Air pollution reduction and climate co-benefits in China's industries

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Air pollution reduction policies can also mitigate CO2 emissions simultaneously in the industrial sector, but the extent of these co-benefits is understudied. We analyse the potential co-benefits for SO2, NOx, particulate matter (PM) and CO2 emissions reduction in major industrial sectors in China. We construct and analyse a firm-level database covering more than 75 thousand observations and scenario simulations are used to estimate the co-benefits. The findings show that substantial co-benefits could be achieved with three specific interventions. Energy intensity improvement can reduce SO2, NOx, PM and CO2 emissions by 26-44%, 19-44%, 25-46% and 18-50% respectively. Reductions from scale structure adjustment such as phasing out small firms and developing large ones can amount to 1-8%, 1-6%, 2-20% and 0.2-3%. Electrification can reduce emissions by 19-25%, 4-28%, 20-29% and 11-12% if the share of electricity generated from non-fossil fuel sources is 70%. The former two interventions have already been put into practice while the third intervention is regarded as a significant contributor for realizing China's carbon neutrality target. Since firm heterogeneity is the essential source for realizing the co-benefits and it directly determines the magnitude of the co-benefits, stricter and sensible environmental policies targeting industrial firms can accelerate China's sustainable transformation.

China is seizing opportunities to achieve its climate commitment to the Pairs Agreement of UNFCCC, while the overall energy-related CO_2 emission continues to rise after a small trough in 2016. Domestically, China has battled air pollution for more than thirty years[1]. Although great achievements have been made, China is still facing severe environmental challenges[2,3]. In 2018, only 121 out of 338 cities at and above the prefecture level met the national air quality standard[4]. Among all emission sources, industrial sectors contributed more than 80% of national sulphur dioxide (SO_2) emission, more than 60% of national nitrous oxide (NO_x) emissions[5], and more than 80% of national carbon dioxide (CO_2) emissions[6]; therefore, it is still the first priority to strengthen the green and low carbon transformation of industrial sectors and a prominent challenge is to guarantee the reinforcement of policies aiming at environmental pollution control and carbon emission reduction. Co-benefits should be deeply investigated by existing environmental policies to avoid excess social costs and make the policy reinforcement tangible.

An increasing number of studies have shown that China has great opportunities to gain climate change mitigation co-benefits through air pollution control[7–9]. For example, the co-benefits can be achieved through changing the energy mix to include more renewables[10–13], or implementing more advanced technologies to improve the energy efficiencies which can reduce energy consumptions per unit of total product or added value[10,11,14–18]. Besides, upgrading the industry structure by reducing the proportion of energy intensive sectors can also realize the co-benefits[19]. Moreover, the scale structure adjustment such as phasing out small firms and developing large ones is another possible intervention to generate the co-benefits[9]. However, most of these studies are focusing on the regional or sectoral level and the existing literature fails to provide micro-level insights. Representative but not firm specific production technologies are typically used in conducting scenario analyses in both top-down[14,20] and bottom-up studies[13,14]. In contrast, there exist significant heterogeneities among firms in that small firms tend to have much higher emission intensities[21–23], firms with different geographical and economic features have different energy and emission efficiencies[24–27], and firms' energy structures also influence their emission behaviour when they are confronted with regulation changes[28]. Ignoring these firm heterogeneities may lead to some biased cost and benefit estimates of environmental policies. Furthermore, the carbon mitigation co-benefits of air pollution control are highly dependent on the relative contribution of measures, i.e. end-of-pipe removal, process control and source reduction, and the latter two usually rely on energy intensity improvement and structural transformation that can trigger co-benefits of CO_2 mitigation. Therefore, to strengthen the co-benefits of environmental and low carbon policies, firm-level analyses are necessary to be conducted to shed light on the source and consequences[29,30].

In this study, we assess the climate co-benefits potentials of air pollution control from the firm-level perspective. We compile a unique firm-level database containing more than 75 thousand nationwide firm observations from seven industrial sectors that are associated with consumption data for four types of energy. Details of the data and methods used to compile the database and conduct the analysis are provided in the Methods section. To the best of our knowledge, this is the first attempt to assess the climate co-benefits for air quality by using such a comprehensive firm-level database.

Results

Drivers of air pollutant reduction in major industrial sectors. We conduct the Logarithmic Mean Divisia Index (LMDI) decomposition[31,32] analysis to investigate the main drivers of SO_2 emission reduction in seven major industrial sectors (see Methods section). From a nationwide perspective, energy intensity was the main driver during the sample period from 2011 to 2014 for most non-power sectors (see Fig. 1) with reduction rates of 7.6% - 11.5%, and the main contribution of energy intensity started in 2013 and was further enhanced in 2014 (see Supplementary Figure 3). Only non-metallic sector and non-ferrous sector stepped backward in their energy intensities due to the regional heterogeneities. For the non-metallic sector, the bad performance in the western region led to the 6.7% increase in national SO_2 emission. Energy intensities have been significantly decreased in eastern and central regions for the non-ferrous sector, but the poor performance of its energy intensity in western region lead to an increase of 2.2% in national SO_2 emission. The end-of-pipe technology was another important driver during the sample period, as it reduces the emissions by 6.8% - 34.4% for most non-power sectors at both the national and regional levels. End-of-pipe technology of non-metallic sector in central region increases the SO_2 emission by 5.6% which leads to an increase in national SO_2 emission by 0.6%. The energy structure only made quite small contributions to reducing the emissions compared to other factors. It reduces SO_2 emission for petroleum sector and non-ferrous sector by 4.3% and 8.1%, respectively, while makes SO_2 emission for other sectors remains quite stable with changes within -0.4% to 1.5%.

For coal-fired power plants (CPPs) in thermal power sector, end-of-pipe technology was the main contributor for SO_2 reduction during the sample period which reduced the SO_2 emissions by 38.2% (Fig. 1f). As for comparisons, three other drivers including generation activity, unabated emission factor and energy intensity only reduced the SO_2 emissions by 2.6%, 2.5% and 2.2%, respectively. The drivers of SO_2 emissions reduction are quite different between CPPs and firms in non-power sectors. More stringent environmental regulations have promoted the CPPs to focus on short-term emissions reduction targets and to meet the requirements by adopting end-of-pipe technologies. For the pollution intensity (defined as the amount of pollution generated before being treated by the end-of-pipe technologies divided by the amount of fossil fuel consumption, see Methods section) driver, it is tightly related to the coal quality that depends heavily on the supply side of washed coals. For the energy intensity driver, since China has experienced the rapid decrease in average coal consumption per unit electricity supplied during the Eleventh Five-year Plan period from 2006 to 2010 (see Supplementary Note 2), there left few spaces for CPPs to further improve their energy intensities. Finally for the generation activity driver, since plants are subjected to satisfying the electricity demand, it is not easy for CPPs to reduce emissions by reducing their generation activities freely[33].

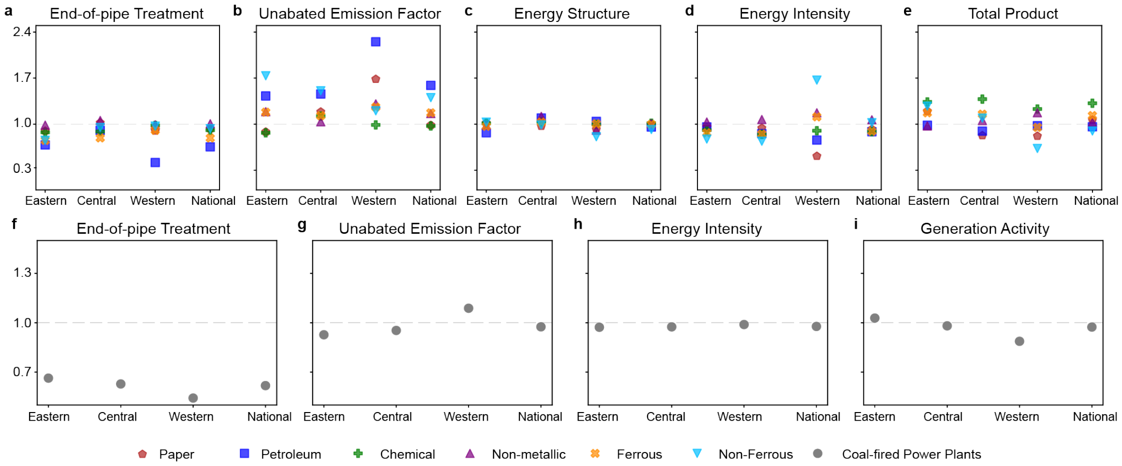

Fig. 1 | Drivers of SO_2 reduction in main industrial sectors. Decomposition analyses are conducted different for the non-power sectors and the CPPs. Air pollutant emissions are decomposed to five factors for the non-power sectors and to four factors for the CPPs (see Methods section). **a-e** are decomposition results for the non-power sectors, while **f-i** are results for the CPPs.

Energy intensity was also the main driver of NOx emission reduction for most non-power sectors (see Supplementary Figure 4, 5 and 8). Improvements in energy intensities have reduced NOx emissions by 5.3% - 18.0%, except for the non-metallic sector (with an increase by 10.1%). Similar to the situation of SO_2 emission reduction, main contribution of energy intensity to the NOx emission reduction also started in 2013 and was further enhanced in 2014. In contrast, only petroleum sector and the ferrous sector had reduced their NOx emissions by 6.5% and 2.4% through improving energy structures. For other sectors, the energy structures had negative contributions and the reason can be largely explained by the deterioration of energy structures in 2012.

As for the decomposition results for PM emissions, we also find that the energy intensity improvement was the main driver of PM emissions reduction in most non-power sectors (see Supplementary Figure 6, 7 and 8). Four non-power sectors, except for the paper sector and the non-metallic sector, have reduced the PM emissions by 5.8% - 27.5% which were mainly due to the energy intensity improvements in 2013. Again, the contributions of energy structures in most non-power sectors were not significant. Only petroleum sector and ferrous sector have reduced their PM emissions by 11.4% and 5.3% respectively through enhancing the energy structures.

Direct co-benefits through energy intensity adjustment. Unlike the end-of-pipe technology which can only reduce air pollutants, energy intensity improvement has the potential in reducing air pollutants and CO_2 emissions in the meantime[34,35]. All of six major industrial sectors can realize substantial co-benefits if firms with higher energy intensities can improve their energy intensities to sub-sectoral level benchmarks (see Methods section). From a nationwide perspective, direct co-benefits present high degree of heterogeneities within sub-sectors as well as across sectors (Fig. 2). It is worth noting that we use “direct co-benefits” since energy intensity adjustment focuses on firms’ behaviours, not related to structural change of sectors (see Supplementary Note 1).

Firstly, direct co-benefits vary largely at the 4-digit sub-sectoral level within the same sector. Sub-sectors in paper sector, chemical sector, non-metallic sector and non-ferrous sector have quite wide ranges of reduction rates of both SO_2 and CO_2 emissions. The non-ferrous sector has the largest range of co-benefit for sub-sectors, its interquartile range (IQR) of reduction rates is 20.9% to 55.8% for SO_2 emissions, 17.5% to 44.6% for NOx emissions, 24.5% to 47.8% for PM emissions and 24.0% to 58.3% for CO_2 emissions. While for the paper sector, although its range of reduction rates of SO_2 and PM emissions are more concentrated, its IQR of reduction rates for NOx and CO_2 emissions is also quite large. Paper sector's IQR is 7.9% to 38.1% for NOx emissions and 9.6% to 41.3% for CO_2 emissions.

Secondly, non-ferrous sector also has the largest average direct co-benefit and paper sector's average direct co-benefit is the smallest (see Supplementary Figure 18). For non-ferrous sector, the average reduction rates of SO_2, NOx, PM and CO_2 emissions are 43.7%, 44.2%, 46.4% and 49.6%, respectively. While for paper sector, the average reduction rates of SO_2, NOx, PM and CO_2 emissions are 25.5%, 24.1%, 32.5% and 18.5%, respectively, which are still large numbers. However, since energy intensities of large scale CPPs are more concentrated in high levels, so the direct co-benefits for CPPs are not so impressive as for non-power sectors. The reduction rates of SO_2, NOx, PM and CO_2 emissions are only 6.1%, 3.6%, 6.0% and 2.5%, respectively.

Different regions also present heterogeneities in direct co-benefits (Fig. 2). Despite the high degree of heterogeneities within sub-sectors as well as across sectors at regional level, direct co-benefits for most non-power sectors are generally becoming larger from eastern region to western region. The main reason is that industrial firms in eastern region generally have lower energy intensities and their energy intensities are more concentrated in a low level. In comparison, industrial firms in western region generally have more diversified high energy intensities. The magnitudes of co-benefits for different sectors in different regions are also various. For example, non-ferrous sector in eastern region has the least co-benefits with reduction rates of 17.8% for SO_2 emissions, 18.5% for NOx emissions, 25.6% for PM emissions and 17.6% for CO_2 emissions. In comparison, non-ferrous sector can realize larger co-benefits in central region as well as in western region. In central region, non-ferrous sector's average reduction rates of SO_2, NOx, PM and CO_2 emissions are 38.1%, 45.0%, 49.3% and 64.0%, respectively. While in western region, non-ferrous sector's average reduction rates of SO_2, NOx, PM and CO_2 emissions are 53.7%, 57.7%, 53.8% and 70.5%, respectively.

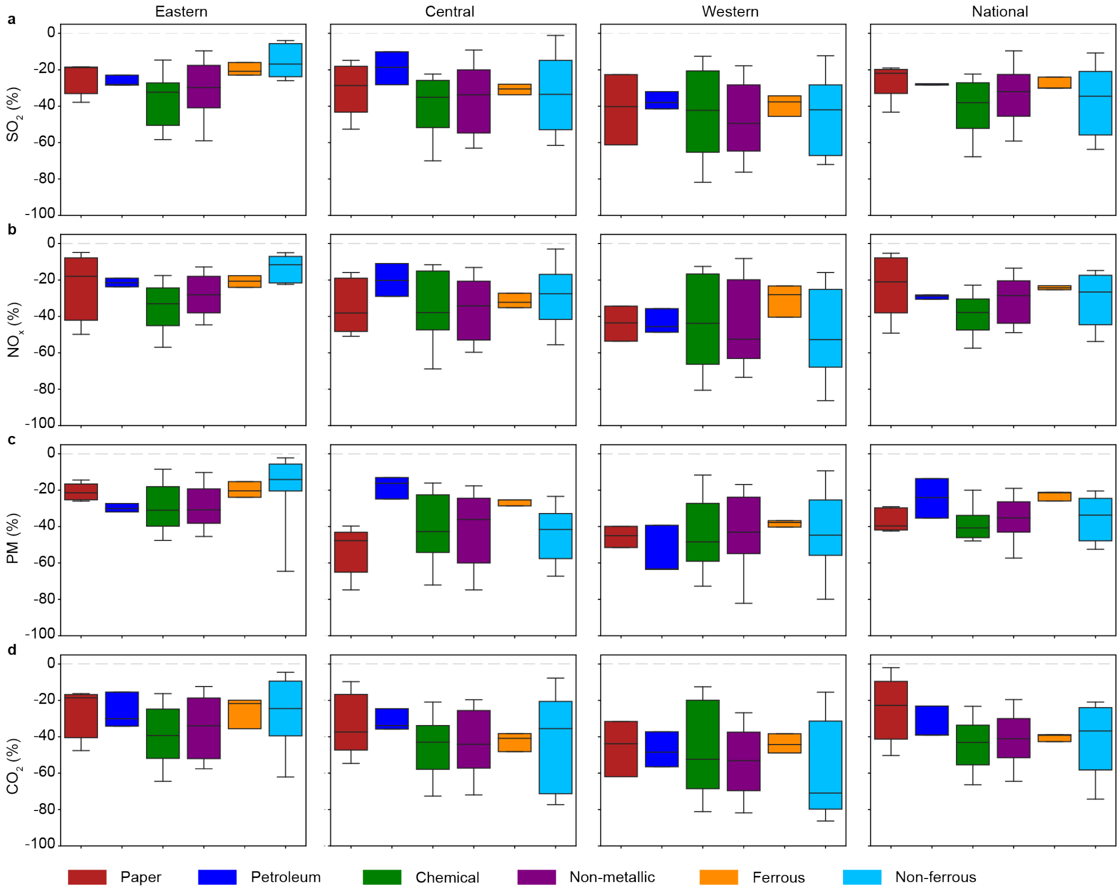

Fig. 2 | Direct co-benefits through energy intensity adjustment. a, SO_2 emissions reduction. **b,** NOx emissions reduction. **c,** PM emissions reduction. **d,** CO_2 emissions reduction. The boxplots show the co-benefits for all sub-sectors, where the boxes are the interquartile range (IQR). Lines within the boxes indicate the medians and whiskers are 10th percentile and 90th percentile. This figure provides co-benefits estimations for the benchmark as the weighted average energy intensity. Co-benefits estimations for other two kinds of benchmarks are shown in Supplementary Figure 16-18.

Indirect co-benefits through scale structure adjustment. Under the scale structure adjustment, air pollutant emissions as well as CO_2 emissions tend to become smaller as more small firms are being shut down (Fig. 3). For brevity, here we only focus on one setting in this scenario, it is that we shut down the smallest 30% of firms or plants in terms of scale (see Methods section). From a nationwide perspective, there exist simultaneous reductions in most sectors except for the paper sector with a slight increase in CO_2 emissions by 0.1%. Among all sectors, petroleum sector has the largest co-benefits that its reduction rates of SO_2, NOx, PM and CO_2 emissions are 7.4%, 5.9%, 19.9% and 3.2%, respectively. CPPs benefit greatly in terms of SO_2 and NOx emissions reduction, with reduction rates of 8.4% and 3.1%, respectively. These are mainly resulting from the gaps among small and large plants' end-of-pipe technologies (see Supplementary Figure 19).

From the regional perspective, for the CPPs, the reduction rates of SO_2 and PM emissions are higher in central and western region than that in eastern region, while the reduction rate of NOx emissions in central region is the highest. Besides, petroleum sector is another special sector that it can benefit a lot in central region. When we reallocate production capacity of the smallest 30% of firms in petroleum sector in central region, its reduction rates of SO_2, NOx, PM and CO_2 emissions are 13.7%, 7.1%, 16.1% and 5.4%, respectively.

In contrast, for CO_2 emissions, although most of the sectors can achieve emissions reductions, there exist some abnormal sectors in eastern region and western region. In eastern region, paper sector and ferrous sector only have a slight increase in their CO_2 emissions by 0.4% and 0.3%, respectively. In western region, paper sector also has a slight increase in its CO_2 emissions by 0.8%, while non-ferrous sector has a relatively large increase in its CO_2 emissions by 1.6%. These abnormal results reflect the fact that large scale firms in these specific sectors do not have lower emission intensities and energy intensities to small scale firms, which is more likely to happen in western region due to its less stringent environment regulations[36–38].

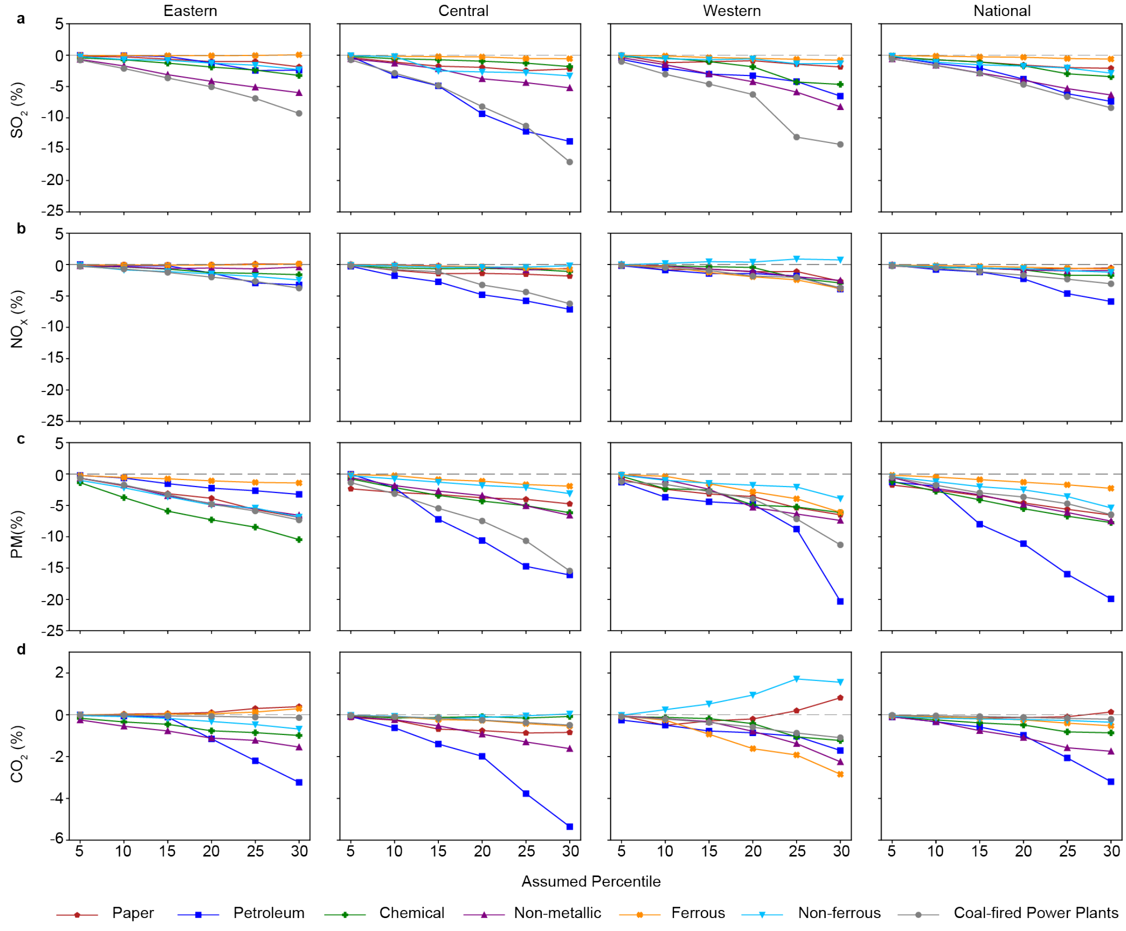

Fig. 3 | Indirect co-benefits through scale structure adjustment. a, SO_2 emissions reduction. **b,** NOx emissions reduction. **c,** PM emissions reduction. **d,** CO_2 emissions reduction. The horizontal axes are percentages of the production scale that are assumed to adjust. Percentiles are from 5 to 30, with an interval of 5.

Indirect co-benefits through electrification. The electrification process in non-power sectors can achieve significant co-benefits of all air pollutants and CO_2 emissions when the ratio of non-fossil fuels in electricity generation structure has reached a target of 70% (Fig. 4). The magnitude of co-benefits is affected by many factors such as boiler conversion efficiency, thermal conversion efficiency of power plant and non-fossil fuel target (see Methods section). Nevertheless, we find a moderate non-fossil fuel target with slightly more than 50% is enough to realize the co-benefits (see Supplementary Figure 22-23), and this target is consistent with China's 2030 energy development target. It is also worth noting that there can also be some trade-offs in emission reductions across different pollutants and CO_2, especially when the non-fossil fuel target is not so ambitious, which will offset the benefits from electrification (Fig. 4 and Supplementary Figure 22-23). As the share of non-fossil fuel in electricity generation becomes larger, the trade-offs are likely to be mitigated.

From the nationwide perspective, co-benefits increase as the proportion of fossil fuel in non-power sectors being replaced by electricity becomes larger. CPPs' advanced end-of-pipe technologies make it beneficial to efficiently reduce the total amount of air pollutants. Although most of the sectors can realize similar magnitudes of co-benefits for SO_2 and PM emissions reduction, co-benefits for NOx emissions are more diversified. Petroleum sector and non-metallic sector have the largest co-benefits for NOx emissions. When 30 percent of fossil fuel used in these two sectors is replaced by electricity, their NOx emissions reduction rates are 19.3% and 27.6%, respectively. While other four sectors only have reduction rates of NOx emissions which are less than 12% under the same assumption. CO_2 emissions reduction rates are quite similar among sectors and are around 12% when 30 percent of fossil fuel used in these sectors are replaced by electricity.

From the regional perspective, co-benefits for most of the sectors in three regions are quite similar with the national results. The only abnormal sector is the non-ferrous sector in eastern region. We find that the non-ferrous sector not only has a lower SO_2 emissions reduction rate, the net NOx emissions change is even positive. When 30 percent of fossil fuel used in non-ferrous sector in eastern region are replaced by electricity, SO_2 emissions reduction rate is 15.3% and NOx emissions increase by 7.5% at the meantime due to the lower unabated emission factor in non-ferrous sector.

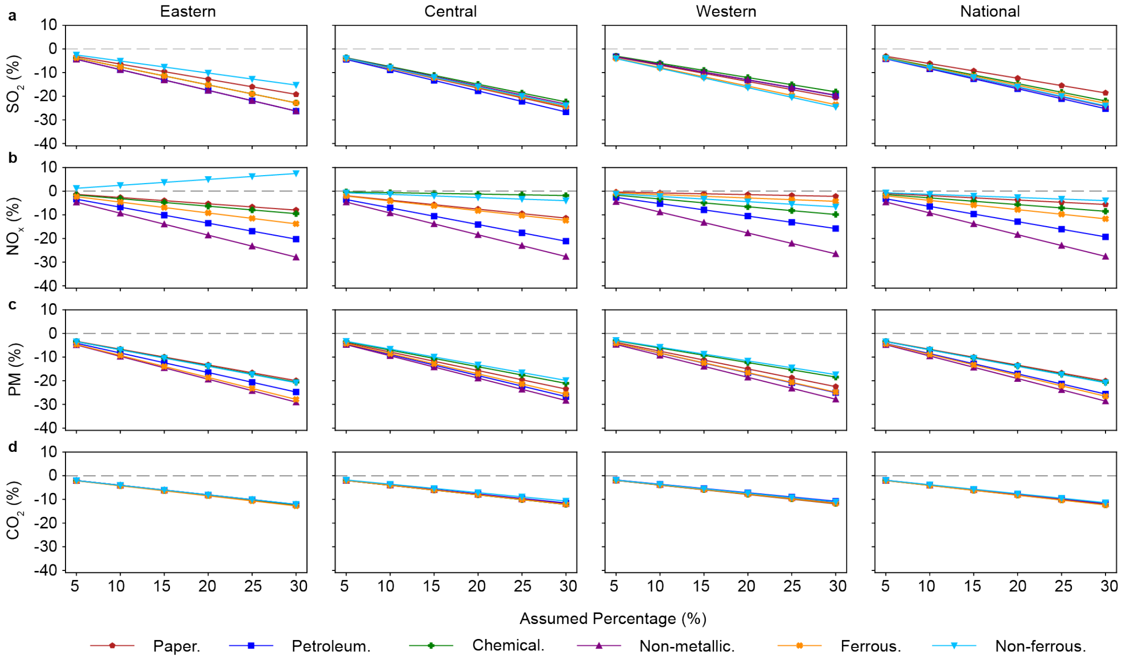

Fig. 4 | Indirect co-benefits of electrification. a, SO_2 emissions reduction. **b,** NOx emissions reduction. **c,** PM emissions reduction.

d, CO_2 emissions reduction. The horizontal axes are percentages of the fossil fuels that are assumed to be replaced by electricity. Percentages are from 5 to 30, with an interval of 5. This figure provides co-benefits estimations for the assumption that ratio of non-fossil fuel in electricity generation structure is 70%. Co-benefits estimations for other two assumptions are shown in Supplementary Figure 22-23.

Discussion

Energy intensity has been proved to be an important contributor for reducing the air pollutant emissions during the period from 2011 to 2014, suggesting that it may be an effective approach in long-run control. Since fossil fuel combustion is the main source of both air pollutants and CO_2[34,35], it is credible and persuasive to achieve climate mitigation co-benefits through the air pollutants control. Besides, production for different sectors will go through a structural change under China's future infrastructure plan, and sectors like the ferrous sector will face a rapidly increasing demand, which may induce more emissions along with the production expansion. Therefore, it requires more efforts to offset the potential growth in air pollutants emissions and CO_2 emissions through the effective energy intensity channel.

Indirect co-benefits can also be achieved through scale structure adjustment and electrification. Firstly, there exist large co-benefit potentials through scale structure adjustment, and similar mandatory measures have already been implemented in China which are known as "phasing out outdated facilities" policies and "phasing out small firms and developing large ones' policies. Taking the thermal power sector as an example, after nearly 15 years' scale structure adjustment, there are still 5544 small generator units which are less than 100 MW in 2018. These small units account for more than 68% of the total units and have huge environmental and climate benefits potential from scale structure adjustment. Secondly, electrification is another feasible and persuasive way to realize the co-benefits. Most of China's newly built CPPs are consist of supercritical units or ultra-supercritical units with low energy intensities, and majority of the existing CPPs with medium size or above have been retrofitted to meet the ultra-low emissions standards. Electrification can thus take the advantage of end-of-pipe technologies in the power sector to combat the air pollution issues. However, further CO_2 emissions reduction still relies on the development of non-fossil fuel in electricity generation structure. China has experienced a rapid development period of renewable energies and this trend is expected to continue in the future. Although most of wind and solar plants as well as hydro power plants locate in western region of China, the future development of Ultra High Voltage (UHV) transmission network will undoubtedly provide strong supports to increase the ratio of non-fossil fuel in electricity generation structure. As a result, electrification is regarded as a significant contributor for realizing China's carbon neutrality target in the future.

Meanwhile, our results show that magnitudes of co-benefits also differ significantly across regions and sectors, suggesting that future policies should be designed more region and sector specifically. As China's regions are in different stages of development, the eastern region commonly plays a leading role in environmental performance in most sectors, so their co-benefits are typically not so large compared to that in other regions. The central and western region can undoubtedly benefit from adopting more advanced technologies to improve energy intensities, as they have greater potentials in terms of emissions reduction.

Last but not the least, each firm's abatement effort is the most important factor in the realization of co-benefits, since they play essential roles in emissions reduction. As a result, it is important to provide incentives for firms to put more efforts on reducing emissions. Some firms lack capabilities and incentives to improve energy intensity by themselves, not only because their fixed assets such as boilers or electric generators cannot be easily liquidated, which names the lock-in effect, but also because they are unfamiliar with or unaware of specific costs such as energy costs for production or compliance costs for environmental policies. Therefore, measures such as using market-based instruments can be adopted to improve the situation. For example, good designed emission trading schemes or environmental taxes can form effective price signals to provide firms incentives to reduce pollutants emissions in order to minimize the costs. Some energy-related consulting services such as energy service companies (ESCOs) are also plausible measures that can provide firms with advanced solutions in energy management and help them to reduce pollutants emissions in the meantime[39].

Methods

Construction of the firm-level emission database. Our data are compiled from three large firm-level databases of Chinese manufacturing firms. The first one is the China's Environmental Statistics Database (CESD) from Chinese Ministry of Ecology and Environment (MEE). The CESD is the basis of the official material, *China Statistical Yearbook on Environment*, and contains firm-level pollution information. The emissions of the firms included in the CESD contribute approximately 85% of China's total major pollutants[40]. Local Environmental Protection Bureaus (EPB) assist in the information collection and conduct irregular inspections to ensure the data quality.

The second one is the Administrative Enterprise Tax Records Database (AETRD) from Chinese State Administration of Tax (SAT). The AETRD covers all General Value-added Tax payers and records their business information. Information such as total product and energy consumptions including coal, oil and electricity consumption are used in this paper. We merge the CESD and AETRD by using firm name and organization code for constructing the new firm-level database for non-power sectors.

The third one is the plant-level coal-fired power plant database (CPPD) compiled from *Annual Compilation of Power Industry Statistics*. The CPPD contains CPPs with installed capacity equal or greater than 6000 kW and records their installed capacity, annual total generation, annual full-load hours, auxiliary power consumption rate, coal consumption per unit electricity supplied, coal consumption per unit electricity generated and annual coal consumption. We merge the CESD and CPPD by using power plant name for constructing the new firm-level database.

The new database contains more than 170 thousand firm-level observations from 2009 to 2014. Emissions of different pollutants for different key sectors account for large proportion of the values reported in the official yearbooks, which means this database has quite good representativeness (see Supplementary Figure 1-2). To the best of our knowledge, our database is the most comprehensive one containing firm-level information for both energy consumption and pollutants emissions among existing literature.

Data preparation. **1.** Sector code adjustment. China has updated its Industrial Classification for National Economic Activities from GB/T 4754-2002 to GB/T 4754-2011 in year 2011. Since 4-digit sub-sectoral level analyses are conducted for evaluating co-benefits, we adjust the sector codes before 2011 according to the new standard.

2. Adjustment for fuel coal consumption. Coal consumption data in the AETRD are the aggregated value of coal consumption for both fuels and raw materials. Since CESD contains both fuel coal consumption and total coal consumption data in year 2010, we use the CESD data to calculate the average percentages of fuel coal consumption for all 4-digit code sub-sectors. Then these average percentages are applied to adjust firms' fuel coal consumption data at the sub-sectoral level from 2011 to 2014.

3. Calculation of fossil fuel and total energy consumption. We aggregate the fuel coal consumption and oil consumption by converting them to amount measured in ton of standard coal equivalent (tce). Fossil fuel consumption is calculated by using eq. (1). We also convert electricity consumption (10 thousand kWh) to amount measured in tce and calculate the total energy consumption by using the eq. (2).

$$FF_i = EC_{fuelcoal} \times 0.7143 + EC_{oil} \times 1.4286 \tag{1}$$

$$EC_i = FF_i + 1.229 \times EC_{ele} \tag{2}$$

4. Correction of outliers. We use ordinary least squares (OLS) regression method to correct the outliers in fossil fuel consumption for every 4-digit sector as eq. (3).

$$ln\,(FF_{it}) = \alpha_0 + \alpha_1 ln\,(SO_{2_{it}}) + \mu_p + \tau_t + \varepsilon_{it} \tag{3}$$

where SO_2 is the amount of firm's SO_2 generated before being treated by the end-of-pipe technologies. Subscript i and t stands for firm i and year t, while τ_t indicate year fixed effect, and considering the provincial disparity in the sulphur content[41], we add the province fixed effect, indicated by μ_p. Fossil fuel consumption level that lies outside the 95% confidence interval of mean is considered as the outlier, and is then replaced by the fitted value. Each firm's coal and oil consumption are then adjusted proportionally, and sub-sectoral average value is applied for firms with missing values.

5. Estimation for firm-level direct CO_2 emission. Production based firm-level CO_2 emissions are estimated by using the eq. (4). Two CO_2 emission factors used in the eq. (4) are taken from Guidelines for Preparation of Provincial GHG (NDRC [2011]1041).

$$EM_{CO_2} = 1.9003 \times EC_{fuelcoal} + 3.0202 \times EC_{oil} \qquad (4)$$

6. Adjustment for total product. Firms whose CO_2 emission intensities (defined as CO_2 emission per unit output) higher than the 95th percentile are regarded as the potential observations with abnormal total product value. We manually check their total products to correct the abnormal value due to the unit error reported by firms.

Identification of the major industrial sectors. China's industrial air pollutants emissions come from several key sectors. Seven major industrial sectors account for 89.75% of whole industrial emissions in 2014[5]. Seven sectors include Manufacture of Paper and Paper Products sector (abbreviated for paper sector), Processing of Petroleum, Coking, Processing of Nuclear Fuel sector (abbreviated for petroleum sector), Manufacture of Raw Chemical Materials and Chemical Products sector (abbreviated for chemical sector), Manufacture of Non-metallic Mineral Products sector (abbreviated for non-metallic sector), Smelting and Pressing of Ferrous Metals sector (abbreviated for ferrous sector), Smelting and Pressing of Non-ferrous Metals sector (abbreviated for non-ferrous sector) and thermal power sector[42]. For the thermal power sector, we focus only on coal-fired power plants. Detailed information of 4-digit sub-sectors in seven major industrial sectors can be found in Supplementary Note 3.

Decomposition of air pollutants (SO_2, NO_X and PM) emissions. In contrast to current researches based on sector-level or region-level analyses[43–46], we adopt the Logarithmic Mean Divisia Index (LMDI) method[31,32] to decompose pollutants emission using firm-level data. For non-power sectors, according to existing studies[44,47–52], emission is calculated by the following formula:

$$EM = \sum_i \frac{EM_i}{PG_i} \times \frac{PG_i}{FF_i} \times \frac{FF_i}{EC_i} \times \frac{EC_i}{TP_i} \times TP_i = \sum_i EOP_i \times EF_i \times ES_i \times EI_i \times TP_i \qquad (5)$$

where subscript *i* stands for individual firm. *EM* is sector's pollutant emission. Five components on the right-hand side are: 1) End-of-pipe treatment (*EOP* = *EM* / *PG*), which is defined as the amount of pollutant emission divided by the amount of pollutant generated (*PG*) before being treated by the end-of-pipe technologies, representing end-of-pipe removal efficiency[47,48]. 2) Unabated emission factor (*EF* = *PG* / *FF*), which is defined as *PG* divided by the amount of fossil fuel consumption (*FF*)[21,52], representing the fossil fuel quality. 3) Energy structure (*ES* = *FF* / *EC*), which is defined as the amount of fossil fuel consumption divided by the amount of total energy consumption (*EC*). 4) Energy intensity (*EI* = *EC* / *TP*), which is defined as energy consumption divided by total product (*TP*). 5) Total product (*TP*). The monetary total products are adjusted to 2009 constant prices at 4-digit sub-sectoral level by using each sub-sector's Producer Price Index (PPI) collected from *China Price Statistical Yearbook*. For the CPP sector, there is no energy structure factor and the energy intensity is defined as fossil fuel divided by total product, and total product is the amount of electricity generated.

Change in sector’s emission between two years is decomposed as follows:

$$\frac{EM_{t_1}}{EM_{t_0}} = D_{eop} \times D_{ef} \times D_{es} \times D_{ei} \times D_{tp} \tag{6}$$

where EM_{t_0} and EM_{t_1} are sector’s emission in year t_0 and t_1. Five indexes on the right-hand side are as follows:

$$D_{eop} = exp\ (\textstyle\sum_i w_i \times ln\ [\frac{EOP_{i,t_1}}{EOP_{i,t_0}}]) \tag{7}$$

$$D_{ef} = exp\ (\textstyle\sum_i w_i \times ln\ [\frac{EF_{i,t_1}}{EF_{i,t_0}}]) \tag{8}$$

$$D_{es} = exp\ (\textstyle\sum_i w_i \times ln\ [\frac{ES_{i,t_1}}{ES_{i,t_0}}]) \tag{9}$$

$$D_{ei} = exp\ (\textstyle\sum_i w_i \times ln\ [\frac{EI_{i,t_1}}{EI_{i,t_0}}]) \tag{10}$$

$$D_{tp} = exp\ (\textstyle\sum_i w_i \times ln\ [\frac{TP_{i,t_1}}{TP_{i,t_0}}]) \tag{11}$$

$$w_i = [\frac{EM_{i,t_1} - EM_{i,t_0}}{\ln(EM_{i,t_1}) - \ln(EM_{i,t_0})} / \frac{EM_{t_1} - EM_{t_0}}{\ln(EM_{t_1}) - \ln(EM_{t_0})}] \tag{12}$$

where w_i is the weight for the adjustment, defined as eq. (12)[53]. If index is smaller than one, then the corresponding factor makes positive contribution to the reduction of pollutants.

Some special treatments have been taken to avoid the divide-by-zero error when $EM_{i,t_1} = EM_{i,t_0}$ or emission equals to zero. For the first case, only a small proportion of the observations will encounter the problem (less than 5% of the sample), we directly drop those observations. For the second case, we replace the zero emission with an epsilon value (i.e., 10^{-10} ton). Since it is also occasional, this will not induce a large bias.

The sample period covers two China's Five-year Plan periods, one is the Eleventh Five-year Plan period (2006-2010) and the other is the Twelfth Five-year Plan period (2011-2014). During the Eleventh Five-year Plan period, China conducted its first National Census of Pollution Sources

(NCPS) in 2008. Based on the results of NCPS, the official statistics reporting system updated the generation and discharge coefficients for each sector according to the technological progresses (National Pollution Census Compilation Committee, 2011). The biggest effect of this change is the amount of pollutants generations and discharges for the same firm reported in the CESD will occur some inconsistencies between year 2010 and 2011. As a result, to keep the data consistency, we conduct the LMDI decomposition analysis for the period from 2011 to 2014. We also put the results of LMDI decomposition for 2009 to 2014 in the Supplementary Information for comparison, see Supplementary Figure 9-15.

Estimation of the direct co-benefits through energy intensity adjustment. Direct co-benefits can be achieved through the energy intensity channel. Fossil fuels are the common sources for CO_2 and air pollutants. At the individual firm level, reducing fossil fuel consumptions will also reduce firm's air pollutants emissions and CO_2 emissions proportionally as shown in eq. (13) and eq. (14).

$$EM_{i,pol} = EOP_{i,pol} \times EF_{i,pol} \times \underbrace{(EC_{i,fuelcoal} \times 0.7143 + EC_{i,oil} \times 1.4286)}_{common\ source} \tag{13}$$

$$EM_{i,CO_2} = \underbrace{1.9003 \times EC_{i,fuelcoal} + 3.0202 \times EC_{i,oil}}_{common\ source} \tag{14}$$

The direct co-benefits are estimated by the following two steps. In the first step, we set a target energy intensity benchmark for each 4-digit sub-sector. The benchmarks are calculated using three different types of average energy intensities to check the robustness. Three types of the sub-sectoral level average energy intensity are weighted average by total product, simple arithmetic mean and median. In the second step, firms in each 4-digit sub-sector whose energy intensities are higher than the benchmark will adjust their energy intensities to the benchmark. Since total product and other factors remain unchanged, each firm's fossil fuel and electricity consumptions will decrease in proportion to the energy intensity. The aggregated co-benefits are then estimated as follows:

$$r_{pol}^{EF} = \frac{\Delta EM_{pol}}{EM_{pol}} = \frac{\sum_j EM_{j,pol} \times (EF_{benchmark} - EF_j)/EF_j}{\sum_i EM_{i,pol}} \tag{15}$$

where subscript *j* indicates firm that needs to be adjusted, *i* indicates all firms in the sub-sector, *pol* indicates different pollutants. It is worth noting that co-benefits are estimated based on the data in 2014, which is the most recent year, and since there is no data for PM in 2014, we use data in 2013 to estimate the reduction rates for PM.

Estimation of indirect co-benefits through scale structure adjustment. For both non-power sectors and CPPs, firms' or plants' scales are positively related to their environmental and energy intensity performances (see Supplementary Figure 19-20). Larger scales will benefit the firms in allocating costs, including those from installation for the end-of-pipe facilities, input for advanced energy technologies and so on. Under the scenarios for scale structure adjustment, we shut down small firms or plants in one sector and reassign the production capacity or electricity supply to those large firms or plants in the same sector. For the sensitivity analysis, we assume different percentages of firms or plants need to be shut down and be reassigned the production, ranging from 5% to 30%, with an interval of 5%. For CPPs, the reduction rates for pollutants and CO_2 emissions are estimated as follows:

$$r_{pol}^{Scale} = \frac{\Delta EM_{pol}}{EM_{pol}} = \frac{r_e \times \sum_n EM_{n,pol} - \sum_m EM_{m,pol}}{\sum_i EM_{i,pol}} \tag{16}$$

$$r_e = \frac{\sum_m ELES_m}{\sum_n ELES_n} \tag{17}$$

where subscript *m* indicates plants to be shut down, *n* indicates plants to be reassigned the production capacity, *i* indicates all plants in the sector, *pol* indicates different pollutants. *ELES* stands for electricity supplied by the plant. For a given percentile τ, we order all CPPs by their electricity supply level from largest to smallest, then *m* is determined by the smallest τ percent of all CPPs and *n* is determined by the largest τ percent of all CPPs.

For non-power sectors, electricity generation feedbacks are taken into consideration, and the reduction rates for different pollutants are calculated as follows:

$$r_{pol}^{Scale} = \frac{r_e \times \sum_n EM_{n,pol} - \sum_m EM_{m,pol} + r_g \times EM_{pol}^{pow}}{\sum_i EM_{i,pol}} \tag{18}$$

$$r_e = \frac{\sum_m TP_m}{\sum_n TP_n} \tag{19}$$

$$r_g = \frac{r_e \times \sum_n ELE_n - \sum_m ELE_m}{0.94 \times ELES^{pow}} \tag{20}$$

where EM_{pol}^{pow} is total pollutant emissions of all CPPs, $ELES^{pow}$ is electricity supplied by all CPPs, *ELE* is the electricity consumption. Considering for the line loss, we set the loss ratio as 0.94 to get the actual expanded demand for electricity. Variable r_g measures the feedback of electricity generation which is the change rate of electricity supplied by all CPPs.

Estimation of indirect co-benefits through electrification. Electrification can take advantage of the differences of environmental performances between power and non-power sectors, especially in end-of-pipe technologies. There also exist significant co-benefits as ratios of non-fossil fuels (such as wind, solar, hydro, nuclear and so on) in electricity generation structure become higher. Since non-power sectors generally use fossil fuels in boilers, so boiler conversion efficiency is a key factor in the realization of co-benefits. The co-benefit from electrification is calculated as follows:

$$r_{pol}^{electrification} = \frac{\Delta EM_{pol} + \Delta EM'_{pol}}{\sum_i EM_{i,pol}} = \frac{-r_s \times \sum_i EM_{i,pol} + (1-r_n) \times r^c \times EM_{pol}^{pow}}{\sum_i EM_{i,pol}} \tag{21}$$

$$r^c = \frac{0.7 \times r_s \times \sum_i FF_i}{0.94 \times 1.229 \times ELES^{pow}} \tag{22}$$

where subscript *i* indicates all plants in the sector, *pol* indicates different pollutants, EM_{pol}^{pow} is total pollutant emissions of all CPPs, $ELES^{pow}$ is electricity supplied by all CPPs. For the parameters in above formula, r_s stands for the proportion of fossil fuel to be substituted in non-power sectors ranging from 5% to 30%, with an interval of 5%. We also assume three values, i.e. 30%, 50% and 70%, for the proportion of non-fossil fuel in electricity generation structure which is represented by r_n. The first value is set according to China's *Thirteenth Five-year Plan for Energy Development* and the second value is set according to China's *Energy Supply and Consumption Revolution Strategy (2016-2030)*. The third value is set according to our own assumption for a more aggressive non-fossil fuel target. The r^c is the conversion parameter that is used to convert fossil fuel energies into electricity's demand. We set the boiler conversion efficiency as 0.7 which is between the efficiencies for most coal boilers (0.6-0.65) and oil boilers (around 0.8) used in China's industrial sectors, and considering for the line loss, we set the loss ratio as 0.94 to get the actual expanded demand for electricity.

Data availability

The firm-level emission database that supports the findings of this study is available from author's GitHub repository (https://github.com/qianhaoqi/NS-co-benefit).

Code availability

Codes that support the findings of this study is available from author's GitHub repository (https://github.com/qianhaoqi/NS-co-benefit).

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Author contributions

H. Q., W. W., J. M. and L. W. conceived the study. J. C. and F. R. provided energy and emission data. H. Q. and S. X. performed analysis. All authors (H. Q., S. X., J. C., F. R., W. W., J. M. and L. W.) interpreted the data. H. Q. and S. X. prepared the manuscript. W. W., J. M. and L. W. revised the manuscript.

Competing interests

The authors declare no competing interests.

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