The *Lancet* Countdown on $PM_{2.5}$ pollution-related health impacts of China's projected carbon dioxide mitigation in the electric power generation sector under the Paris Agreement: a modelling study

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Summary

Background Except for comparing the implementation costs of the Paris Agreement with potential health benefits at the national levels, previous studies have not explored the health impacts of the nationally determined contributions (NDCs) by countries and in regional details. In this *Lancet* Countdown study, we aimed to estimate and monetise the health benefits of China's NDCs in the electric power generation sector, and then compare them with the implementation costs, both at the national and regional levels.

Methods In this modelling study, we linked the Multi-regional model for Energy Supply system and their Environmental ImpaCts, the Multi-resolution Emission Inventory for China model, the offline-coupled Weather Research and Forecasting model, the Community Multiscale Air Quality model, and the Integrated Health Impact Assessment model with a time scope from 2010 to 2050. We calculated the $PM_{2.5}$ concentrations and compared the health impacts and implementation costs between two scenarios that reflect CO_2 and air pollutant emissions—the reference (REF) scenario (no climate policy) and the NDC scenario (100% realisation of NDC targets: CO_2 emission intensity needs to be about 40% below 2010 emissions by 2030 [roughly 35% below 2030 emissions in REF], and about 90% below 2010 emissions by 2050 [roughly 96% below 2050 emissions in REF]).

Findings Under a comparatively optimistic health benefits valuation condition, at the national level, 18–62% of implementation costs could be covered by the health benefits in 2030. In 2050, the overall health benefits would substantially increase to 3–9 times of the implementation costs. However, northwest China would require the highest implementation costs and will also have more premature deaths because of a more carbon-intensive energy structure than business as usual. By 2030, people in northwest China (especially in Gansu, Shaanxi, and Xinjiang provinces) would need to bear worse air quality, and 10 083 (95% CI 3419–16 138) more premature deaths annually. This undesirable situation would diminish by about 2050. A solution that assumes no growth in air pollutant emissions in 2030 at the regional level is technically feasible, but would not be cost-effective.

Interpretation Our results suggest that cost–benefit analysis of climate policy that omits regional air pollution could greatly underestimate benefits. A compensation mechanism for inter-regional interests (including financial, technological, and knowledge support) should be established for regions that give up their human health benefits for the sake of the whole nation to realise the climate change targets.

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See **Comment** page e147

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Introduction

Climate change is the biggest global health threat of the 21st century[1] and tackling it could be the greatest global health opportunity of this century.[2] To address climate change and support in the Paris Agreement, countries around the world have submitted 174 pledges to the UN (known as nationally determined contributions; NDCs),[3] setting out how far they intend to reduce their greenhouse gas emissions. These NDCs have covered up to 96·4% of global greenhouse gas emissions,[3] and will lead to the upgrade of industrial structure, increase of energy efficiency, and decarbonisation of production technologies, which often, as a side-effect, reduces atmospheric emissions and improves air quality and thus human health. Because most countries have introduced new climate change policies or targets in their NDCs, no timely and quantitative studies have explored the effects of NDCs on air quality and human health to date. Evaluating NDCs' co-benefits for health would have substantial meanings for the optimisation of policy making for climate change to be more cost-effective and socially acceptable.[2,4]

As early as the 1990s, researchers have started to explore the health co-benefits of carbon dioxide (CO_2) reduction.[4–12] For a long time, studies in developed countries have

Research in context

Evidence before this study

Many previous global-scale studies have reported that the health co-benefits of mitigating greenhouse gas emissions would be most notable in east Asian regions. One study even estimated that two-thirds of the global co-benefits would occur in China in 2030. Another study explored the health co-benefits of low-carbon fuels and technologies in China and found that the introduction of technologies at US$70/tonne of carbon dioxide (CO_2) abated can reduce the burden of disease by 550 disability-adjusted life-years, per million of the population. Similar case studies have been done in Beijing, Shanghai, Shanxi, Taiyuan, Xi'an, Suzhou, and in electricity and cement sectors, all showing the notable health co-benefits from low-carbon technologies and climate policies.

Few studies in China have monetised the health co-benefits and compared them with the technology or policy costs. One study used a general equilibrium model, and another study used an integrated top-down and bottom-up model, both of which found that hidden health co-benefits could exceed the mitigation costs. However, because of an absence of data, most studies relied on other countries' baseline mortality data, contingent valuation results for healthy lives, resulting in rough and uncertain estimations. Furthermore, very few studies looked at the benefit to cost ratio at a subnational level and therefore did not differentiate between regional winners and losers, which might lead to flawed policy making for climate change.

Added value of this study

This study adds to the spatial details in previous assessments by estimating the health co-benefits at national, regional, and provincial levels, by using the China-specific or regional-specific health status and health valuation data. We therefore provide a novel analysis on how China's nationally determined contribution (NDC) targets will affect human health in China and in different regions, which can help policy makers for climate change and public health authorities make better decisions.

Implications of all the available evidence

The national level analysis in this study is consistent with previous studies; the health co-benefits of China's NDC goals are very likely to far exceed the costs. It suggests that cost–benefit analysis of climate change policy that omits regional air pollution could greatly underestimate benefits. Besides, the health co-benefit to cost ratio decreases at higher amounts of CO_2 abatement because abatement costs rise but changes to air quality and health co-benefits are not as extensive. Therefore, evaluation of the health co-benefits is more important at the early phase of a long-term climate change mitigation strategy. The regional level analysis shows that some provinces classed as winners, such as Guangdong, Heilongjiang, and Liaoning, will have the most notable health benefits, whereas other provinces (mainly concentrated in northwest China, especially Gansu, Shaanxi, and Xinjiang) will need to give up their own air quality and human health benefits to help realise national NDC targets. We would suggest that inter-regional interest compensation mechanisms (including financial, technological, and knowledge support) should be established for those regions classed as losers.

been more extensive and sophisticated than studies in developing countries.[8] However, it is widely recognised that the developing countries possess the largest health co-benefits for each tonne of CO_2 reduced,[12,13] which makes furthering the investigations in these regions more imperative. One of the main reasons for this research gap is the shortage of country-specific or even region-specific surveys for baseline incidence data and the absence of studies on values of a statistical life. Some studies are left with no choice but to directly use or translate from developed countries' baseline incidence data,[13,14] resulting in rough and uncertain estimations. Another research gap exists in both developed and developing countries. Most studies to date focus on health co-benefits of reductions in CO_2 at the national level. However, carbon policies are usually made and applied at regional levels, resulting in rather different regional benefit to cost ratios and creating so-called winner and loser regions.[15] Therefore, the inadequately addressed regional-level health effects of CO_2 reduction are even more notable for exploration,[15,16] to avoid the overoptimistic estimations and better inform regional policy making.

In 2016, CO_2 emission by China was estimated as 26% of the world total, double the amount by the USA.[17] In 2015, the electric power generation sector in China alone consumed 52% of the total coal consumption[18] and emitted more than 40% of the total CO_2 in China.[19] In the meantime, this sector contributed 27% of the total sulphur dioxide (SO_2) emission and 25% of the total emission of nitrogen oxides (NO_X) in China, which are the key precursors of secondary $PM_{2·5}$.[20] Through comprehending that the NDCs would require a huge cost but would also bring tremendous health benefits, we aimed to use the largest developing country—China—as the research objective in our study to investigate the health co-benefits of realising the NDC targets in China's power generation sector (panel 1). In this study, we aimed to estimate and monetise the health benefits of China's NDCs in this sector and compare them with the implementation costs, both at the national and regional levels, and to answer three questions of key policy relevance. This is a case study of The *Lancet* Countdown,[21] which is an annual report published in *The Lancet* that tracks the world's response to climate change, and the resulted health benefits.

Methods

Study design

The time scope of this study is from 2010 to 2050. We set up two scenarios to reflect the CO_2 and air pollutants emissions and the corresponding health impacts without NDC targets (reference [REF] scenario) and with 100% realisation of NDC targets (NDC scenario). More specifically, the REF scenario assumes no climate policies. The NDC scenario assumes that the CO_2 emission intensity needs to be about 40% below 2010 emissions by 2030 (in absolute terms, roughly 35% below 2030 emissions in REF), and about 90% below 2010 emissions by 2050 (in absolute terms, roughly 96% below 2050 emissions in REF; panel 2).[23,24] These two scenarios share the same socioeconomic assumptions, including the future net electricity demand, the discount rate, and the total number and geographical distribution of the population (the rationales and details of scenario settings are in the appendix).

The three questions of key policy relevance were (i) how would China's NDCs in the power generation sector affect the national and regional air pollutant emissions? (ii) How much money would it be worth for the national or regional health benefits or losses induced by NDCs and how would they compare with the implementation costs? (iii) What would be the implications for China to implement NDCs and to balance regional interests? To answer these research questions, we linked the Multi-regional model for Energy Supply system and their Environmental ImpaCts (MESEIC), the Multi-resolution Emission Inventory for China (MEIC) model, the offline-coupled Weather Research and Forecasting (WRF) model, the Community Multiscale Air Quality (CMAQ) model, and the Integrated Health Impact Assessment (IHIA) model (appendix).

MESEIC is an energy system model that can produce the lowest cost technology mix for each region that fulfils both future electricity demand and CO_2 and local air pollutants emission constraints. We used the model to obtain the SO_2 and NO_X emissions and power generation costs in each region for the two scenarios. The changes in power generation costs between two scenarios are the NDC implementation costs. The modelled SO_2 and NO_X emissions were then used to replace the corresponding emissions of the power generation sector in MEIC. We assumed emissions for other sectors in MEIC to remain unchanged. By importing the updated emission inventory from MEIC and meteorological parameters from WRF, we used CMAQ to calculate the $PM_{2·5}$ concentrations for each scenario. Finally, we used the IHIA model to estimate changes in the mortality under different $PM_{2·5}$ concentration scenarios. We calculated monetised health benefits according to mortality change and value of a statistical life (VSL) in China and we used these for comparison with the NDC implementation costs.

Panel 1: China's NDC targets

On June 30, 2015, China submitted its intended nationally determined contributions (INDC) to the UN Framework of Climate Change Convention. On Sept 3, 2016, China ratified the Paris Agreement, and thus the INDC formally converted to NDC.

China's mitigation actions by 2030 are[22]:

- To achieve the peaking of carbon dioxide (CO_2) emissions by 2030 and making best efforts to peak early
- To lower CO_2 emissions per unit of gross domestic product by 60–65% from the 2005 amount
- To increase the share of non-fossil fuels in primary energy consumption to about 20%
- To increase the forest stock volume by roughly 4·5 billion m^3 more than 2005

Other NDCs related to adaptation and detailed supporting policies and measures can also be found in China's submission.[22]

See Online for appendix

Panel 2: From China's NDC targets to the emission reduction targets in the electric power generation sector

Although China released its nationally determined contribution (NDC) targets, we still had to translate those targets into specific targets for the power generation sector to reach the research objectives of this study. Despite the countless possibilities, we refer to the analysis results of two very important projects—the Modelling and Informing Low-Emission Strategies (MILES) Project,[23] and the Deep Decarbonization Pathway Project (DDPP).[24] Both project reports were released in 2015. The Chinese research group for the MILES project believed that the carbon intensity of electricity production would need to fall by 40% between 2010 and 2030, and the Chinese DDPP project inherited this judgment for carbon intensity in 2030 and further projected that the carbon intensity of electricity production would need to fall by 90% between 2010 and 2050. Therefore, the 40% and 90% decreases in carbon intensity in electricity production in 2030 and 2050, respectively, were taken as the new constraints in the Multi-regional model for Energy Supply system and their Environmental ImpaCts (MESEIC) model to produce the optimal technology mix and the corresponding air pollutant emissions in each power-grid region, further driving the changes in the downstream linked models. Both the MILES and DDPP reports emphasised that these future intensity changes should not be taken as predictions, but rather as credible, detailed, and internally coherent explorations of pathways towards achieving the headline ambition announced in the NDCs and in the long-term global climate goals. We understand that altering the inputs of carbon intensity constraints would produce different results in MESEIC and the downstream linked models. However, to concentrate the sources of uncertainty and to better understand the results, we consider these two credible pathways as the most suitable inputs for MESEIC and the downstream linked models.

Modelling framework for air pollutant emissions

MESEIC is a multiperiod, bottom-up, technological, optimisation model for China's power generation sector.[25,26] The model divides China's power generation sector into six regional power grids—north, northeast, east, central, northwest, and south. Each of the grids has its specific energy resource endowment and power generation technology mix. The appendix shows the corresponding provinces in each grid in China. We assumed growing inter-regional transmission capacity among grids according to the State Grid Corporation's

For more on the **State Grid Corporation of China** see http://www.sgcc.com.cn/

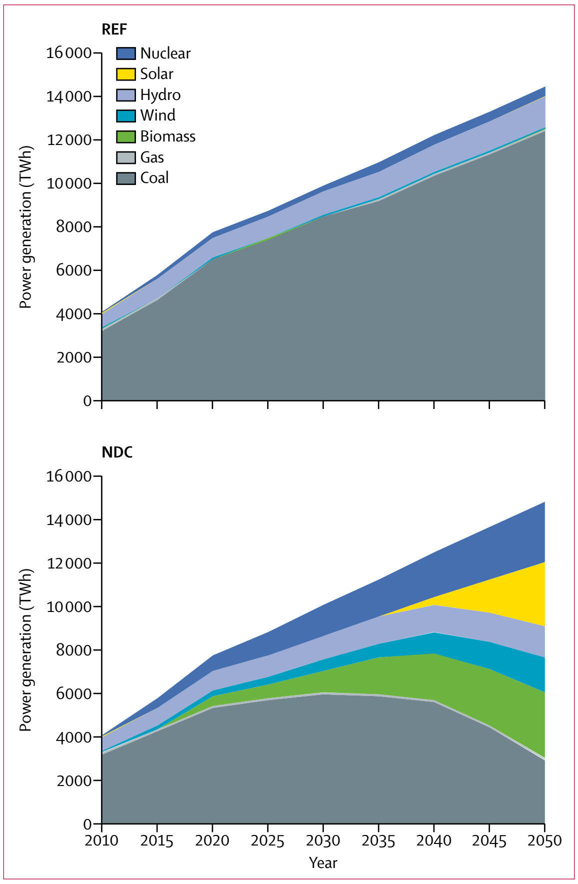

Figure 1: **Electric power generation by different technologies in China from 2010 to 2050**
REF=reference. NDC=nationally determined contributions.

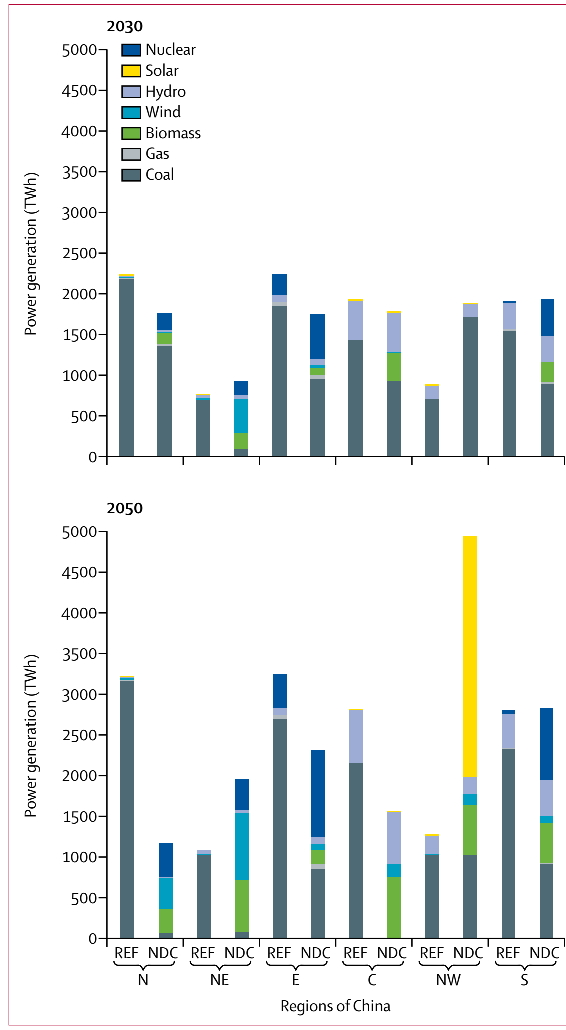

Figure 2: **Electric power generation by different technologies in six regions of China in 2030 and 2050**
REF=reference. NDC=nationally determined contributions. N=north. NE=northeast. E=east. C=central. NW=northwest. S=south.

plan and studies in China.[25] The MESEIC determines how much of the available technologies and resources are used to satisfy a certain end-use demand, subject to various constraints (such as CO_2 and air pollutants emissions constraints), while minimising total energy system costs. Therefore, the detailed outputs of the model are the optimal installed capacity and generation technology mix, the CO_2 and local air pollutants emissions, and the minimised total power generation cost in China and the six regions.

Modelling framework for air pollutant concentrations

MEIC is a technology-based, bottom-up, air pollutant inventory that covers multiple air pollutants and greenhouse gases.[27–29] We used the 2010–50 regional SO_2 and NO_X emissions in the power generation sector in the REF and NDC scenarios from MESEIC to replace the corresponding emissions in MEIC. Anthropogenic emissions outside China and emissions from non-power generation sectors remained constant with the 2010 emissions. Thus, the calculated emission changes were solely a response to the CO_2 emission reductions in the power generation sector under NDCs. We imported the updated emission inventory from MEIC, together with the meteorological parameters simulated by the WRF (version 3.5.1) model, into CMAQ (version 5.1) for air quality simulation. $PM_{2.5}$ concentrations under the REF and NDC scenarios from CMAQ simulations were our major concern because $PM_{2.5}$ is the most robust indicator of long-term mortality. We further imported the $PM_{2.5}$ concentrations under the REF and NDC scenarios into the health-modelling framework for evaluation of the health benefit.[30,31]

Modelling framework for health impacts

The IHIA model is a program, developed at Tsinghua University (Beijing, China), that estimates the number and economic value of health impacts resulting from changes in $PM_{2.5}$ concentration under a 36 km × 36 km grid by combining methods of concentration-response

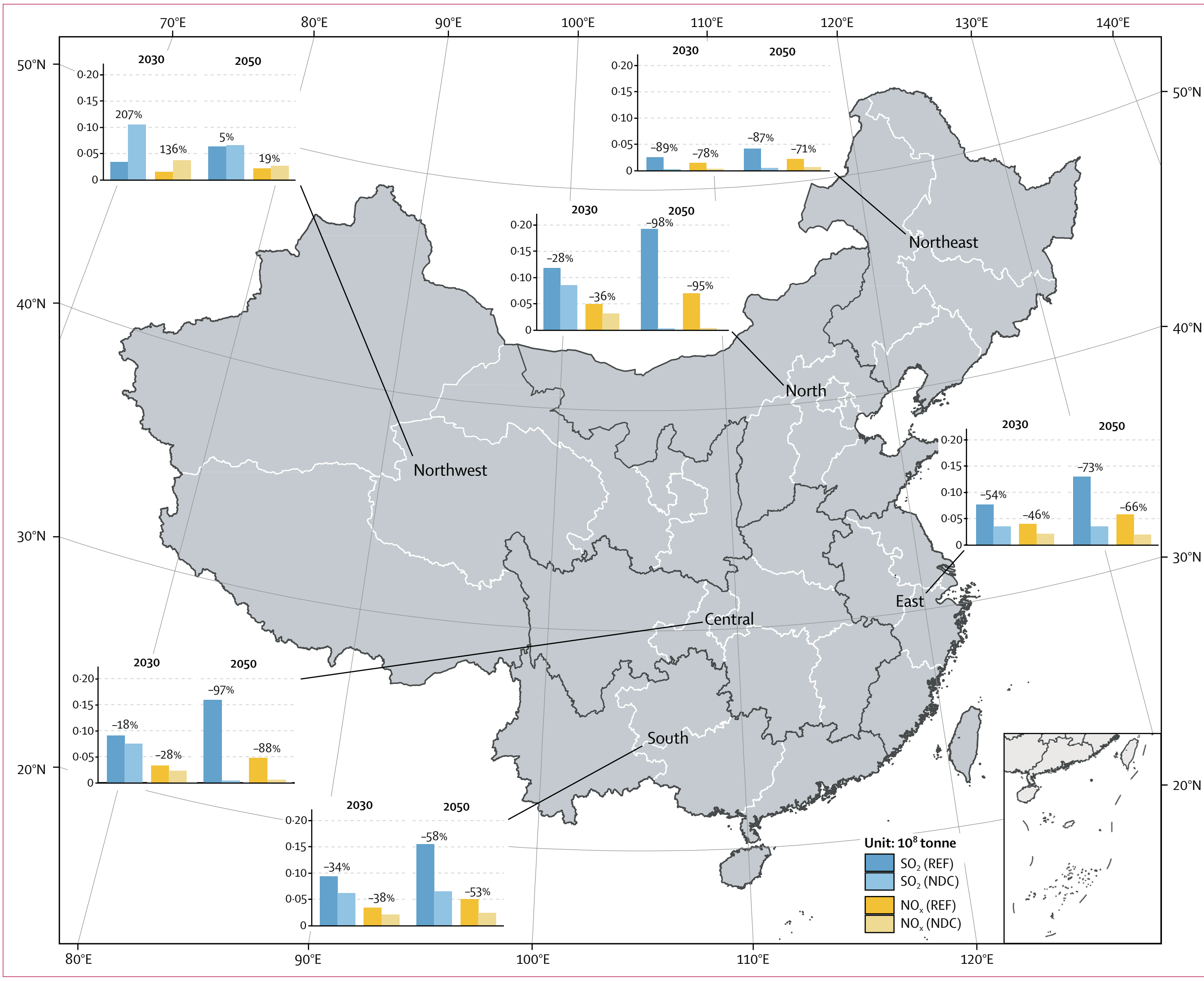

Figure 3: **SO_2 and NO_x emissions in six regions of China under REF and NDC scenarios in 2030 and in 2050**
REF=reference. NDC=nationally determined contributions. NO_x=nitrogen oxides. SO_2=sulphur dioxide. N=north. E=east.

functions,[32] life table,[33] and health benefits evaluation based on VSL.[34,35] Additionally, to improve the model resolution, we used a provincial scale disease burden dataset, which contained ischaemic heart disease, chronic obstructive pulmonary disease (COPD), stroke, and lung cancer mortality at the provincial level.[36,37] Therefore, after we imported the $PM_{2·5}$ concentrations under REF and NDC scenarios into the IHIA model, the detailed outputs of the model were the avoided premature deaths and the monetised health co-benefits in China and the 31 provinces. Detailed parameters regarding relative risk, attributable fraction, the baseline incidence of the given health effect, and the assumptions on fertility and mortality are in the appendix. Finally, we compared the NDC compliance costs with the monetised health co-benefits at the regional and the national level.

Uncertainty analysis

A full quantitative analysis for uncertainty among all factors is computationally impossible.[15] In this study, we discuss the uncertainties in the framework of air pollutant emissions and concentrations and did sensitivity analysis in the health modelling framework (appendix).

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the paper. All authors had full access to all the data in the

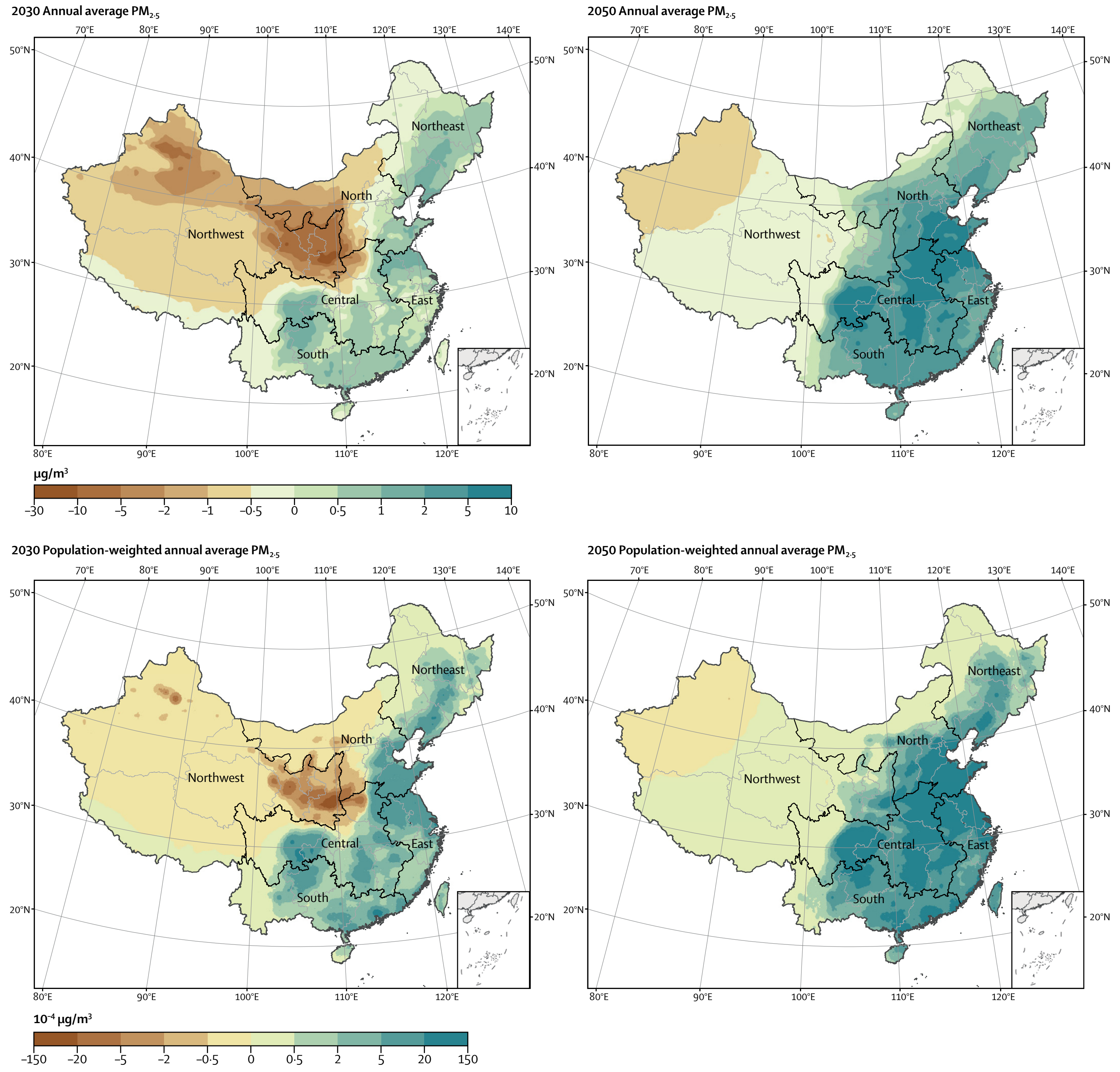

Figure 4: **Changes in $PM_{2.5}$ concentrations in China between REF and NDC scenarios in 2030 and 2050**
A negative value of change represents that $PM_{2.5}$ in the NDC scenario is lower than the REF scenario. In 2050, the amount of air quality degradation in northwest China would be much more alleviated than in 2030, as a result of the decarbonisation in the electric power generation technology mix in this region. REF=reference. NDC=nationally determined contributions. N=north. E=east.

study and the corresponding author had full responsibility for the decision to submit for publication.

Results

With the energy system model, we obtained the power generation costs and SO_2 and NO_X emissions in each region under the REF and NDC scenarios in China. Under the REF scenario, the coal-fired power generation would keep growing during the 2010–50 period (figure 1). The total shares of the renewables and nuclear power would remain at comparatively low amounts. However, under the NDC scenario, dramatic structural changes

	REF	NDC	Avoided premature deaths
2030			
Ischaemic heart disease	667 887 (337 002–1 120 676)	663 214 (334 726–1 112 116)	4674 (2276–8 561)
Stroke	1 180 148 (370 229–2 148 770)	1 171 083 (366 824–2 134 750)	9065 (3405–14 524)
COPD	321 376 (135 171–548 694)	317 928 (133 027–543 836)	3448 (2144–4858)
Lung cancer	285 423 (104 018–462 050)	282 648 (102 830–458 169)	2776 (1188–3881)
Total	2 454 835 (946 419–4 280 190)	2 434 873 (937 407–4 248 871)	19 962 (9013–31 320)
2050			
Ischaemic heart disease	1 566 326 (787 655–2 631 262)	1 471 401 (739 315–2 464 969)	94 925 (48 340–166 293)
Stroke	2 639 077 (824 064–4 829 192)	2 476 792 (756 255–4 584 418)	162 285 (67 809–254 054)
COPD	811 115 (346 944–1 375 444)	729 383 (299 087–1 256 386)	81 732 (47 856–119 058)
Lung cancer	479 085 (174 854–775 932)	449 458 (160 543–736 084)	29 627 (14 311–41 333)
Total	5 495 602 (2 133 517–9 611 830)	5 127 034 (1 955 200–9 041 857)	368 568 (178 317–569 973)

Data are mean (95% CI). Data were rounded before calculating totals. REF=reference. NDC=nationally determined contributions. COPD=chronic obstructive pulmonary disease.

Table: **Effects on mortality by cause of death in REF and NDC scenarios and number of avoided premature deaths in 2030 and 2050**

would happen in the power generation sector of China (figure 1). The power generation from coal-fired units would peak at 2025–30 and gradually decline (figure 1). Meanwhile, the total shares of the renewables and nuclear power would increase drastically from 20% in 2010 to about 80% in 2050 (figure 1).

Regarding the changes in power generation from different technologies in China's six regional power grids in 2030 and 2050, in five of the six regions, the power generation from coal-fired units will be reduced remarkably for the NDC scenario compared with the REF scenario; by contrast, the renewables and nuclear power will be promoted substantially (figure 2). The northwest region is the only region that will increase its generation from REF to NDC in 2030 for coal-fired units (figure 2). Because the coal in the northwest region is so abundant and cheap, it will have a key role in the cost minimisation of all six regions and in transmitting electricity to other regions. In 2030 and 2050, respectively, 57% and 76% of electricity produced in the northwest would be for other regions.

The drastic changes in the power generation technology mix brought by NDC targets will result in the notable changes in air pollutant emissions and concentrations simultaneously. Compared with the REF scenario, except the northwest, the other five regions in the NDC scenario would have an 18–89% reduction in SO_2 and a 28–78% reduction in NO_x in 2030, and those reductions in these five regions would become even more striking in 2050 (figure 3). For the northwest region, the SO_2 and NO_x emissions would increase by 209% and 136%, respectively, in 2030 in the NDC scenario, whereas in 2050, the rate of increase of SO_2 and NO_x emissions in the NDC scenario compared with REF would become comparatively modest at 5% and 19%, respectively (figure 3). The main reason is because as an energy resource centre, the northwest region undertakes most tasks to produce low-cost electricity for the other regions.

With atmospheric models, we obtained the detailed $PM_{2·5}$ concentrations under the REF and NDC scenarios in China. We found that meeting the NDC targets would lead to air quality improvement in most regions except northwest China. Under the NDC scenario, in 2030 and 2050, about 50% and 86%, respectively, of the national territory would have a declining $PM_{2·5}$ concentration (figure 4). In northeast, east, central, and south China, the decline of $PM_{2·5}$ concentrations would be very notable (figure 4). According to the recommended interim-3 target of WHO (35 μg/m³), 83% and 84% of China's territory would be able to meet this target under the NDC scenario in 2030 and 2050, respectively. In contrast to previous studies, we also observed that certain parts of China would have an increasing concentration of $PM_{2·5}$—mainly concentrated in the northwest of China.

When we summarised the effects on mortality in REF and NDC scenarios by type of health burden at national level, NDC can avoid 19 962 (95% CI 9013–31 320) premature deaths in 2030 and 368 568 (178 317–569 973) in 2050 in China (table). The largest health benefit would appear to come from the decrease in the number of stroke cases, followed by ischaemic heart disease, COPD, and lung cancer. The provincial-level results are shown in the appendix. As for the geographical distribution of the health impacts, it broadly follows the pattern of changes in population-weighted $PM_{2·5}$ concentrations (figure 4), and they would be unevenly distributed in China. The developed areas (especially all eastern regions, and the eastern parts of the south and central regions) would benefit the most from the implementation of NDCs, because of the remarkable decline in $PM_{2·5}$ concentrations and the dense population in those areas (figure 5). Guangdong, one of the most developed provinces in China, would become the top beneficiary province with the mean number of avoided premature deaths reaching 4691 (95% CI 1472–7503) in 2030, and 45 474 (14 579–73 519) in 2050 (figure 5). However, people in the northwest region

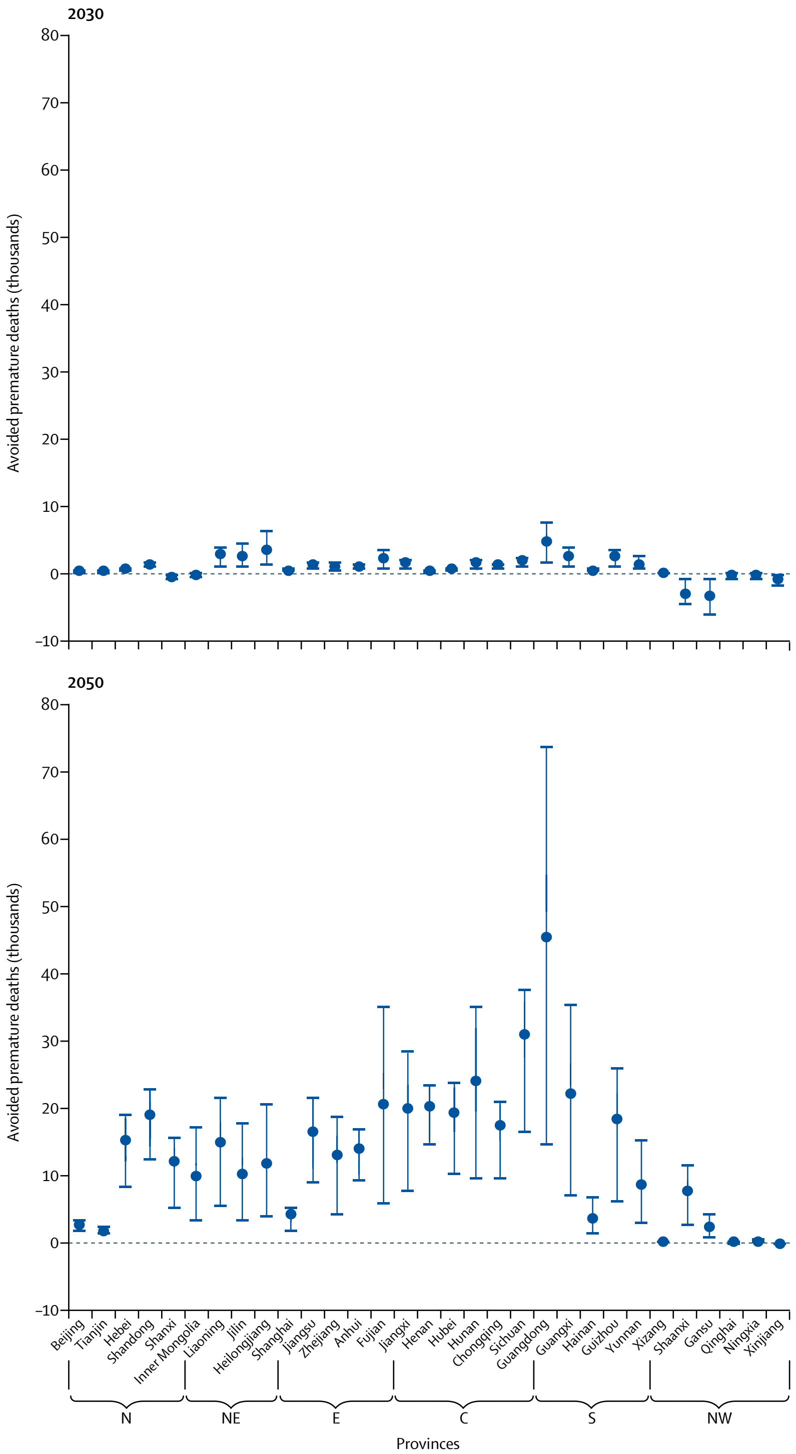

***Figure 5:* Number of avoided premature deaths because of NDC in each province of China in 2030 and 2050**
N, NE, E, C, S, and NW under each province represent the power grid region this province belongs to. Usually one province only belongs to one power grid region. The only exception is Inner Mongolia. The western part of Inner Mongolia belongs to the north China grid and the eastern part belongs to the northeast China grid. The vertical line for each province represents discrete health impact uncertainty simulations. Those uncertainties stem from incidence variations of the given health effect and variations in concentration-response functions. The number of avoided premature deaths is shown as median (circle) and 95% CI (bars). REF=reference. NDC=nationally determined contributions. N=north. NE=northeast. E=east. C=central. NW=northwest. S=south.

(especially in provinces like Gansu, Shaanxi, and Xinjiang) would have to give up their own health to help realise the national climate targets. In 2030, Gansu, Shaanxi, and Xinjiang would have the worst air quality, with the mean number of premature deaths in NDC increasing by 3610 (95% CI 1149–6392) for Gansu, 3181 (1180–4629) for Shannxi, and 1175 (466–2085) for Xinjiang (figure 5). The total incremental premature deaths in 2030 in northwest China would reach up to 10 083 (3419–16 138). Along with the decarbonisation of energy structure in the northwest region, the health losses (increase in premature deaths) in 2050 would be low. Therefore, having proper policies to alleviate and compensate for their losses is crucial.

Co-benefits of avoided air pollution mortality were monetised using many studies on VSLs, and were compared with the NDC implementation costs, which are represented by the changes of total power generation cost. Partridge and Gamkhar[34] believe that the mean value of VSLs provides a more valid comparison with the cost and the median value of VSLs provides a useful lower bound to the VSLs. Our study follows their judgment. Therefore, we mainly used the benefit (mean) to compare with the NDC compliance costs; however, we think the benefit (median) offers a conservative (or lower bound) estimation of the benefit to cost ratio. From the national perspective, the benefits estimated with the mean value of multiple VSLs studies range from US$2·72 billion to $9·45 billion in 2030, and from $53·79 billion to $171·93 billion in 2050, while the benefits estimated from median value of multiple VSLs studies range from $0·83 billion to $3·05 billion in 2030, and from $17·38 billion to $55·55 billion in 2050 (figure 6). The implementation costs to realise NDC targets would be about $15·26 billion in 2030, and $19·57 billion in 2050. Therefore, roughly 18–62% of NDC implementation cost could be offset by the health co-benefits in 2030. In 2050, the health co-benefits could reach up to 3–9 times the implementation cost. Based on the conservative estimation with the median value of VSLs, about 5–20% of the NDC cost would be offset by the health co-benefits in 2030, and in 2050, the health co-benefits could reach up to 89–280% of the implementation cost. From a regional perspective, in 2030, south, northeast, and central China would have the greatest health co-benefits, covering 33–103% for the NDC implementation cost in the south, 14–44% in the northeast, and 25–79% in the centre. Eastern and northern China will also have health co-benefits; however, as they become net electricity-import regions, their NDC implementation cost will be negative (ie, the total power generation cost will decrease). In 2050, all regions except northwest China would have more remarkable health co-benefits than 2030 and the health co-benefits would all significantly surpass their respective regional NDC implementation cost (figure 6). The only health loss would happen in the northwest region, where they will also have the highest regional NDC implementation cost. The NDC implementation cost in northwest China would be as high as \$7·94 billion in 2030, and \$16·25 billion in 2050. However, in 2030, the northwest region would have from \$0·95 billion to \$4·54 billion health losses (conservative estimation \$0·31–1·47 billion). Although, in 2050, the northwest region would have modest health gains—worth \$1·03–4·87 billion (conservatively \$0·33–1·57 billion); compared with the corresponding regional NDC implementation cost, the health gains would still be hard to compete with.

Our research results were all derived from one group of technology options, which minimises the total power generation costs in all regions. This group of technology options has unfortunately resulted in so-called health-loser regions when realising NDC targets. In reality, policy makers might not strictly adhere to technology options that are model suggested and offer the lowest cost; but is there ever a possibility that no region would become a health loser? To answer this question, we assumed that no changes happened to the modelling results in all regions, except the northwest, and added one new constraint to northwest China—no growth in air pollutant emissions in 2030—to the energy model. Therefore, the incremental power generated in northwest China would all be produced by renewable and new energy units, or ultra-low emission coal-fired units, instead of traditional coal-fired units. We found that these scenarios are technically feasible, but the incremental cost in northwest China could reach as high as \$20·78 billion with renewable and new energy units and \$29·54 billion with ultra-low emission coal-fired units. However, the avoided health losses would only be worth about \$0·95–4·54 billion (using the non-conservative mean value). Clearly this scenario would not be a cost-effective choice from an economic perspective. Adaptation measures (which are out of the scope of this research) could be used to alleviate the negative health impacts.

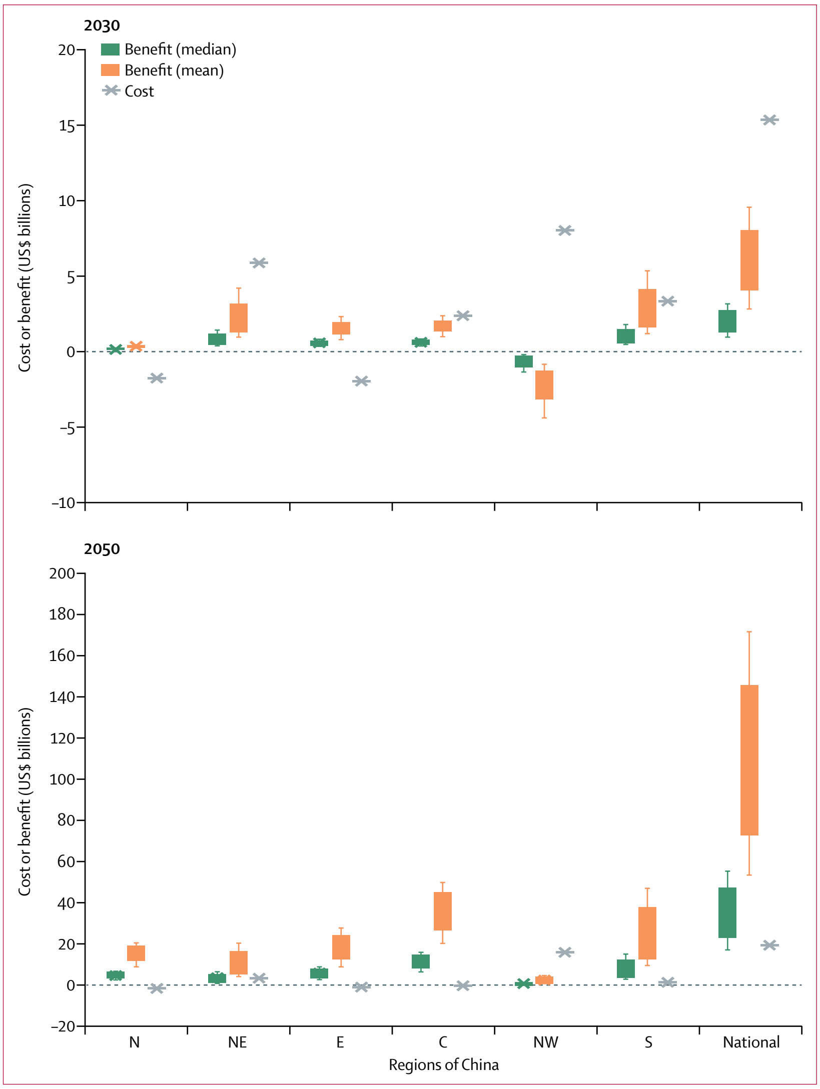

Figure 6: **NDC implementation costs and the monetised health co-benefits under median and mean VSLs in each region and in China for 2030 and 2050**
Vertical line for each region represents discrete health co-benefits uncertainty simulations. The health co-benefits are shown as median (horizontal line), quartiles (box), and 95% CI (vertical line). REF=reference. NDC=nationally determined contributions. VSL=value of a statistical life. N=north. NE=northeast. E=east. C=central. NW=northwest. S=south.

Discussion

The scale of health co-benefits brought by CO_2 emission reduction will be very substantial in China. However, because our study uses a multiregional, bottom-up, technological optimisation model, revealing the spatial distributions of health benefits and, more importantly, health losses becomes feasible and innovative so as to better prepare the government and local people with information and policies. Obviously the health impacts are distributed quite unevenly in China. As a whole, China would achieve both the air quality and human health improvement due to the compliance with NDC targets. The benefit to cost ratio could reach 18–62% in 2030, and the even larger 266–852% in 2050.

In 2030, the top three regions to benefit will be the south, northeast, and centre of China, and the top three provinces to benefit will be Guangdong, Heilongjiang, and Liaoning. In 2050, the top three regions to benefit will be central, southern, and eastern China, and the top three provinces to benefit will be Guangdong again, Sichuan, and Hunan. However, during this period, people in the northwest (especially in Gansu, Shaanxi, Xinjiang, Qinghai, and Tibet) would have to give up their own health benefits to realise the national climate targets. Therefore, it is fair and crucial to have good policy preparation to alleviate and compensate for their losses.

The findings obtained in this study could give direct and quantitative guidance on the making of plans for benefits or losses for reallocation under NDCs. Therefore, they could be used to establish a compensation mechanism for inter-regional interests. Policy makers might also require the simultaneous transfer of advanced pollution control technologies and the related expertise when the electricity produced is transmitted in the opposite direction. Besides, the government could enhance the preparation of medical facilities according to the relevant illnesses caused by air pollution, and could strive to extend personal prevention strategies to defend against air pollution.

Under the current assumption of VSL, we estimate that a large proportion of implementation costs to realise NDC targets could be offset by the health co-benefits. Along with the increasing wealth of Chinese people, and the rising concerns regarding air quality and their own health, the willingness to pay and VSL are expected to increase. So is this share of implementation costs. However, we must be cautious to interpret this result. It is too arbitrary to conclude that as long as the NDC's incremental cost could be offset by health benefits, more aggressive climate policies should be undertaken. Because the health benefit of the co-effects of NDCs is only one dimension, other co-effects might conversely increase the social cost of NDC. For example, Hejazi and colleagues[38] found that mitigation in the USA could increase water stress and therefore adds to implementation cost of NDCs, which was also reported for some other countries by Wan and colleagues.[39] More systematic and comprehensive evaluations on multiple dimensions of co-effects of NDCs need to be done to assess the aggressiveness of the current NDCs and create further guidance on enhancing future NDCs. Haines and colleagues[4] and Nemet and colleagues[12] also advocate for the necessity to fully consider other co-effects, such as health risks from nuclear power generation and carbon capture and storage, crop yields, acid deposition, macroeconomic shocks, fuel poverty, and geopolitical conflicts. Nevertheless, our results still suggest that cost–benefit analysis of climate policy that omits regional air pollution might greatly underestimate benefits, and health impacts should be carefully considered by both the national and regional decision makers in realising intended NDCs and NDCs.

Contributors

WC, CW, and PG designed the study. WC did the literature review and wrote the draft paper. JH, YZ, XZ, and QZ did the modelling and analysis, with contributions from WC, CW, and PG. JH, WC, PG, and CW interpreted the results. All authors commented on the draft and revised version of the paper and approved the submission texts.

Declaration of interests

We declare no competing interests.

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References

1 Costello A, Abbas M, Allen A, et al. Managing the health effects of climate change: *Lancet* and University College London Institute for Global Health Commission. *Lancet* 2009; **373:** 1693–733.

2 Watts N, Adgar WN, Agnolucci P, et al. Health and climate change: policy responses to protect public health. *Lancet* 2015; **386:** 1861–914.

3 CAIT Climate Data Explorer. Paris contributions map. http://cait.wri.org/indc/ (accessed Feb 6, 2018).

4 Haines A, McMichael AJ, Smith KR, et al. Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *Lancet* 2009; **374:** 2104–14.

5 Ekins P. The secondary benefits of CO_2 abatement: how much emission reduction do they justify? *Ecol Econ* 1996; **16:** 13–24.

6 Shindell DT, Lee Y, Faluvegi G. Climate and health impacts of US emissions reductions consistent with 2°C. *Nat Clim Change* 2016; **6:** 503–07.

7 Buonocore JJ, Luckow P, Norris G, et al. Health and climate benefits of different energy-efficiency and renewable energy choices. *Nat Clim Change* 2016; **6:** 100–05.

8 Haines A. Health co-benefits of climate action. *Lancet Planet Health* 2017; **1:** e4–5.

9 Morisetti N, Blackstock JJ. Impact of a changing climate on global stability, wellbeing, and planetary health. *Lancet Planet Health* 2017; **1:** e10–11.

10 Rao S, Klimont Z, Leitao J, et al. A multi-model assessment of the co-benefits of climate mitigation for global air quality. *Environ Res Lett* 2016; **11:** 124013.

11 Chang KM, Hess JJ, Balbus JM, et al. Ancillary health effects of climate mitigation scenarios as drivers of policy uptake: a review of air quality, transportation and diet co-benefits modeling studies. *Environ Res Lett* 2017; **12:** 113001.

12 Nemet GF, Holloway T, Meier P. Implications of incorporating air-quality co-benefits into climate change policymaking. *Environ Res Lett* 2010; **5:** 014007.

13 West JJ, Smith SJ, Silva RA, et al. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. *Nat Clim Change* 2013; **3:** 885–89.

14 Aunan K, Fang J, Vennemo H, Oye K, Seip HM. Co-benefits of climate policy—lessons learned from a study in Shanxi, China. *Energ Policy* 2004; **32:** 567–81.

15 Thompson TM, Rausch S, Saari RK, et al. A systems approach to evaluating the air quality co-benefits of US carbon policies. *Nat Clim Change* 2014; **4:** 917–23.

16 Shih HC, Crawford-Brown D, Ma HW. The influence of spatial resolution on human health risk co-benefit estimates for global climate policy assessment. *J Environ Manage* 2015; **151:** 393–403.

17 Olivier JGJ, Schure KM, Peters JAHW. Trends in global CO_2 emissions: 2017 report. Dec 12, 2017. http://www.pbl.nl/en/publications/trends-in-global-co2-and-total-greenhouse-gas-emissions-2017-report (accessed Feb 7, 2018).

18 ZhiYan Consulting. 2016 China coal consumption analysis. 2016. http://www.chyxx.com/industry/201612/474520.html (accessed Feb 7, 2018; in Chinese).

19 Su S, Zhao J, Hu J. Greenhouse gas emissions from power sector in china from 1990 to 2050. *Adv Clim Chang* 2015, **11:** 353–362 (in Chinese).

20 GBD MAPS Working Group. Burden of disease attributable to coal-burning and other major sources of air pollution in China. Special report 20. Boston, MA: Health Effects Institute, 2016.

21 Watts N, Amann M, Ayeb-Karlsson S, et al. The *Lancet* Countdown on health and climate change: from 25 years of inaction to a global transformation for public health. *Lancet* 2018; **391:** 581–630.

22 NDRC. Enhanced actions on climate change: China's intended nationally determined contributions. 2015. http://www4.unfccc.int/submissions/INDC/Published%20Documents/China/1/China%27s%20INDC%20-%20on%2030%20June%202015.pdf (accessed June 30, 2017; in Chinese).

23 Teng F, Gu A, Yang X, Wang X. Pathways to deep decarbonization in China. 2015. http://www.iddri.org/Publications/CHN_DDPP_report.pdf (accessed June 30, 2017).

24 Spencer T, Pierfederici R. Beyond the numbers: understanding the transformation induced by INDCs. 2015. http://www.iddri.org/Publications/Beyond-the-numbers-Understanding-the-transformation-induced-by-INDCs (accessed June 30, 2017).

25 Hui J, Cai W, Wang C, Ye M. Analyzing the penetration barriers of clean generation technologies in China's power sector using a multi-region optimization model. *Appl Energ* 2017; **185:** 1809–20.

26 Wang C, Ye M, Cai W, Chen J. The value of a clear, long-term climate policy agenda: a case study of china's power sector using a multi-region optimization model. *Appl Energ* 2014; **125:** 276–88.

27 Zhang Q, Streets DG, Carmichael GR, et al. Asian emissions in 2006 for the NASA INTEX-B mission. *Atmos Chem Phys* 2009; **9:** 5131–53.

28 Lei Y, Zhang Q, He K, Streets DG. Primary anthropogenic aerosol emission trends for china, 1990–2005. *Atmos Chem Phys* 2011; **11:** 931–54.

29 Zheng B, Huo H, Zhang Q, et al. High-resolution mapping of vehicle emissions in china in 2008. *Atmos Chem Phys* 2014; **14:** 9787–805.

30 Kappos AD, Bruckmann P, Eikmann T, et al. Health effects of particles in ambient air. *Int J Hyg Envir Heal* 2004; **207:** 399–407.

31 WHO. Health aspects of air pollution with particulate matter, ozone and nitrogen dioxide. 2003. http://www.zukunftsplan-statt-autobahn.de/WAe/Material/Studien/WHO-Health_Aspects_of_Airpollution.pdf (accessed June 30, 2017).

32 Burnett RT, Rd PC, Ezzati M, et al. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. *Environ Heal Persp* 2014; **122:** 397–403.

33 Gao G, Guo X, Huang S. Modern practical health statistics. Suzhou: Suzhou University Press, 2010 (in Chinese).

34 Partridge I, Gamkhar S. A methodology for estimating health benefits of electricity generation using renewable technologies. *Environ Int* 2012; **39:** 103–10.

35 Gao T, Li G, Xu M, et al. Health economic loss evaluation of ambient $PM_{2.5}$ pollution based on willingness to pay. *J Environ Heal* 2015; **32:** 697–700 (in Chinese).

36 Wang Y. Chinese disease surveillance system death surveillance dataset 2010. Beijing: Press of Military Medical, 2011 (in Chinese).

37 Institute for Health Metrics and Evaluation. GBD compare. http://vizhub.healthdata.org/gbd-compare/ (accessed June 30, 2017).

38 Hejazi MI, Voisin N, Liu L, et al. 21st century United States emissions mitigation could increase water stress more than the climate change it is mitigating. *Proc Natl Acad Sci USA* 2015; **112:** 10635–40.

39 Wan L, Wang C, Cai W. Impacts on water consumption of power sector in major emitting economies under INDC and longer term mitigation scenarios: an input-output based hybrid approach. *Appl Energ* 2016; **184:** 26–39.