Therefore, the decay for the pollution factors is not additionally specified.

In order to evaluate all three types of pollutants in a universal measure, these pollutants are further converted into equivalent pollutants using the equivalent pollutant factors (Table 2), which are derived from Environmental Protection Tax Law of the People's Republic of China (Standing Committee of the National People’s Congress of the People’s Republic of China, 2016).

$$POLeq_{r,ele,t} = \sum_{air} \left(POL_{r,ele,air,t} \times \overline{peq_{air}} \right) \tag{5}$$

$$ele \in \{col, gas, ofu\}$$

$$air \in \{SO_2, NO_x, PM\}$$

Where:

$POLeq_{r,ele,t}$ refers to the aggregated equivalent air pollutant from power technology ele in region r in year t, measured in tonnes.

$\overline{peq_{air}}$ refers to the equivalent air pollutant factor of pollutant air, measured in tonnes per tonne.

Table 2 Equivalent pollutant factors

	SO_2	NO_x	PM
Equivalent pollutant factor (tonnes/tonne)	0.95	0.95	4

Note: Factors are derived from Environmental Protection Tax Law of the People's Republic of

China (Standing Committee of the National People's Congress of the People's Republic of China, 2016).

2.3.2 Decomposition analysis on air pollutants

The Logarithmic Mean Divisia Index (LMDI) method is applied to decompose the drivers of air pollutant reductions. The algorithm was originally proposed by Ang (2005). The total reductions from the baseline scenario to the policy scenarios are decomposed into three main factors, namely power generation (ΔGEN), power mix (ΔSTR), and pollution intensity (ΔPOI). The decomposition only includes three fossil fuel power technologies, i.e., coal, gas, and other fuel. 'Power generation' refers to the change in total generation of the fossil fuel power. 'Power mix' refers to the change in the share of each power technology. 'Pollution intensity' refers to the change in air pollutants per unit generation from each power technology. Here pollution intensity reduction at the national level has two mechanisms. One is technology improvement – less fossil fuel is used to produce the same amount of electricity, which is reflected by the substitution of energy input and capital input in the model. The other is burden shift – the same amount of electricity is now produced by some other provinces that have more advanced technologies. The latter mechanism only exists in the national average pollution intensity reduction because there is no burden shift in an individual province.

The additive decomposition is given by:

$$\Delta POL = \Delta GEN + \Delta STR + \Delta POI \tag{6}$$

$$\Delta GEN = \sum_{elef}\left(\frac{POL'_{ele} - POL^0_{ele}}{\ln POL'_{ele} - \ln POL^0_{ele}} \ln\frac{GEN'}{GEN^0}\right) \tag{7}$$

$$\Delta STR = \sum_{elef}\left(\frac{POL'_{ele} - POL^0_{ele}}{\ln POL'_{ele} - \ln POL^0_{ele}} \ln\frac{STR'_{ele}}{STR^0_{ele}}\right) \tag{8}$$

$$\Delta POI = \sum_{elef}\left(\frac{POL'_{ele} - POL^0_{ele}}{\ln POL'_{ele} - \ln POL^0_{ele}} \ln\frac{POI'_{ele}}{POI^0_{ele}}\right) \tag{9}$$

$$ele \in \{col, gas, ofu\}$$

Where:

POL'_{ele}, POL^0_{ele} refer to the air pollutants from fossil fuel power technology ele in the policy and baseline scenarios, respectively, measured in tonnes.

GEN', GEN^0 refer to the total power generation from fossil fuel power technology in the policy and baseline scenarios, respectively, measured in MWh.

STR'_{ele}, STR^0_{ele} refer to the share of fossil fuel power technology $elef$ in the policy and baseline scenarios, respectively, measured in %.

POI'_{ele}, POI^0_{ele} refer to the pollution per unit generation of fossil fuel power technology ele in the policy and baseline scenarios, respectively, measured in tonnes per MWh.

2.4 Data sources

The base year input-output data and energy consumptions are derived from the input-output table and energy inventory of China from CEADs in 2015 (Zheng et al., 2020). The provincial power generations are derived from China Electric Power Yearbook (National Bureau of Statistics, 2016a). The transfer of payments among the households, the central government, and foreign accounts are derived from the national and provincial Statistical Yearbooks (National Bureau of Statistics, 2016b), Fiscal Yearbooks (National Bureau of Statistics, 2016c), Tax Yearbooks (National Bureau of Statistics, 2016d), and Social Statistical Yearbooks (National Bureau of Statistics, 2016e). Provincial and sectoral carbon emission inventories are derived from CEADs database (Shan et al., 2018). The unit-level coal power information are derived from the Global Energy Monitor (Global Energy Monitor, 2016). The air pollutant inventory of the power sector is derived from the CEAP database (Tang et al., 2019).

2.5 Scenarios development

This study aims at comparing the distributional impacts of a mandatory policy and an ETS which achieve the same carbon emission abatement goal. To this end, three scenarios are developed. There is a Business-as-Usual (BaU) scenario and two policy scenarios. The two policy scenarios include a Coal power Phase-Out scenario (CPO) and an Output-Based Allocation (OBA) scenario. These scenarios are summarised in Table 3.

(1) Business as Usual (BaU)

The BaU scenario is called the baseline, which is a reference case where current policy maintains and no further policy is implemented. The annual productivity growth and energy efficiency improvement parameters from 2015 to 2019 are calibrated so that the baseline GDP growth, energy consumptions, carbon emissions and air pollutant emissions match the historical data. These parameters are assumed to maintain from 2020 to 2030 so that the model can provide a reasonable development trajectory in the study period. The estimated development trajectory in the baseline scenario is comparable to the estimations from other CGE models in this field. The corresponding comparison can be found in the Appendix.

(2) Coal power Phase-Out (CPO)

The CPO scenario represents the case when a mandatory coal power phaseout policy is implemented. This mandatory phaseout policy shuts down the coal power units that do not satisfy certain standards. Under China's current policy, the coal power units under 300MW and have been operated for 20-25 years will be mandatorily shut down if they cannot comply with the national pollution standards (National Development and Reform Commission, 2016). To reflect this policy trend in the model, the coal power units which are under 300MW, at the same time were built before 2010 will be phased out in 2030. Those chosen units are assumed to be phased out gradually on a linear basis from 2020 to 2030. Here a linear trajectory can avoid sudden shocks and thus avoid unrealistic model behaviour. The provincial growth rate limits of coal power generation under this phaseout standard are listed in Table S5 in the Appendix. After simulation, the carbon emissions in this scenario are recorded by the model and will be used as an exogenous emission cap for the emissions trading scenario below.

(3) Output-Based Allocation (OBA)

A nationwide ETS with output-based allocation is activated in this scenario. The ETS covers coal and gas power generation sectors in consistent with China's current situation. The emission permits are freely allocated to the ETS participants and can be traded across provinces. The total carbon emissions at the national level given by the simulation of CPO scenario are used as the emission cap in this scenario, which ensures that the two carbon emission abatement policies achieve the same goal.

Table 3 Summary of scenarios development

Scenarios	ETS	Phase-out policy
BaU	No	No
CPO	No	Yes
OBA	Output-based allocation; the emission cap the power sector equals the total emission generated in the CPO scenario	No

3 Results

3.1 Overview of impacts on the power system and emission reductions

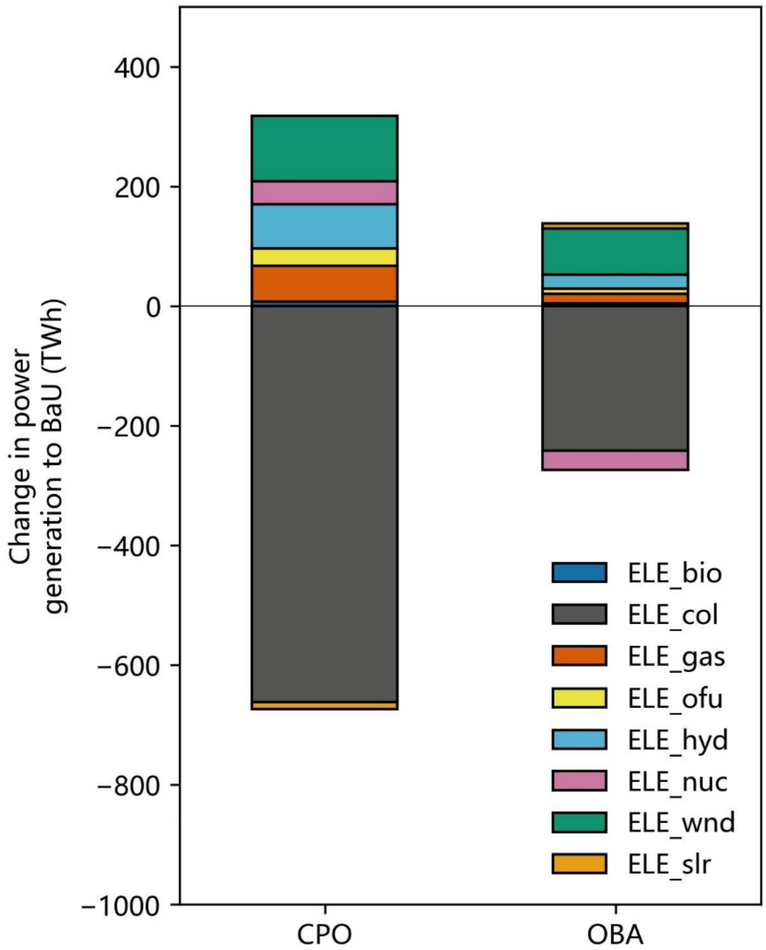

Figure 2 Changes in national power generation in 2030 when compared with the BaU scenario.

Both mandatory phaseout and ETS lead to a noticeable shift from fossil fuel power to renewable energy in the power sector (Figure 2). Given that these two policy scenarios are set to achieve an identical carbon emission reduction target, the results show that mandatory phaseout policies are more effective in reducing coal power generation and increasing renewable generation. The reduction in coal power generation in the CPO scenario is more than twice of that in the OBA scenario. In this regard, the increase in gas, wind, hydro, and nuclear power is more significant in the CPO scenario. The provincial results provide a clearer illustration on the sources of these changes (Appendix, Figure S6). Some provinces respond oppositely under the two policies. For example, coal power generation in Inner Mongolia increases in the CPO scenario but decreases in the OBA scenario when compared with the BaU scenario; while coal power generation in Guangdong decrease in the CPO scenario but increase in the

OBA scenario when compared with the BaU scenario. These results indicate that the effect of phasing out coal power generation induced by the two policies could be complementary in certain cases. The coal power units in provinces such as Inner Mongolia would be reactivated when the mandatory coal power phaseout policy creates an electricity generation gap; the coal power units in provinces such as Guangdong would benefit from the ETS due to their relatively lower carbon intensities.

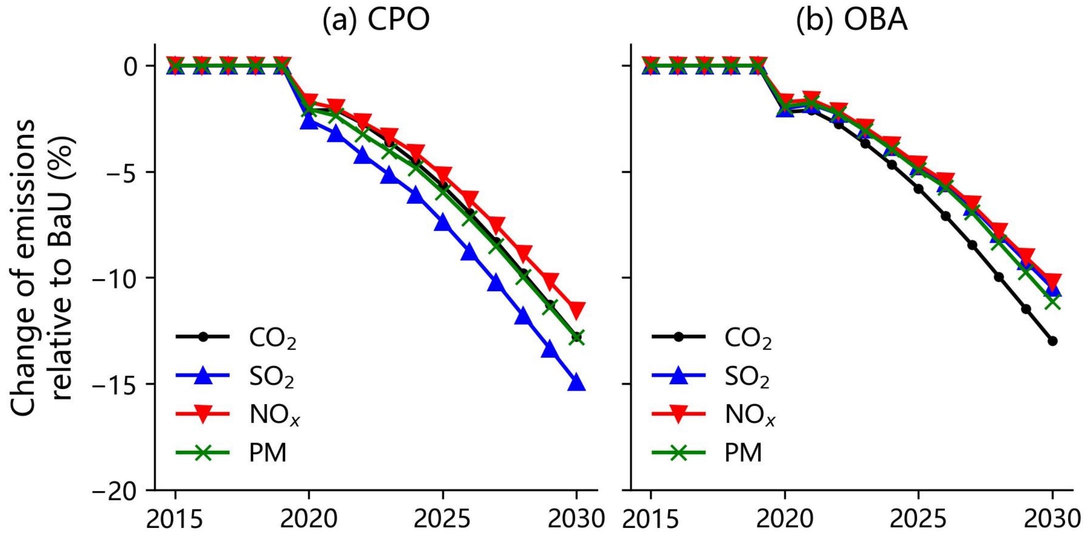

Figure 3 Relative changes of carbon emissions and air pollutants from the power sector when compared with the BaU scenario.

Note: This figure shows the total carbon emissions from the power sector, including coal, gas, and other fuel power, while China's nationwide ETS only covers coal and gas power. Therefore, the total carbon emissions in the CPO and OBA scenarios shown in this figure are not identical, but the sum of carbon emissions from coal and gas power in these two scenarios are the same due to the scenarios setting.

Figure 3 shows the changes of carbon emissions and air pollutants from the power sector when compared with the BaU scenario. It is not surprising that the carbon emissions in the two scenarios are almost identical because both policies are set to achieve the same carbon emission reduction goal in the coal and gas power sectors. The carbon emission reductions from the power sector in these two policy scenarios from the BaU scenario are 12.8% and 13.0% in 2030. Despite the similar carbon emission reductions, the impacts of the two policies on air pollutants are different. In the CPO scenario, the mandatory coal power phaseout policy leads to a 14.9%, 11.5%, and 12.8% reduction in SO_2, NO_x, and PM in 2030, respectively. The synergetic reduction of SO_2 is most significant among all three air pollutants. In contrast, the synergetic reductions of air pollutants are slower in the OBA scenario. The ETS leads to a 10.2% to 11.1% reduction of the three air pollutants from the BaU scenario in 2030.

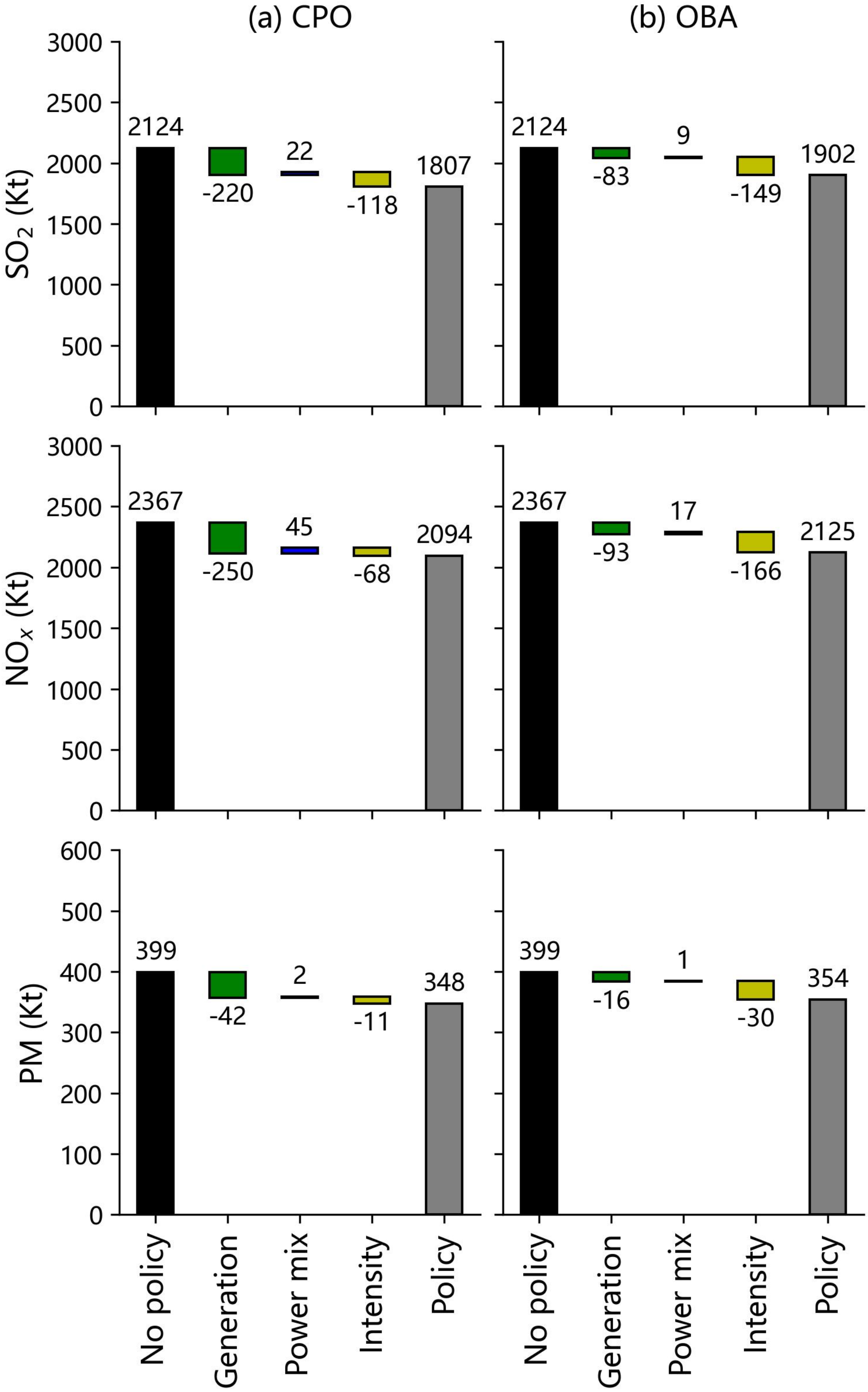

Figure 4 Decomposition of air pollution reductions in fossil fuel power in 2030

Note: Logarithmic Mean Divisia Index (LMDI) is used to decompose different impact factors. Factors are decomposed in additive terms.

The air pollution reductions in the power sector are decomposed into power generation changes, power mix changes, and pollution intensity changes, applying the Logarithmic Mean Divisia Index (LMDI). The results are shown in Figure 4. It is found that the dominant drivers of pollution reduction are different in the CPO and OBA scenarios. The dominant driver in the CPO scenario is power generation, which means the reduction of the three air pollutants can be mainly explained by the generation losses. The air pollution reductions contributed by generation losses account for 210, 250, and 42 Kt in terms of SO_2, NO_x, and PM respectively. In contrast, the dominant driver in the OBA scenario is pollution intensity. The pollution reductions contributed by intensity reductions account for 149, 166, 30 Kt in terms of SO_2, NO_x, PM, respectively. The ETS in the OBA scenario creates economic incentives for fossil fuel power to not only reduce their generation, but also improve the generation technology so that less fossil fuel is needed when generating one unit of electricity; thus, the air pollutants can be reduced. Such an economic incentive does not exist in the CPO scenario because mandatory phaseout policies directly shut down the chosen units.

3.2 Distributional impacts on air pollutant emissions

The distribution of air pollutant reductions presents great regional disparities. Figure 5 shows the spatial distribution of air pollutants from the power sector in 2030. In terms of the spatial distribution, the results in the BaU scenario shows that the baseline air pollutants mainly come from Shandong, Liaoning, and Xinjiang.

In terms of policy impacts, regional disparities of air pollutant reductions are greater in the CPO scenario. The air pollutant reductions mainly come from southwest provinces, such as Guizhou, Sichuan, Xinjiang. However, the north and middle provinces suffer from more air pollutants when compared with the baseline. There are two typical mechanisms that can explain the increase of air pollutant emissions in the CPO scenario. One typical case is Inner Mongolia, which locates at the northeast part of China with abundant wind and solar resources. In the baseline, coal power is phased out quickly without policy interventions while wind and solar power become the dominant source of electricity in Inner Mongolia. However, these retired coal power units would be reactivated when the mandatory coal power phaseout policy creates electricity generation gaps in other provinces, leading to the increase of air pollutant emissions in Inner Mongolia. Another typical case is Hubei, which locates in the middle of China with a lack of wind and solar resources. Despite the fact that half of the power generation in Hubei currently comes from hydro resources, the development potential of hydro power is limited in the future, thus Hubei would need coal power to support its economic development as long as these coal power units are not restricted by the mandatory coal power phaseout policy.

In contrast, the ETS leads to less provincial disparities. Most provinces experience less air pollutants from the power sector in the OBA scenario. The largest air pollutant reductions come from Xinjiang, Sichuan, and Heilongjiang. It is worth mentioning that air pollutant emissions slightly increase in coastal and more economically developed provinces in the OBA scenario when compared with the BaU scenario, including Guangdong, Shanghai, Zhejiang, Anhui. This can be explained by the lower carbon intensities of coal power in these provinces, which bring advantages to these coal power units in the nationwide ETS.

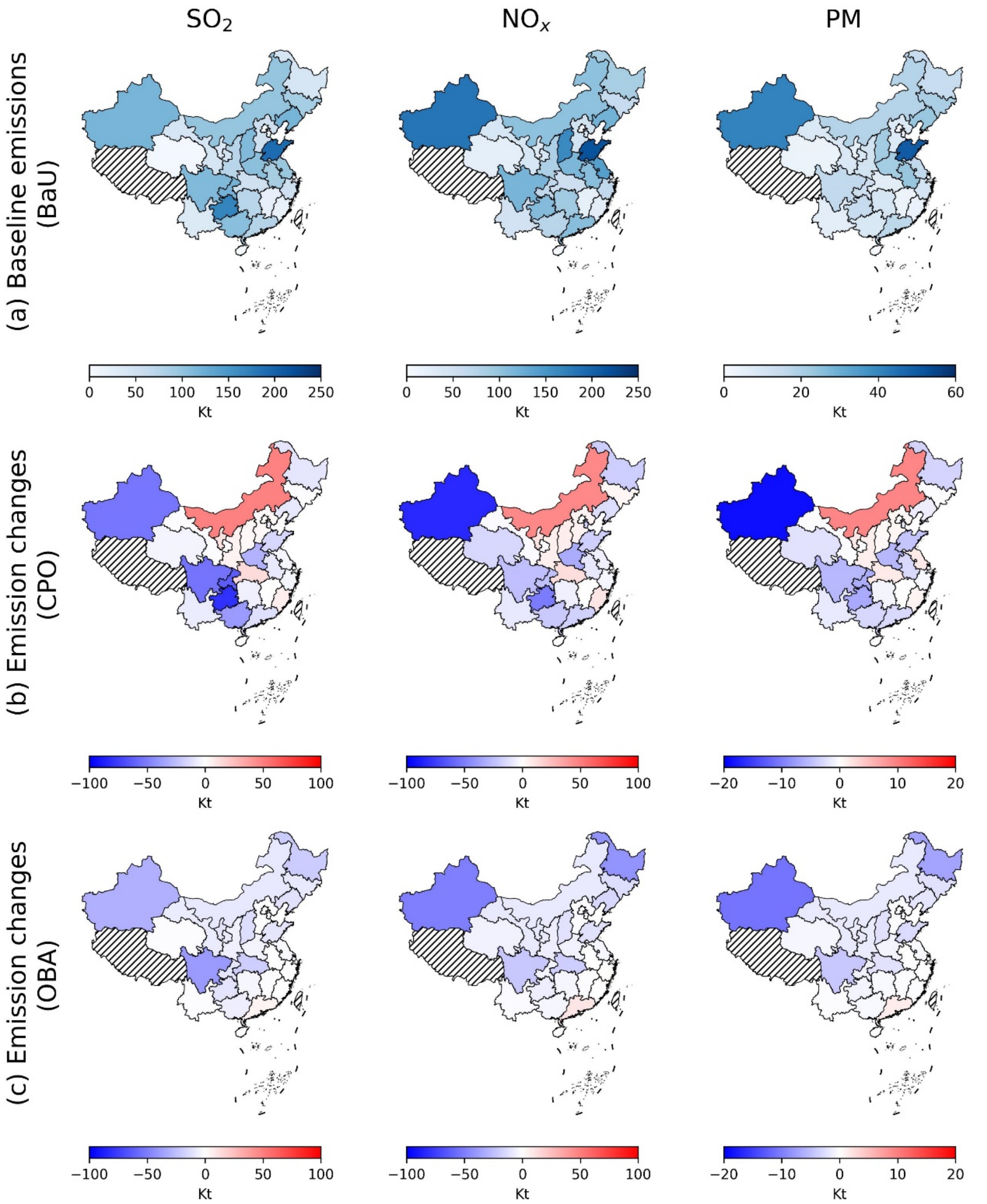

Figure 5 Provincial distribution of air pollutants from the power sector in 2030. (a) Baseline air pollutant emissions (b) Emission changes in the CPO scenario relative to the BaU scenario. (c) Emission changes in the OBA scenario relative to the BaU scenario.

3.3 Distributional impacts on economic performances

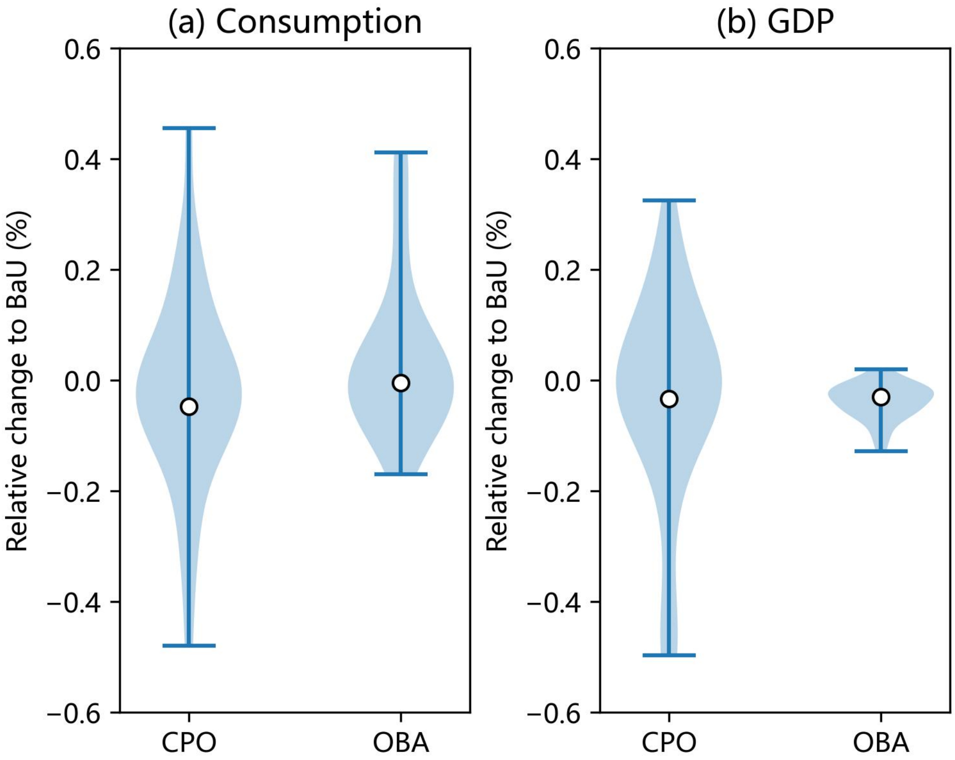

Figure 6 Changes in national and provincial consumptions and GDP in the CPO and OBA scenarios in 2030

Note: The bars represent the maximum and minimum provincial changes. The shadowed area represents the distribution of provincial results. The dots represent the national changes. The detailed results can be found in Table S6 in the Appendix. Consumption refers to the total social consumption in the economic system.

Figure 6 shows the relative changes in consumptions and GDP across the provinces in the CPO and OBA scenarios in 2030. At the national level, these results indicate that the economic impacts in the CPO scenario are larger than those in the OBA scenario. The national consumption decreases by 0.047% and 0.005% in the CPO and OBA scenarios, and the national GDP decreases by 0.034% and 0.030% in the CPO and OBA scenarios. At the provincial levels, the ETS in the OBA scenario leads to fewer provincial disparities than the mandatory policy in the CPO scenario, thus reducing distributional impacts across the provinces. The changes of provincial consumptions range from -0.5% to 0.5% in the CPO scenario, but from -0.2% to 0.4% in the OBA scenario. Similarly, the change of GDP ranges from -0.5% to 0.3% in the CPO scenario, but from -0.1% to 0.02% in the OBA scenario. The detailed provincial results are listed in Table S6 in the Appendix, which show that Guizhou, Chongqing, Guangxi experience larger economic losses in the CPO scenario, while Qinghai, Ningxia, Xinjiang experience larger economic losses in the OBA scenario.

3.4 Co-benefits and trade-offs between economic development and pollution reduction

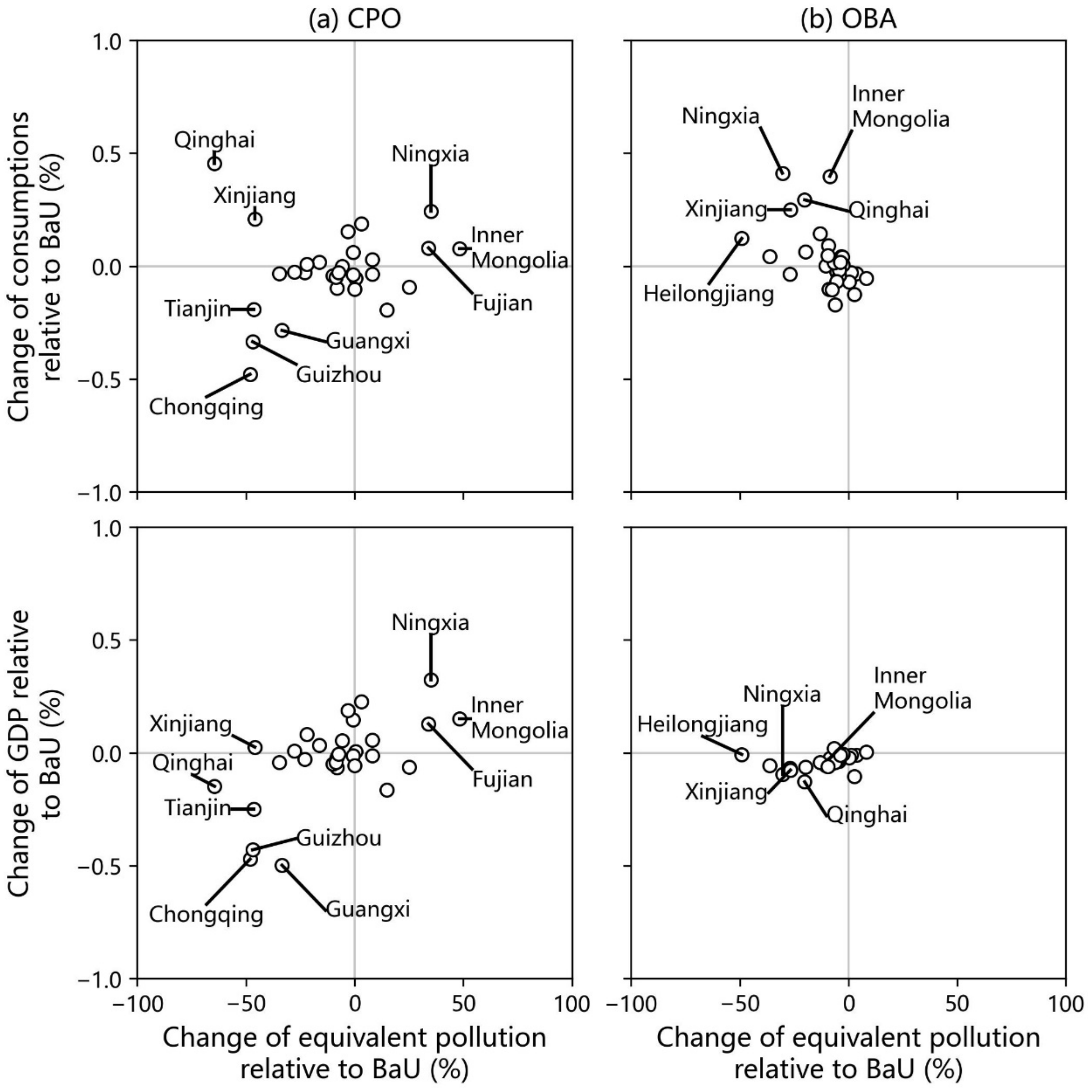

Figure 7 Changes in consumption and GDP versus changes in equivalent air pollutants at the provincial level in the CPO and OBA scenarios in 2030.

Note: Each plot represents one provincial result. The detailed results can be found in Table S6 and Table S7 in the Appendix. Consumption refers to the total social consumption in the economic system.

The provincial economic development and air pollution reductions are compared so as to identify the provincial disparities of co-benefits and trade-offs between economic development and environment protection (Figure 7). GDP and consumptions reflect the overall economic performance and household welfare respectively. The emissions of SO_2, NO_x, and PM are transferred into equivalent pollutants and aggregated in order to reflect overall impacts on air pollution reduction.

The results show that the mandatory coal power phaseout policy leads to larger distributional impacts across the provinces in terms of both economic performances and air pollution reductions. Provincial results in the CPO scenario are distributed at top right, bottom left, and centre of the axes, while provincial results in the OBA scenario are mostly centralised. These results show a trade-off that environmental benefit comes with economic losses in most of the provinces in the CPO scenario (Figure 7a). For example, the mandatory coal power phaseout leads to notable increases in both economic performances and air pollutant emissions in Inner Mongolia, Ningxia, and Fujian, but notable decreases in Chongqing, Guizhou, Guangxi, Tianjin, and Qinghai. In contrast, such trade-off is mitigated in the OBA scenario (Figure 7b). Especially, the distributional impact on provincial GDP is mitigated by the ETS. In addition, some of the provinces gain both economic and environmental benefits. For example, Qinghai and Xinjiang experience consumption increases and air pollution reductions in both CPO and OBA scenarios. More provinces experience such "double dividend" in the OBA scenario, such as Inner Mongolia, Ningxia, and Heilongjiang.

Furthermore, the differentiated provincial impacts on economic performances, especially GDP, and air pollution reductions would affect provincial preference for the national-level policies. For example, if economic growth is a prioritised concern, the policy that would lead to a higher GDP would be more favourable to the local government. Table 4 lists such provincial preference between the mandatory phaseout (CPO) and emissions trading (OBA) policies. The results show that the mandatory policy (CPO) would be favourable to a larger number of provinces, as well as the majority of population, than the emissions trading policy (OBA) regardless of whether the GDP growth or the air pollution reduction is prioritised. It is worth mentioning that the national average GDP in the CPO scenario is lower than that in the OBA scenario (Figure 6). These results indicate that although an ETS would be economically more beneficial at the national level, it may not be the best option for the majority of the provinces or the population. In addition, only 37% of the provinces and 48% of the population are consistent on the preference between the mandatory and ETS policies. These results indicate that the priority of the development strategies of the local governments in China would largely affect their preferences between the two types of policies.

Table 4 Provincial preferences between the mandatory coal power phaseout policy (CPO) and the emissions trading (OBA)

		GDP prioritised		Share of provinces	Share of population
		CPO	OBA		
Air pollution prioritised	CPO	Zhejiang, Henan, Hunan, Guangdong, Sichuan, Yunnan, Xinjiang	Tianjin, Shanghai, Anhui, Shandong, Guangxi, Chongqing, Guizhou, Qinghai	50%	60%
	OBA	Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Jiangsu, Fujian, Hainan, Shaanxi, Gansu, Ningxia	Beijing, Heilongjiang, Jiangxi, Hubei	50%	40%
Share of provinces		60%	40%		
Share of population		66%	34%		

Note:

This table summarises the provinces' preference to the CPO and OBA policies when the GDP or air pollution is prioritised. For example, Tianjin would prefer the OBA policy if GDP is prioritised but prefer the CPO policy if air pollution is prioritised. This table also provides the share of provinces and populations under each preference. For example, 66% of the population would prefer the CPO policy if GDP is prioritised. The share of population is calculated by provincial population in 2021, derived from the China Statistical Yearbook.

4 Discussion

This study contributes to academic literature by evaluating the distributional impacts of the mandatory phaseout policy and the ETS when decarbonising the power system, thus elaborating the differences of these policies from a regional perspective. The findings of this study, as summarised in Table 5, indicate differences between these two policies in provincial distributional impacts and trade-offs despite achieving the same carbon emission reduction goal. These findings provide important policy implications.

Table 5 Summary of the findings of this study comparing the mandatory coal power phaseout policy and the ETS.

Properties	Mandatory coal power phaseout (CPO)	Rate-based emissions trading system (ETS)
Decarbonising the power system	Capable.	Capable.
Negative effects on economic development	High.	Low.
Synergetic reductions of air pollutant emissions	More effective at the national level, especially SO_2.	Moderate effect.
Distributional impact across provinces in terms of economic growth and air pollution reduction	High.	Low.
Trade-offs across provinces between economic growth and air pollution reduction	Obvious.	Not obvious.

First, policy makers should seek to address climate change mitigation in the context of multiple economic and environmental objectives. Studies have suggested that co-benefits in air pollution control induced by climate change mitigation policies are substantial, but they are often overlooked in policymaking. The analysis results of this study suggested that air pollutants from the power sector, as a localised problem, can lead to environment degradation in certain provinces depending on which policy instrument is used. Therefore, evaluation on air pollution synergies should be integrated into the policymaking and assessment progress. The first step would be a clear articulation of the objectives and their synergetic mechanisms. Although binding targets for both carbon emissions and air pollution have been proposed in China's national development plans, such as the FYPs, the link among these objectives should be explicitly stated, especially in sectoral policies such as the power sector.

Second, multi-objective policymaking requires coordination between central and local governments. Province-specific context would bring barriers to the implementation of the national policy. Local governments would gain or lose political interests under a certain national policy. The findings of this study show that some of the middle and south provinces, including Guizhou, Guangxi, and Chongqing, are likely to obtain substantial air pollution reductions when decarbonising the power system by the mandatory coal power phaseout policy, but at the cost of substantial economic losses. One of the local realities of these provinces is that they largely depends on hydro power, whose available capacity would be limited by local water resources and future climate risks (Van Vliet et al., 2016); while another local reality is that these provinces are underdeveloped provinces, in which the local government would prioritise the economic performance. These factors suggest that the mandatory coal power phaseout policy in these provinces should be designed with caution. On the other hand, the findings of this study show that the incentives of phasing out coal power would be weakened by the nationwide ETS in some of the east provinces, including Shanghai, Guangdong, Zhejiang, and Anhui. The health damages from the corresponding air pollution increases would be particularly harmful considering the higher population density in these provinces. The local government should design specific policies aiming at the synergetic control of carbon emission and air pollution rather than merely relying on the single market-based policy instrument.

Third, introducing the ETS would mitigate the distributional impacts across provinces at the expense of economic or environmental benefit in some provinces, thus subnational supportive policies should be formulated according to the local contexts. For example, local governments could mobilise financial and administrative resources to help their coal power companies to transform, such as loans and permissions (Tan et al., 2021). Supportive social security policies would prevent social problems such as job losses that are induced by rapid coal power phaseout (Forum, 2020). Provincial specific coal power phaseout regulations and stricter end-of-pipe air pollution standards would prevent air quality degradations in those provinces where the coal power units have advantages in the nationwide ETS (Tang et al., 2019).

This study is subject to certain limitations due to the research scopes and data availability. First, this study only focuses on the power system decarbonisation policies, specifically the policies for phasing out coal, while future studies could evaluate the provincial distributional impacts of decarbonisation policies in other industrial sectors or the whole economy. Second, this study does not consider internalising the air pollutant by similar pricing tools such as environmental tax, which would lead to further social and economic impacts. Third, the health co-benefits from air pollutant reduction are not covered in this study. In the future it is suggested to evaluate regional disparities of avoided health damage so that a more comprehensive understanding on regional gains and losses can be obtained.

5 Conclusions

Mandatory and market-based policies are both effective in decarbonising the power system, leading to synergetic reductions of carbon emissions and air pollutant emissions. However, these synergetic impacts vary across different provinces, resulting in significant distribution impacts. This study adopts a multi-regional CGE model to evaluate the synergetic and distributional impacts of power system decarbonisation policies in China. Two types of decarbonisation policies, namely the mandatory coal power phaseout policy and the rate-based ETS, are compared through a scenario analysis where the same carbon emission reduction goal is achieved. The main findings from the model simulation and scenarios analysis are concluded as follows.

(i) Both the mandatory phaseout policy and ETS are able to promote power system decarbonisation and renewable energy penetration, leading to synergetic air pollutant reductions. The main driver of these air pollutant reductions is power generation reduction under the mandatory phaseout policy, but carbon intensity reduction under the ETS policy.

(ii) The mandatory phaseout policy is more effective than the ETS in reducing the air pollutant emissions from the power generation sector at the national level, especially SO_2. In contrast, the ETS leads to lesser economic losses, both in terms of GDP and consumption, than the mandatory phaseout policy.

(iii) The ETS reduces distributional impacts across provinces, including impacts on GDP, consumptions, and air pollutant reductions. In contrast, there are notable trade-offs in Chinese provinces between economic growth and air pollution reduction under the mandatory phaseout policy.

(iv) The mandatory phaseout policy is more favourable to the majority of provinces, as well as the majority of population in China, no matter whether the GDP growth or the air pollution reduction is prioritised as the provincial development strategy.

References

Anderson, C.M., Kissel, K.A., Field, C.B., Mach, K.J., 2018. Climate change mitigation, air pollution, and environmental justice in California. Environmental Science & Technology 52, 10829–10838. https://doi.org/10.1021/acs.est.8b00908

Ang, B.W., 2005. The LMDI approach to decomposition analysis: a practical guide. Energy Policy 33, 867–871. https://doi.org/10.1016/j.enpol.2003.10.010

Bielen, D.A., Macpherson, A.J., Simon, H., Fann, N., 2020. CABOT-O_3: An optimization model for air quality benefit-cost and distributional impacts analysis. Environmental Science & Technology 54, 13370–13378. https://doi.org/10.1021/acs.est.0c01053

Cai, B., Bo, X., Zhang, L., Boyce, J.K., Zhang, Y., Lei, Y., 2016. Gearing carbon trading towards environmental co-benefits in China: Measurement model and policy implications. Global Environmental Change 39, 275–284. https://doi.org/10.1016/j.gloenvcha.2016.05.013

Chen, X., Yang, T., Wang, Z., Hao, Y., He, L., Sun, H., 2020. Investigating the impacts of coal-fired power plants on ambient PM2.5 by a combination of a chemical transport model and receptor model. Science of The Total Environment 727, 138407. https://doi.org/10.1016/j.scitotenv.2020.138407

Cifuentes, L., Borja-Aburto, V.H., Gouveia, N., Thurston, G., Lee Davis, D., 2001. Hidden health benefits of greenhouse gas mitigation. Science 293, 1257–1259. https://doi.org/10.1126/science.1063357

Cushing, L., Blaustein-Rejto, D., Wander, M., Pastor, M., Sadd, J., Zhu, A., Morello-Frosch, R., 2018. Carbon trading, co-pollutants, and environmental equity: Evidence from California's cap-and-trade program (2011–2015). PLOS Medicine 15, e1002604. https://doi.org/10.1371/journal.pmed.1002604

Deng, H.M., Liang, Q.M., Liu, L.J., Anadon, L.D., 2017. Co-benefits of greenhouse gas mitigation: A review and classification by type, mitigation sector, and geography. Environmental Research Letters 12. https://doi.org/10.1088/1748-9326/aa98d2

Dong, H., Dai, H., Dong, L., Fujita, T., Geng, Y., Klimont, Z., Inoue, T., Bunya, S., Fujii, M., Masui, T., 2015. Pursuing air pollutant co-benefits of CO2 mitigation in China: A provincial leveled analysis. Applied Energy 144, 165–174. https://doi.org/10.1016/j.apenergy.2015.02.020

Ferris, M.C., Munson, T.S., 2000. GAMS/PATH user guide: Version 4.3. Washington, DC: GAMS Development Corporation.

Forum, P.O., 2020. Fossil electricity retirement deadlines for a just transition. Science 370, 2018–2021. https://doi.org/10.1126/science.abe0375

Fragkos, P., Fragkiadakis, K., Sovacool, B., Paroussos, L., Vrontisi, Z., Charalampidis, I., 2021. Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union. Energy 237, 121591. https://doi.org/10.1016/j.energy.2021.121591

Fu, T., Cao, J., Zhang, X., Lee, S., Zhang, Q., Han, Y., Qu, W., Han, Z., Zhang, R., Wang, Y., 2012. Carbonaceous aerosols in China: top-down constraints on primary sources and estimation of secondary contribution. Atmospheric chemistry and physics 12, 2725–2746. https://doi.org/10.5194/acp-12-2725-2012

Gao, J., Hou, H., Zhai, Y., Woodward, A., Vardoulakis, S., Kovats, S., Wilkinson, P., Li, L., Song, X., Xu, L., Meng, B., Liu, X., Wang, J., Zhao, J., Liu, Q., 2018. Greenhouse gas emissions reduction in different economic sectors: Mitigation measures, health co-benefits, knowledge gaps, and policy implications. Environmental Pollution 240, 683–698. https://doi.org/10.1016/j.envpol.2018.05.011

Global Energy Monitor, 2016. Global Coal Plant Tracker.

Huang, X., Srikrishnan, V., Lamontagne, J., Keller, K., Peng, W., 2023. Effects of global climate mitigation on regional air quality and health. Nature Sustainability. https://doi.org/10.1038/s41893-023-01133-5

International Carbon Action Partnership (ICAP), 2021. Emissions Trading Worldwide: Status Report 2021.

International Energy Agency (IEA), 2021. An Energy Sector Roadmap to Carbon Neutrality in China.

Lejano, R.P., Kan, W.S., Chau, C.C., 2020. The hidden disequities of carbon trading: Carbon emissions, air toxics, and environmental justice. Frontiers in Environmental Science 8, 593014. https://doi.org/10.3389/fenvs.2020.593014

Li, J., Fang, L., Chen, S., Mao, H., 2022. Can low-carbon pilot policy improve atmospheric environmental performance in China? A quasi-natural experiment approach. Environmental Impact Assessment Review 96, 106807. https://doi.org/10.1016/j.eiar.2022.106807

Li, M., Zhang, D., Li, C.T., Mulvaney, K.M., Selin, N.E., Karplus, V.J., 2018. Air quality co-benefits of carbon pricing in China. Nature Climate Change 8, 398–403. https://doi.org/10.1038/s41558-018-0139-4

Li, X., Qiao, Y., Shi, L., 2017. The aggregate effect of air pollution regulation on CO2 mitigation in China's manufacturing industry: an econometric analysis. Journal of Cleaner Production 142, 976–984. https://doi.org/10.1016/j.jclepro.2016.03.015

Liu, F., Zhang, Q., Tong, D., Zheng, B., Li, M., Huo, H., He, K., 2015. High-resolution inventory of technologies, activities, and emissions of coal-fired power plants in China from 1990 to 2010. Atmospheric Chemistry and Physics 15, 13299–

13317. https://doi.org/10.5194/acp-15-13299-2015

Liu, Z., Mao, X., Tu, J., Jaccard, M., 2014. A comparative assessment of economic-incentive and command-and-control instruments for air pollution and CO2 control in China's iron and steel sector. Journal of Environmental Management 144, 135–142. https://doi.org/10.1016/j.jenvman.2014.05.031

Mendelsohn, R., Dinar, A., Williams, L., 2006. The distributional impact of climate change on rich and poor countries. Environment and Development Economics 11, 159–178. https://doi.org/10.1017/S1355770X05002755

National Bureau of Statistics, 2016a. China Electric Power Yearbook (in Chinese). China Statistics Press.

National Bureau of Statistics, 2016b. China Statistical Yearbook (in Chinese). China Statistics Press.

National Bureau of Statistics, 2016c. China Fiscal Yearbook (in Chinese). China Statistics Press.

National Bureau of Statistics, 2016d. China Tax Yearbook (in Chinese). China Statistics Press.

National Bureau of Statistics, 2016e. China Social Statistical Yearbook (in Chinese). China Statistics Press.

National Development and Reform Commission, 2016. Notice on Further Eliminating Outdated Capacity in the Coal Power Industry.

National Development and Reform Commission, 2015. China 2050 High renewable energy penetration scenario and roadmap study: executive summary.

Nie, C., Lee, C.-C., 2023. Synergy of pollution control and carbon reduction in China: Spatial–temporal characteristics, regional differences, and convergence. Environmental Impact Assessment Review 101, 107110. https://doi.org/10.1016/j.eiar.2023.107110

Rao, S., Klimont, Z., Leitao, J., Riahi, K., Van Dingenen, R., Reis, L.A., Calvin, K., Dentener, F., Drouet, L., Fujimori, S., Harmsen, M., Luderer, G., Heyes, C., Strefler, J., Tavoni, M., Van Vuuren, D.P., 2016. A multi-model assessment of the co-benefits of climate mitigation for global air quality. Environmental Research Letters 11, 124013. https://doi.org/10.1088/1748-9326/11/12/124013

Rutherford, T.F., 1999. Applied general equilibrium modeling with MPSGE as a GAMS subsystem: An overview of the modeling framework and syntax. Computational economics 14, 1–46.

Shan, Y., Guan, D., Zheng, H., Ou, J., Li, Y., Meng, J., Mi, Z., Liu, Z., Zhang, Q., 2018. China CO 2 emission accounts 1997-2015. Scientific Data 5, 170201. https://doi.org/10.1038/sdata.2017.201

Shi, Y., Zhu, Y., Gong, S., Pan, J., Zang, S., Wang, W., Li, Z., Matsunaga, T., Yamaguchi, Y., Bai, Y., 2022. PM2.5-related premature deaths and potential health benefits of controlled air quality in 34 provincial cities of China during 2001-2017. Environmental Impact Assessment Review 97, 106883. https://doi.org/10.1016/j.eiar.2022.106883

Shonkoff, S.B., Morello-Frosch, R., Pastor, M., Sadd, J., 2011. The climate gap: Environmental health and equity implications of climate change and mitigation policies in California—a review of the literature. Climatic Change 109, 485–503. https://doi.org/10.1007/s10584-011-0310-7

Standing Committee of the National People's Congress of the People's Republic of China, 2016. Environmental Protection Tax Law of the People's Republic of China (in Chinese).

Tan, H., Thurbon, E., Kim, S.Y., Mathews, J.A., 2021. Overcoming incumbent resistance to the clean energy shift: How local governments act as change agents in coal power station closures in China. Energy Policy 149, 112058. https://doi.org/10.1016/j.enpol.2020.112058

Tang, L., Qu, J., Mi, Z., Bo, X., Chang, X., Anadon, L.D., Wang, S., Xue, X., Li, S., Wang, X., Zhao, X., 2019. Substantial emission reductions from Chinese power plants after the introduction of ultra-low emissions standards. Nature Energy 4, 929–938. https://doi.org/10.1038/s41560-019-0468-1

Tang, R., Zhao, J., Liu, Y., Huang, X., Zhang, Y., Zhou, D., Ding, A., Nielsen, C.P., Wang, H., 2022. Air quality and health co-benefits of China's carbon dioxide emissions peaking before 2030. Nature Communications 13, 1–9. https://doi.org/10.1038/s41467-022-28672-3

Tietenberg, T.H., 1985. Emissions trading, an exercise in reforming pollution policy. Johns Hopkins University Press, Washington, D.C.

Van Vliet, M.T.H., Wiberg, D., Leduc, S., Riahi, K., 2016. Power-generation system vulnerability and adaptation to changes in climate and water resources. Nature Clim Change 6, 375–380. https://doi.org/10.1038/nclimate2903

Watts, N., Adger, W.N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A., others, 2015. Health and climate change: Policy responses to protect public health. The Lancet 386, 1861–1914.

Wu, R., Dai, H., Geng, Y., Xie, Y., Masui, T., Tian, X., 2016. Achieving China's INDC through carbon cap-and-trade: Insights from Shanghai. Applied Energy 184, 1114–1122. https://doi.org/10.1016/j.apenergy.2016.06.011

Xie, Y., Dai, H., Dong, H., Hanaoka, T., Masui, T., 2016. Economic impacts from PM2.5 pollution-related health effects in China: A provincial-level analysis. Environmental Science & Technology 50, 4836–4843. https://doi.org/10.1021/acs.est.5b05576

Yu, Z., Geng, Y., Calzadilla, A., Wei, W., Bleischwitz, R., 2023. Combining mandatory coal power phaseout and emissions trading in China’s power sector. Energy Economics 122, 106694. https://doi.org/10.1016/j.eneco.2023.106694

Zhang, Y., Jiang, S., Lin, X., Qi, L., Sharp, B., 2023. Income distribution effect of carbon pricing mechanism under China’s carbon peak target: CGE-based assessments. Environmental Impact Assessment Review 101, 107149. https://doi.org/10.1016/j.eiar.2023.107149

Zheng, H., Zhang, Z., Wei, W., Song, M., Dietzenbacher, E., Wang, X., Meng, J., Shan, Y., Ou, J., Guan, D., 2020. Regional determinants of China’s consumption-based emissions in the economic transition. Environmental Research Letters 15, 74001. https://doi.org/10.1088/1748-9326/ab794f