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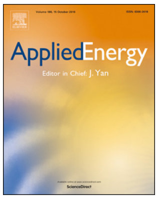

Potential co-benefits of electrification for air quality, health, and CO_2 mitigation in 2030 China

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HIGHLIGHTS

- China can simultaneously curb air pollution and reduce carbon emissions.
- Air quality, health and CO_2 impacts of 2030 electrification scenarios are assessed.
- Electrification with renewables benefits air quality, health and CO_2 mitigation.
- Depending on which sectors are electrified, spatial patterns of health benefits differ.

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ABSTRACT

Electrification with decarbonized electricity is a central strategy for carbon mitigation. End-use electrification can also reduce air pollutant emissions from the demand sectors, which brings public health co-benefits. Here we focus on electrification strategies for China, a country committed to both reducing air pollution and peaking carbon emissions before 2030. Considering both coal-intensive and decarbonized power system scenarios for 2030, we assess the air quality, health and climate co-benefits of various end-use electrification scenarios for the vehicle and residential sectors relative to a non-electrified coal-intensive business-as-usual scenario (BAU). Based on an integrated assessment using the regional air pollution model WRF-Chem and epidemiological concentration–response relationships, we find that coal-intensive electrification (75% coal) does not reduce carbon emissions, but can bring significant air quality and health benefits (41,000–57,000 avoided deaths in China annually). In comparison, switching to a half decarbonized power supply (~50% coal) for electrification of the transport and/or residential sectors leads to a 14–16% reduction in carbon emissions compared to BAU, as well as greater air quality and health co-benefits (55,000–69,000 avoided deaths in China annually) than coal intensive electrification. Furthermore, depending on which end-use sector is electrified, we find different regional distributions of air quality and health benefits. While electrifying the transport sector improves air quality throughout eastern China, electrifying the residential sector brings most benefits to the North China Plain region in winter where coal-based heating contributes substantially to air pollution.

1. Introduction

China is facing the dual challenge of simultaneously reducing air pollution and carbon emissions. Driven by record-high smog events in recent years, improving air quality to protect human health is a top priority of the Chinese government [1,2]. China is the world's top carbon emitter, but has pledged in its' nationally determined contributions (NDCs) under the Paris climate agreement to reduce the carbon intensity of its economy and to peak its carbon emissions by 2030 or earlier [3]. Identifying win-win strategies to mitigate air pollution and carbon emissions is therefore critical for Chinese policymakers [4–9]. Prior research has found various strategies that are potentially beneficial for both objectives, including reducing final energy use [7], improving industrial energy efficiency [4,9–11], curbing coal combustion [4,12,13], and increasing renewable energy use [5].

Accelerated end-use electrification powered by a decarbonized

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electricity system can be a key economy-wide strategy for China to address air pollution and carbon mitigation goals in the 2030 time horizon. China is already the largest market for electric vehicles (EVs), accounting for more than 40% of the EVs sold in the world in 2016 [14]. It is also a growing market for electric heating devices and cooking stoves, since recent government policies encourage the use of electricity to displace coal and gasoline [15]. While China is a fast-growing market for electric technologies, the CO_2 and air quality implications of electrification will depend heavily on the carbon intensity and air pollutant emissions of the electricity mix as well as on what end-uses the electricity displaces. Electrifying end-use sectors can reduce emissions from gasoline and diesel vehicles, as well as from solid fuel used for residential heating and cooking. However, electrification requires the generation of additional electricity. If electrification is powered by carbon- and coal-intensive electricity, the dominant form of electricity currently in China, the increase in CO_2 and air pollutant emissions to produce the additional electricity largely offsets the emission reductions from displacing direct combustion of fossil fuels with electricity in the end-use sectors [16–19]. In comparison, if China rapidly decarbonizes its power sector and maximizes electrification across all sectors (especially in the transport and residential sectors), a few studies have found that these efforts may allow China to peak its carbon emissions before 2030 [20,21], while simultaneously reducing emissions of air pollutants [10].

In this study, we examine the impacts of end-use electrification on air quality, health and CO_2 emissions in 2030 China. We base our analysis on what can realistically be achieved by 2030, and evaluate the potential contribution of various forms of electrification on carbon mitigation and air pollution abatement. By utilizing approaches from energy system analysis, emissions accounting, air pollution modeling and public health, we are able to provide an integrated assessment of the impacts and co-benefits of various electrification scenarios.

Most prior studies have evaluated the environmental implications of the transport [10,17,18,22–24] and residential sectors [25–29] independently, and focused on specific parts of China (e.g. Beijing [27], northern China [29], North China Plain region [30,31], 42 major cities [24]). Here we use a consistent integrated assessment framework to examine these two sectors together for the whole country. Our multi-sectoral and multi-regional perspective allows national and regional decision makers to prioritize their efforts across sectors and regions, given the regional differences in transportation and heating demands, as well as the level of local air pollution and health risks.

While many studies on electrification have only quantified the impacts on CO_2 emissions alone [17,20,26], or on CO_2 and air pollutant emissions [10,18,31], we develop an integrated assessment framework that facilitates the inclusion of air quality, health and climate considerations into China's electricity supply and end-use electrification strategies. We first quantify CO_2 and air pollutant emissions, but go beyond that to evaluate the implications of these emissions on regional air quality and human health, based on a state-of-the-science atmospheric chemistry and transport model (WRF-Chem) and epidemiological concentration-response relationships. Such an assessment on ambient air quality and health is especially valuable for residential electrification. Although heating and cooking is a major contributor to air pollution and health risks in China [25,27,30,32], to our knowledge, the air quality and health benefits of residential electrification have not been evaluated previously for the whole country (some quantified the impacts only on air pollutant emissions [29,31]; some focused on specific regions in China [30]).

2. Method

Based on a business-as-usual scenario (BAU) in 2030 that assumes a continued dominance of coal in China's power system, we examine the air quality, public health and carbon implications of various electrification scenarios. Since air pollution can be addressed by conventional control strategies, such as installing end-of-pipe control devices on power plants, we first design an improved air pollution control scenario that includes an accelerated implementation of conventional air pollution control strategies. We then design a series of electrification scenarios that include not only conventional air pollution control strategies, but also electrification of end-use sectors. We consider supply- and demand-side strategies for electrification: (1) decarbonization of the electricity supply at various levels, (2) electrification of demand in the transportation and/or residential heating/cooking sectors, and (3) a combination of (1) and (2).

2.1. Emission scenarios (Table 1)

Our BAU scenario is based on a province-level emission scenario for the year 2030 (Evaluating the Climate and Air Quality Impacts of Short-lived Pollutants, ECLIPSE_v5a_CLE [33]), developed at IIASA with the GAINS (Greenhouse Gas – Air Pollution Interaction and Synergies) model. This BAU scenario has a coal-intensive energy structure and assumes the implementation of air pollution control strategies consistent with China's 12th Five-year Plan (2010–2015).

We then design an improved air pollution control scenario (AP_Cntrl) that maintains the same fuel sources as BAU but implements air pollution controls in the power, transportation and residential sectors, the three sectors potentially influenced by electrification. In AP_Cntrl, for each subsector (e.g. coal-fired supercritical power plants in the power sector, 2-axis vehicles in the transport sector, coal-based heating stoves in the residential sector), we assume a 20% increase in end-of-pipe controls (details of the air pollution control strategies are summarized in Supplementary Table S1). For instance, if end-of-pipe controls are used on 73% subcritical coal power plants under BAU, in AP_Cntrl we assume 93% of plants will use them.

We also design seven electrification scenarios that include the same increased penetration of air pollution control strategies as AP_Cntrl, and pair them with various electrification designs for the power mix and targeted end-use sector(s). Three electrification scenarios depend on the coal-intensive power mix in BAU (i.e., 75% coal, or 680ton CO_2eq/GWh): electrification of 30% of on-road vehicles (ELE_{BAU}_Trans), electrification of 30% of residential coal-based cooking and heating stoves (ELE_{BAU}_Resid), and electrification of 30% of both the transport and residential sectors (ELE_{BAU}_Trans&Resid). We also design four electrification scenarios that decarbonize approximately half of the electricity sector (i.e. 52% coal or 480ton CO_2eq/GWh): Decarbonization of the power sector without end-use electrification (ELE_{LowC}), and three scenarios that use this half decarbonized electricity to electrify 30% of on-road vehicles (ELE_{LowC}_Trans), 30% of residential coal-based cooking and heating stoves (ELE_{LowC}_Resid), or both (ELE_{LowC}_Trans&Resid). This decarbonization level is broadly in line with China's current targets, but appears conservative when compared with literature exploring possible decarbonization levels in China that can be achieved by 2030 [34–37]. We also explore more ambitious decarbonization and electrification scenarios in Supplementary Table S4 and Figs. S3 and S4.

Electrifying end-use sectors reduces the amount of direct energy use in the transport and/or residential sector, but requires generating additional electricity above the BAU levels. For transport electrification scenarios, we use the 2025 projections for China in Huo et al. [10] to estimate the energy consumption per unit distance travelled for conventional and electric vehicles, i.e. 5.9 L/100 km for gasoline-based internal combustion engine vehicles and 15 kWh/100 km for pure electric vehicles. Essentially, we assume that to displace conventional vehicles with electric ones for 100 km travel distance, 5.9 L gasoline can be avoided while 15 kWh electricity needs to be generated.

For scenarios on residential electrification, we assume the electricity needed to fuel an electric stove is the same as the final energy needed for a conventional stove (the conversion efficiency for coal-based cooking stoves is assumed to be 30%, based on the BAU scenario). For heating, we assume electric resistance heaters are adopted to displace coal-based heating. The conversion efficiency from electricity to heat for resistance heaters is assumed to be 100%. The amount of electricity needed to power the electric resistance heaters is therefore the same as the amount of heat produced from coal-based stoves. We also consider the application of heat pumps, which have higher capital cost and higher heat-to-electricity conversion efficiency [38]. Due to the small amount of coal-based heating stoves in BAU, the differences in CO_2 and air pollutant emissions between the scenarios using electric resistance heaters and heat pumps are negligible ($< 0.1\%$ of national total BAU emissions). We therefore only present the results for the scenarios using resistance heaters, with discussions on heat pump-based scenarios in the Discussion and the Supplementary Materials. The emission factors for CO_2 and air pollutants are also consistent with the BAU scenario.

2.2. Regional atmospheric chemistry simulation and evaluation

We conduct air quality simulations for BAU, AP_Cntrl and all the electrification scenarios. We use WRF-Chem v3.6 [39], a regional state-of-the-science air pollution model that can simulate the transport, mixing, and chemical transformation of primary and secondary fine particulate matter ($PM_{2.5}$) and other pollutants. While our emission scenarios are designed for the year 2030, we use 2014 meteorological fields for the air quality simulations, the year for which we conducted WRF-Chem model evaluation [4]. We conduct simulations in East Asia for January, April, July and October at $27 \times 27\,km^2$ horizontal resolution with 31 vertical layers from the surface to 100 hPa, with a ~ 30 m deep surface layer. WRF-Chem uses RADM2 gas-phase chemistry and the MADE-SORGAM aerosol scheme, with the meteorological fields nudged towards the NCEP FNL [40] data every 6 h. We use chemistry initial and boundary conditions from the global chemistry transport model, MOZART-4 [41] for the year 2014. Since the emission scenarios developed using GAINS only estimate changes in annual total provincial emissions, we follow the spatial and temporal pattern of the Multi-resolution Emission Inventory (MEIC) [42] for the year 2012 (0.25×0.25 degree) to allocate annual provincial emissions hourly to individual grid boxes. For anthropogenic emissions outside China, we use the national total emissions projected for 2030 in the ECLIPSE_v5a_CLE scenario, and then use the patterns in the 2010 emissions from the Hemispheric Transport of Air Pollution (HTAP) v2 inventory for spatial and temporal allocation [43]. Biogenic emissions are calculated online based on the Model of Emissions of Gases and Aerosols from Nature (MEGAN) [44]. Fire emissions are taken from the Global Fire Emissions Database (GFED) v4 for the year 2014 [45]. All anthropogenic emissions are emitted to the model surface layer. More information can be found in Supplementary Table S2.

To evaluate the model performance, we conducted WRF-Chem simulations using emission inventories and meteorological fields for 2014, and compared the model results with 2014 observational data for 31 cities in China. Detailed evaluation results are reported in our previous paper, Peng et al. [4].

2.3. Evaluating health impacts from air pollution exposure

We focus on ambient fine particulate matter ($PM_{2.5}$, particulate matter with diameter 2.5 μm or less), the air pollutant with the largest impact on human health [46]. We consider four diseases associated with long-term exposure to $PM_{2.5}$ for adults (i.e. ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD) and lung cancer (LC)), as well as acute lower respiratory infection (ALRI) for children. For each disease, we use the following equation to calculate the mortality changes in each province for each scenario relative to BAU. The definition and data source for each variable is summarized in Table 2.

$$\mathbf{\Delta Mortality_d = I_{d,BAU} \cdot Pop \cdot \left(\frac{RR_d(C_s)}{RR_d(C_{BAU})} - 1\right)}$$

3. Results

3.1. CO_2 and air pollutant emissions

Power, transportation and residential sectors are targeted for activity and emission changes in the air pollution control scenario (AP_Cntrl) and seven electrification (ELE) scenarios. In 2030 BAU, these three sectors together account for roughly 2/3 of national total CO_2 emissions. They also emit large quantities of air pollutants, contributing 31% SO_2, 65% NO_x, 47% CO, 35% PM_{10}, 44% $PM_{2.5}$, 86% BC, 76% OC and 32% VOC nationally (Fig. 1). The power sector alone is projected to contribute half of total carbon emissions, while its contribution to SO_2, NO_x and PM is estimated to decrease to roughly 10–20% due to end-of-pipe controls that are projected to be implemented under existing policies. The transportation sector remains the largest emitter of NO_x, while the residential sector contributes most to particulate pollution, especially BC and OC. Compared to present-day emissions [4], total BAU air pollutant emissions across all five sectors are much smaller in 2030 than 2015, largely due to strengthened air pollution controls (SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, BC, OC, VOC emissions are 15%, 12%, 30%, 23%, 29%, 31%, 35%, 12% lower in 2030 compared to 2015). However, driven by the projected increase in fossil energy use over time, the total BAU carbon emissions in 2030 are 31% greater than those in 2015.

For CO_2 emissions (Fig. 2), improved conventional air pollution control in AP_Cntrl does not reduce carbon emissions, and may cause a small net increase if the operation of end-of-pipe controls lowers plant efficiency (See Supplementary Fig. S1). Among the electrification scenarios, significant reduction in carbon emissions is observed only when the power sector is decarbonized (14–16% reduction in national total carbon emissions across ELE_{LowC}-related scenarios). This is because if electrification is powered by carbon-intensive electricity obtained with 75% coal (as at present), the increases in electricity production and associated increases in carbon emissions are almost as large as the avoided emissions in the transport and/or residential sectors, leading to negligible net reductions in total carbon emissions (Fig. 3). Our finding is thus consistent with previous research for China [10,16–19,49,50].

For air pollutant emissions (Fig. 2), the conventional control strategies implemented in the AP_Cntrl scenario can significantly reduce air pollutant emissions compared to BAU (comparing AP_Cntrl to BAU: reductions of 2% of SO_2, 3% of NO_x, 5% of CO, 3% of PM_{10}, 4% of $PM_{2.5}$, 7% of BC, 10% of OC and 3% VOC nationally). Electrification can further reduce air pollutant emissions, especially by avoiding emissions from end-use sectors. However, since installing air pollution control technologies on coal power plants already lowers air pollutant emissions significantly, electrification using coal-intensive electricity results in only slightly smaller reductions in air pollutant emissions than electrification with a half decarbonized power mix. Decarbonizing the power sector in ELE_{LowC} (reducing coal share from 75% to 52%) leads to greater reductions in SO_2 and NO_x than AP_Cntrl, due to the displacement of coal units with zero-emitting renewable and nuclear generation. Among the electrification scenarios, the largest reduction in emissions of air pollutants is in ELE_{LowC}_Trans&Resid, which combines the effects of conventional air pollution control, power sector decarbonization and electrification of 30% of the transport and residential sectors (comparing ELE_{LowC}_Trans&Resid to BAU: reductions of 8% of SO_2, 14% of NO_x, 11% of CO, 8% of PM_{10}, 9% of $PM_{2.5}$, 21% of BC, 16% of OC and 5% VOC nationally).

3.2. Air quality and health impacts

3.2.1. Simulated surface $PM_{2.5}$ concentrations

In BAU (Fig. 4a), the surface $PM_{2.5}$ concentrations are generally higher in East and Central China (annual mean: 50–80 $\mu g/m^3$), particularly in winter and autumn. While such spatial and temporal patterns are consistent with present-day pollution patterns, the BAU $PM_{2.5}$

Table 1
Scenario summary.

Abbreviation		**Description**		
BAU		Uses the IIASA 2030 scenario, ECLIPSE_v5a_CLE		
AP_Cntrl		For the power, transportation and residential sectors, increase the penetration of air pollution controls in BAU by 20%		
		Conventional air pollution control	**Electrification strategy design**	
			Carbon Intensity of Electricity Sector	***End-use Sector***
Electrification scenarios	**ELE$_{\mathrm{BAU}}$_Trans**	Same as AP_Cntrl	BAU (75% coal, or 680ton CO_2eqGWh)	Electrify 30% on-road vehicles
	ELE$_{\mathrm{BAU}}$_Resid			Electrify 30% coal-based heating and cooking stoves (using electric resistance heater and electric stoves)
	ELE$_{\mathrm{BAU}}$_Trans&Resid			Electrify 30% on-road vehicles and 30% residential coal-based heating and cooking stoves
	ELE$_{\mathrm{LowC}}$		Approximately half decarbonized (52% coal, or 480ton CO_2eqGWh)	No Change
	ELE$_{\mathrm{LowC}}$_Trans			Electrify 30% on-road vehicles
	ELE$_{\mathrm{LowC}}$_Resid			Electrify 30% coal-based heating and cooking stoves (using electric resistance heater and electric stoves)
	ELE$_{\mathrm{LowC}}$_Trans&Resid			Electrify 30% on-road vehicles and 30% residential coal-based heating and cooking stoves

concentrations in 2030 are lower than the simulated concentrations in 2014 [4], due to lower air pollutant emissions.

With improved air pollution control, the annual mean surface $PM_{2.5}$ concentrations in AP_Cntrl are lowered by roughly 1–3 $\mu g/m^3$ (1–5%) for most parts of China relative to BAU. In addition to improved air pollution control, electrification can further reduce $PM_{2.5}$ levels by an additional 1–9 $\mu g/m^3$ throughout the country. The reductions are roughly 0–1 $\mu g/m^3$ greater when electrification is powered by a half decarbonized electricity sector compared to a coal-intensive one.

We also find that the regional patterns of air quality improvement depend on the choice of the end-use sectors. Decarbonizing the power sector alone without end-use electrification in ELE$_{\mathrm{LowC}}$ leads to a 1–4 $\mu g/m^3$ reduction (1–9%) in annual mean concentrations in many parts of China. Electrifying the transport sector in ELE$_{\mathrm{BAU}}$_Trans and ELE$_{\mathrm{LowC}}$_Trans contributes to a 1–4 $\mu g/m^3$ and 1–5 $\mu g/m^3$ reduction (1–8% and 1–11%) in annual mean $PM_{2.5}$ throughout East and Central China. In comparison, electrifying the residential sector in ELE$_{\mathrm{BAU}}$_Resid and ELE$_{\mathrm{LowC}}$_Resid leads to much larger reductions in the North China Plain (NCP) region (6–8 $\mu g/m^3$ and 7–9 $\mu g/m^3$, or 8–11% and 10–12%) than in other parts of China, because in this region coal-

Table 2
Summary of data for health impact assessment. (See below-mentioned references for further information.)

Variables	Definition	Data Source
$I_{d,BAU}$	Disease-specific (d) annual *BAU* mortality rate in the total adult or child population	Global Burden of Disease (GBD) Study 2013 [47]
Pop	For IHD, stroke, COPD and LC: Total adult population aged 25 and above For ALRI: Children below age 5	Projected provincial total population: Consistent with ECLIPSE V5a scenario [33]. Age distribution: Assumed to be the same as the 2013 pattern reported in the GBD dataset [47]. Spatial distribution within each province: Assumed to be the same as those in 2010, based on the most recent county-level census data [48].
$RR_d(C_s)$ and $RR_d(C_{BAU})$	Relative risks (RR) of disease *d* for the respective age groups at the $PM_{2.5}$ levels of C_s in scenario *s* and C_{BAU} in *BAU*	Global Burden of Disease GBD Study 2013 [47]*
C_s and C_{BAU}	Annual mean exposures in scenario *s* and BAU: Four-month average of the simulated population-weighted, provincial-averaged $PM_{2.5}$ concentrations**	Our WRF-Chem simulations

Notes:
[*] Sensitivity analyses on linear RR functions are presented in Supplementary Fig. S2.
[**] Specifically, we first estimate county-averaged $PM_{2.5}$ concentrations by averaging the concentrations for all the WRF-Chem grids located within that county. We then calculate population-weighted provincial-averaged $PM_{2.5}$ concentrations by weighting the $PM_{2.5}$ concentrations for each county within that province by the ratio of county total population to provincial total population.

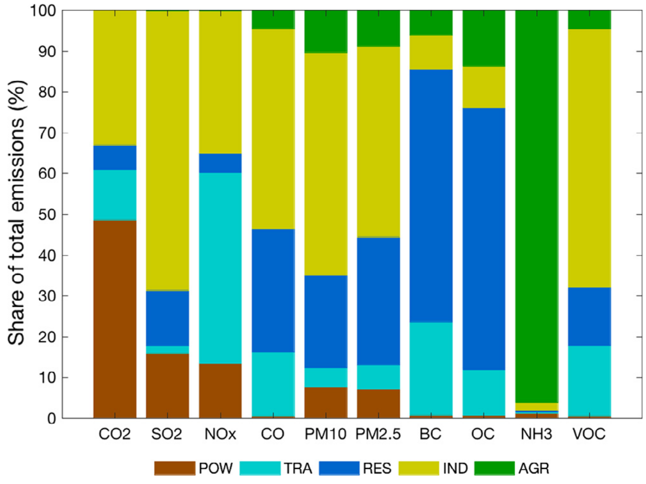

Fig. 1. Contribution of the power, transportation, residential, industry and agricultural sectors to national annual total emissions in 2030 BAU.

based heating is a substantial contributor to local air pollution in winter [30]. When both sectors are electrified in $\mathrm{ELE}_{\mathrm{BAU}}$_Trans&Resid and $\mathrm{ELE}_{\mathrm{LowC}}$_Trans&Resid, we find a 1–5 μg/m^3 and 1–10 μg/m^3 reduction (1–11% and 1–15%) in annual mean $PM_{2.5}$ throughout China, with the largest reduction found in the NCP region. In terms of the seasonal patterns, the absolute reductions are greater in January and October, largely due to higher BAU pollution levels in these two months.

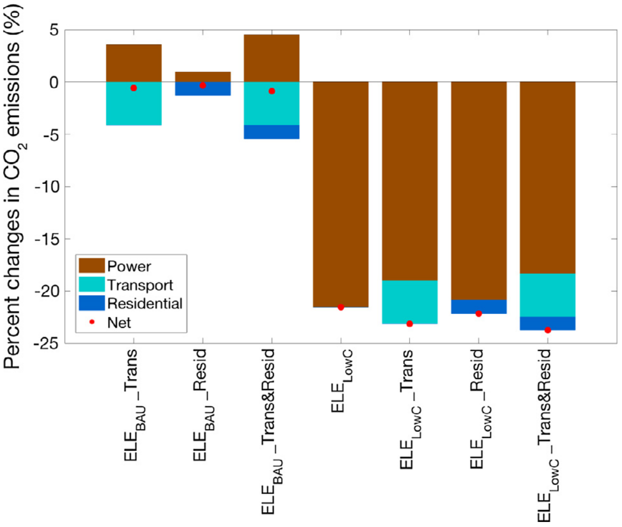

Fig. 3. Percent changes in sectoral CO_2 emissions in the electrification scenarios relative to all-sector BAU emissions (bars). The red dots indicate net changes in all three sectors (same as the bars in the CO_2 subplot in Fig. 1). In our scenarios, the emissions in the industrial sector are unaffected by electrification and thus remain unchanged. See Table 1 for a summary of the scenarios.

3.2.2. *Public health impacts*

We estimate the national total premature mortalities associated with outdoor air pollution exposure to be 0.89 million in BAU in 2030 (confidence interval due to relative risk functions: 0.44 to 1.3 m). Due to reduced $PM_{2.5}$ levels, the AP_Cntrl scenario leads to 23,000 (11,000, 35,000) avoided deaths nationally in 2030, equivalent to 2.6% of total air-pollution-related premature mortalities in BAU (Fig. 4). In addition to conventional air pollution control, using coal-intensive electricity to electrify the transport, residential and both sectors leads to 41,000 (21,000, 60,000), 38,000 (20,000, 54,000) and 57,000 (32,000, 80,000) avoided premature deaths nationally in $\mathrm{ELE}_{\mathrm{BAU}}$_Trans, $\mathrm{ELE}_{\mathrm{BAU}}$_Resid and $\mathrm{ELE}_{\mathrm{BAU}}$_Trans&Resid, respectively (i.e. 4.7%, 4.3% and 6.4% of total air-pollution-related deaths in BAU; see Fig. 4). If a half-decarbonized electricity sector is used to electrify these end-use sectors, we find a 34%, 32% and 21% greater reduction in premature deaths for $\mathrm{ELE}_{\mathrm{LowC}}$_Trans, $\mathrm{ELE}_{\mathrm{LowC}}$_Resid and $\mathrm{ELE}_{\mathrm{LowC}}$_Trans&Resid,

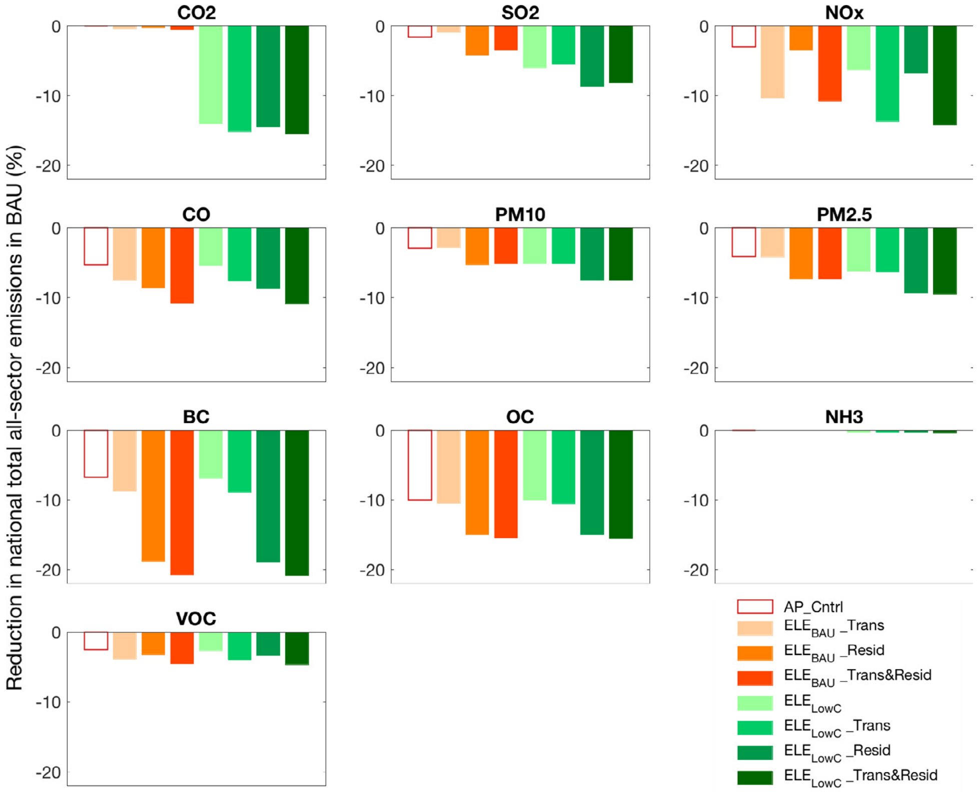

Fig. 2. Percent reduction in national total all-sector emissions in each scenario compared to BAU for the year 2030. See Table 1 for a summary of the scenarios.

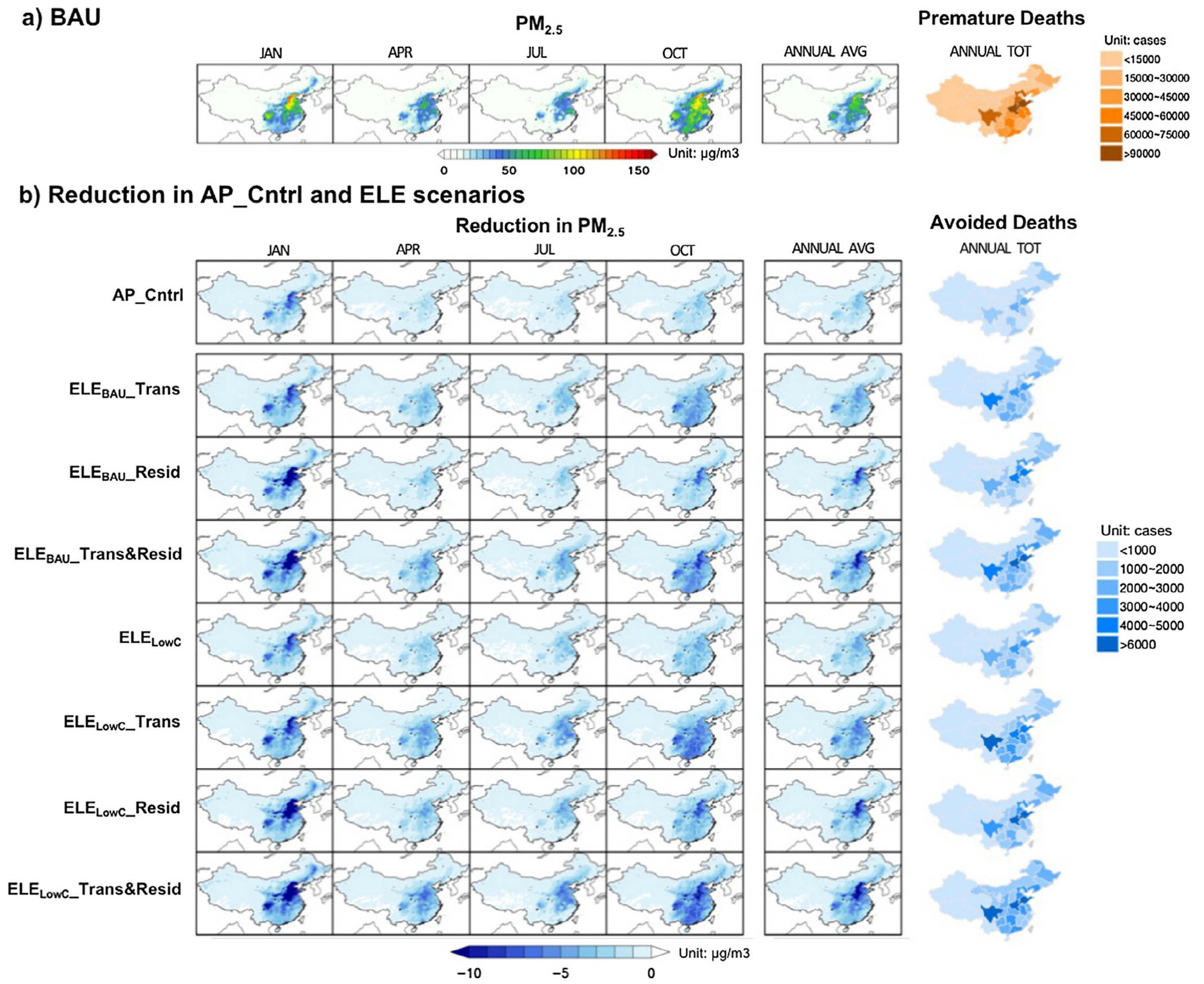

Fig. 4. Monthly and annual mean $PM_{2.5}$ concentrations (first five columns) and the resulting annual premature mortalities by province (last column): (a) BAU; (b) Reductions in AP_Cntrl and ELE scenarios. See Table 1 for a summary of the scenarios.

than in the related scenarios using coal-intensive electricity (i.e. 55,000 (28,000, 77,000), 50,000 (28,000, 70,000) and 69,000 (37,000, 98,000) cases, respectively; or 6.2%, 5.6% and 7.8% of total air-pollution-related deaths in BAU). Decarbonizing the power sector alone without end-use electrification in ELE_{LowC} leads to 35,000 (18,000, 50,000) avoided annual deaths nationally (or 3.9% of total air-pollution-related deaths in BAU; see Fig. 4).

Regarding spatial distribution, more premature deaths are avoided in the northern and southwestern provinces. This is mainly driven by their large local population size and relatively large reduction in local $PM_{2.5}$. In addition, we also observe large health benefits concentrated in the North China Plain (NCP) region when the residential sector is electrified, which is consistent with the results on $PM_{2.5}$ concentrations.

4. Discussion

4.1. Policy implications and applications

Our study develops an integrated assessment framework to inform power system supply designs and end-use electrification choices in China to address air quality, health and climate objectives. This framework can be applied to various spatial scales and different electrification strategies (e.g. the decarbonization level, the scale of electrification, and which sectors to electrify) that are of interest to decision makers. Quantifying these environmental co-benefits also deepens the understanding of trade-offs in the adoption of electric technology. It provides a more comprehensive assessment of the societal benefits, and creates additional incentives for accelerating the speed of electrification.

Based on the scenarios designed in this analysis for 2030 China, we highlight the following policy implications.

4.1.1. National perspective: Co-control air pollution and carbon emissions through electrification (Fig. 5)

Nationally, we find that improving conventional air pollution control strategies could significantly reduce air pollution and associated health impacts (in AP_Cntrl: 2.6% reduction in national total air-pollution-related deaths in 2030). However, these control measures do not mitigate carbon emissions, and may even result in a net increase in carbon emissions if we consider the reduced plant efficiency to operate control devices (Supplementary Fig. S1). This suggests that policies that target only air pollution abatement may bring no climate benefits or even dis-benefits.

Compared to improving conventional air pollution control alone,

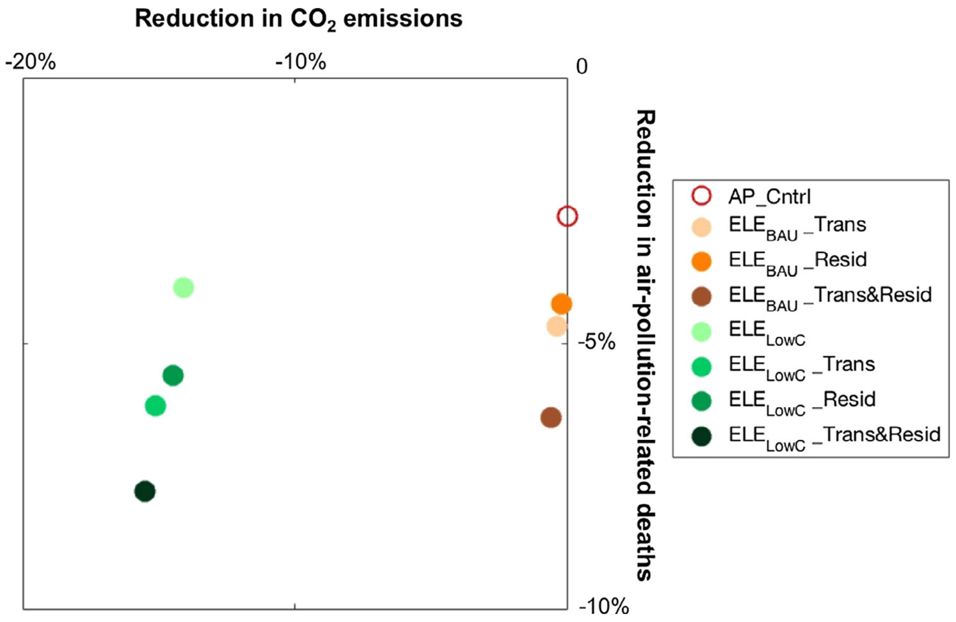

Fig. 5. Addressing air pollution and climate impacts through electrification in China. The x and y axes indicate the percent reduction in national total CO_2 emissions and air-pollution-related deaths in each scenario compared to BAU, respectively. See Table 1 for a summary of the scenarios.

electrification could further reduce air pollution and mortality impacts nationally, especially when both the transport and residential sectors are electrified. In addition, we find greater air quality and health benefits when end-use electrification is coupled with a decarbonized power system. For instance, the avoided premature mortalities are 20% greater when the transport and residential sectors are electrified using half decarbonized electricity (52% coal), compared to coal-intensive electricity (75% coal). This is because relying mainly on low-carbon electricity to power the end-use sectors avoids the increase in air pollutant emissions from electricity generation.

Although electrification can bring notable health benefits even with coal-intensive electricity, significant carbon mitigation is possible only when it is coupled with decarbonization efforts in the power sector. The electrification scenarios that use half decarbonized electricity contribute to a 14–16% reduction in annual national total carbon emissions, while those based on a coal-intensive power mix (75% coal) lead to no reduction. Our finding is thus consistent with prior studies that show the lower the carbon intensity of the power mix, the greater the carbon mitigation benefits from electrification [10,16–19,49,50].

Therefore, national decision-makers that aim to co-control air pollution and carbon emissions through electrification need to recognize the importance of concurrent efforts in decarbonizing the power generation fleet. However, given the long lead time to build the infrastructure for economy-wide electrification and power sector decarbonization, immediate efforts to accelerate the adoption of electric vehicles and heating/cooling technologies could lay the foundation for long-term decarbonization, even though near-term carbon mitigation is limited.

4.1.2. A subnational perspective: Regional distribution of air quality and health co-benefits

We find different regional distributions of the health co-benefits in the transport electrification scenarios compared to the residential electrification scenarios. Electrifying the transport sector leads to more uniformly-distributed benefits across population centers in East and Central China (e.g. ELE_{BAU}_Trans and ELE_{LowC}_Trans). In contrast, electrifying the residential sector brings more local benefits to the North China Plain region (e.g. ELE_{BAU}_Resid and ELE_{LowC}_Resid), where residential coal use for heating in winter has been found to be a major source of local air pollution [30].

Our results suggest that regional decision makers need to understand not only the synergies and tradeoffs between air quality and climate goals, but also different levels of air quality and health benefits due to electrification strategy designs. Such differences in local health co-benefits may result in divergent local priorities: some regions may focus on bringing more electric vehicles to the road, while others may prioritize investing in transmission and distribution networks to connect more households with electricity.

In addition to regional differences, urban populations may benefit more from transport sector electrification, while rural populations may benefit more from residential sector electrification. Although this is beyond the scope of our analysis, the distributional consequences of electrification between urban and rural populations have been evaluated in prior studies [24,51], and can be an important future area for research.

4.2. Uncertainty analyses

We conduct sensitivity analyses for four major sources of uncertainties. First, we consider the potential efficiency penalties due to the operation of end-of-pipe air pollution control technologies on power plants. We find a net increase in carbon emissions in the AP_Cntrl scenario, as well as the electrification scenarios that depend on carbon-intensive electricity (Supplementary Fig. S1). For electrification scenarios that depend on a half decarbonized electricity sector, the net reduction in carbon emissions is still substantial.

Second, we consider using heat pumps instead of resistance heaters in our residential electrification scenarios. While resistance heaters convert electricity to heat, heat pumps only use electricity to move heat from cooler to warmer places in winter and the opposite in summer. Therefore, depending on ambient temperature, the electricity-to-heat conversion efficiency for heat pumps can be 1–3 times greater than that for resistance heaters (Supplementary Table S3). As a result, to electrify coal-based heating stoves, using heat pumps would require 1/3 of the electricity needed for resistance heaters. However, such a difference in heating electricity demand is only 0.14% of the total electricity demand in BAU, due to large total demand and small electrification scale (30%). Therefore, compared to BAU, the differences driven by heat pumps versus resistance heaters are negligible for national total electricity generation and associated emissions ($<$ 0.1% of national total air pollutant/CO_2 emissions in BAU).

Third, we apply alternative relative risk (RR) functions to assess the mortality impacts from air pollution exposure (Supplementary Fig. S2). Our main results use concave RR functions, which are consistent with recent epidemiological evidence that the marginal mortality risks decrease with increasing $PM_{2.5}$ concentrations at high PM2.5 levels. Since $PM_{2.5}$ reductions occur in many locations that are quite polluted in BAU, applying linear RR functions would increase the magnitudes of avoided deaths in our scenarios and the differences across them.

Fourth, we consider more ambitious implementation of the electrification scenarios that target both transport and residential sectors ($ELE_{BAU_}$Trans&Resid and $ELE_{LowC_}$Trans&Resid, Supplementary Table S3 and Figs. S3 and S4). We assume that 50% of on-road vehicles and residential stoves are electrified (compared to 30% in the main scenarios). For the scenario using decarbonized power (i.e. $ELE_{LowC_}$Trans &Resid), we also assume the power system is further decarbonized with only 37% coming from coal (compared to 52% in the main scenarios). Comparing ambitious to moderate implementation, we find 38% and 47% more avoided deaths in the scenarios using coal-intensive and decarbonized electricity respectively. In addition, the carbon mitigation benefits would almost double if the power system is decarbonized to this level. Therefore, increasing the scale of low-carbon generation on the supply side and end-use electrification on the demand side can significantly increase the air quality, health and climate benefits.

In addition to the above factors for which we conduct quantitative sensitivity analyses, there are three other uncertainties. First, recent research found that emission inventories may underestimate vehicle emissions in China because full enforcement of emission standards, as assumed in the inventories, is challenging in reality [52–54]. This leads to a potential underestimation of emissions from conventional vehicles in BAU, and hence an underestimation of the air quality benefits from electrifying the transport sector. Second, in our WRF-Chem simulations, we allocate all power sector emissions to the surface layer, while in reality coal power plants use tall smokestacks. As a result, we may overestimate the effect of coal power plant discharges on surface $PM_{2.5}$ concentrations and human exposure. Third, when evaluating the health impacts, we assume present and 2030 demographic patterns are the same. However, China's population is projected to age. An older age structure will lead to greater total health impacts from air pollution exposure, due to higher risks for the older population [47]. We thus may underestimate the health benefits from electrification in 2030.

4.3. Directions for future research

To further understand the air quality and climate implications of electrification, future research should consider integrating the impact assessment approach used in this analysis with power system models. Power system models provide detailed representations of the generation system, transmission system and end-use sectors. They could guide power system decisions to achieve electrification, e.g. how much renewable electricity can be integrated when coupled with electric vehicles and heating options [35,38,55], and the implications of long-distance transmission on renewable integration and electricity losses. In addition, while our analysis only focuses on annual total emissions, a finer temporal horizon is necessary to model the environmental implications of high renewable penetration. Some studies based on hourly or minute-level analyses found an increase in air pollution and carbon emissions when fossil generation is frequently ramped up and down to manage the intermittent output from renewables [56,57]. An integrated modeling of the power system and the environmental impacts has been applied to the power market in the U.S. [58,59]. For China, some efforts have been made to use the output from power system models for a subsequent evaluation of the air quality and carbon impacts [60]. Future efforts that lead to further integration would be valuable.

Furthermore, our electrification scenarios only consider expanding electricity use in the transport and residential sectors. However, electrifying some industrial processes is possible [61]. Since the industrial sector is a major emitter of air pollutants and CO_2 in BAU, displacing fossil energy use in some industrial processes with electricity could bring additional air quality and climate benefits.

Finally, we suggest future research consider two additional impacts of air pollution for a more comprehensive assessment. First, ozone, another important air pollutant, can lower crop yields in China [62] and globally [63], which has implications for food security. Transport electrification can lower NO_x emissions. Since NO_x emissions are ozone precursors, such reductions in NO_x may reduce ozone concentrations (in a NO_x-limited regime typical of agricultural regions) and associated yield loss. Second, aerosols have direct radiative effects and indirect effects on clouds, both of which would impact on the climate system. Previous studies found that the removal of aerosols in East Asia may increase surface warming [64,65], hence requiring more aggressive carbon mitigation policies to meet desired climate targets.

5. Conclusion

Electrification of China's transport and/or residential sector in 2030 can mitigate both air pollution impacts and carbon emissions. However, different electrification strategies will lead to different sizes and regional patterns of the co-benefits. First, electrification based on coal-intensive electricity can bring significant air quality and health benefits, but no carbon mitigation benefits. Switching to a partially decarbonized power supply will both increase health benefits and also dramatically reduce carbon emissions. Second, electrifying the transport or residential sector will lead to different regional distributions of air quality and health benefits. While electrifying the transport sector improves air quality in eastern population centers, electrifying the residential sector brings more local benefits to northern China in winter where coal-based heating is a large contributor to air pollution. Policymakers should therefore also consider the distributional consequences when designing electrification strategies.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2018.02.048.

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