Incorporating health co-benefits into technology pathways to achieve China's 2060 carbon neutrality goal: a modelling study

Shihui Zhang, Kangxin An, Jin Li, Yuwei Weng, Shaohui Zhang, Shuxiao Wang, Wenjia Cai, Can Wang, Peng Gong

Summary

Background The announcement of China's 2060 carbon neutrality goal has drawn the world's attention to the specific technology pathway needed to achieve this pledge. We aimed to evaluate the health co-benefits of carbon neutrality under different technology pathways, which could help China to achieve the carbon neutrality goal, air quality goal, and Healthy China goal in a synergetic manner that includes health in the decision-making process.

Methods In this modelling study, we used Shared Socioeconomic Pathway 2 with no climate policy as the reference scenario, and two representative carbon neutrality scenarios with identical emission trajectories and different technology pathways—one was led by renewable energies and the other was led by negative emission technologies. We had three modules to analyse health co-benefits and mitigation costs for each policy scenario. First, we used a computable general equilibrium model that captures the operation of the whole economic system to investigate the carbon mitigation costs and air pollutant emission pathways of different technology portfolios. Second, we used a reduced complexity air quality model to estimate the concentrations of particulate matter in the atmosphere from the air pollutant emission pathways. Finally, we used a health impact evaluation model to estimate premature deaths, morbidity, and the resulting loss of life expectancy, then these health impacts were monetised according to value of a statistical life and cost of illness. We compared the monetised health co-benefits against the corresponding mitigation costs to explore the cost-effectiveness of different technology portfolios. A series of uncertainties embodied in carbon neutrality pathways and models were considered.

Findings In our models, sole dependence on improving end-of-pipe air pollution control measures is not sufficient for all Chinese provinces to meet the 2005 WHO $PM_{2·5}$ standards (10 μg/m^3) by 2060. Only a combination of strong climate and air pollution control policies can lead to substantial improvement of air quality across China. If the carbon neutrality pathway led by developing renewable energies was followed, the air quality of all provinces could meet the WHO guideline by 2060. With the realisation of carbon neutrality goals, the total discounted mitigation costs (discount rate 5%) from 2020–60 would range from 40–125 trillion Chinese yuan (CNY), and 22–50 million cumulative premature deaths could be avoided. China has the potential to increase the associated life expectancy by 0·88–2·80 years per person in 2060 versus the reference scenario. The health benefits are higher in the renewable energies-led scenarios, whereas the mitigation costs are smaller in the negative emission technologies-led scenarios. If the value of a statistical life is set higher than 12·5 million CNY (39% of the Organisation for Economic Co-operation and Development value), the health co-benefits will be higher than mitigation costs, even when considering all included uncertainties, implying the cost-effectiveness of China's carbon neutrality goal.

Interpretation The life expectancy increase from the realisation of China's 2060 carbon neutrality goal could be equivalent to the past 5–10 years of life expectancy growth in China. Choosing an appropriate carbon neutrality pathway affects the health of China's population both today and in the future. Our findings suggest that, if China incorporates health co-benefits into climate policy making and puts a high value on people's health, it should choose a carbon neutrality pathway that relies more on developing renewable energies and avoid over-reliance on negative emission technologies.

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For the Chinese translation of the abstract see **Online** for appendix 1

Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science (Shi Zhang PhD, Y Weng BS, W Cai PhD), **State Key Joint Laboratory of Environment Simulation and Pollution Control (SKLESPC), and School of Environment** (Shi Zhang, K An BS, J Li BS, Prof S Wang PhD, Prof C Wang PhD), **and Tsinghua-Rio Tinto Joint Research Centre for Resources, Energy and Sustainable Development, International Joint Laboratory on Low Carbon Clean Energy Innovation, Laboratory for Low Carbon Energy** (Shi Zhang, W Cai, Prof C Wang), **Tsinghua University, Beijing, China; School of Economics and Management, Beihang University, Beijing, China** (Sha Zhang PhD)**; Pollution Management Research Group, Energy, Climate, and Environment Program International Institute for Applied Systems Analysis, Laxenburg, Austria** (Sha Zhang)**; State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing, China** (Prof S Wang)**; Department of Earth Sciences and Department of Geography, The University of Hong Kong, Hong Kong Special Administrative Region, China** (Prof P Gong PhD)

Correspondence to:
Dr Wenjia Cai, Ministry of Education Key Laboratory for Earth System Modeling, Department of Earth System Science, Tsinghua University, Beijing 100084, China
wcai@tsinghua.edu.cn

Introduction

China, the world's largest emitter of carbon dioxide, has made an ambitious pledge to become carbon neutral before 2060, which is the country's first long-term climate goal.[1] As the realisation of the carbon neutrality goal will lead to a fundamental transition in China's energy structure, or even economic structure, its impact on emissions of air pollutants and public health will also be profound and long lasting. Therefore, it is important to evaluate the health implications of the carbon

See **Online** for appendix 2

Research in context

Evidence before this study

We searched Web of Science for articles published in English between Jan 1, 2009, and July 15, 2021, using the keywords "co-benefits" and "air quality". We selected articles by searching the keyword "China" within the topic. Our search returned 180 studies, 28 of which were relevant to this topic. Ten studies with comparable scenario settings and methods to this study are discussed in detail in appendix 2 (pp 40–42). Nearly all previous studies have confirmed a large health co-benefit associated with mitigation actions in China because of the dangerously high air pollution concentrations and high population density. These studies also found that the health co-benefit might completely offset the mitigation costs under certain assumptions. However, these evaluations were based on less ambitious mitigation goals and a restricted number of pathways (such as the 2°C target pathway and nationally determined contributions pathway). To our knowledge, studies simultaneously exploring the public health and economic outcomes of China's carbon neutrality goal, announced in September, 2020, have not been published. Few pathways have been discussed and a series of important questions remain open for systematic investigations.

Added value of this study

To our knowledge, this modelling analysis is the first to assess both the mitigation costs and health co-benefits of China's carbon neutrality goal. Based on an integrated assessment model framework, we quantified the range of mitigation costs and health co-benefits under various carbon neutrality pathways with different technology portfolios and carbon emission trajectories. We considered multiple uncertain factors, such as the level of stringency of air pollution control policies (ie, the requirement to use end-of-pipe air pollution control technologies), baseline incidences of health endpoints, the shape of concentration–response functions, and the value of a statistical life. We found that, as the reliance on negative emission increases, both the mitigation costs and health co-benefits will decrease. We also explored whether it is possible to achieve carbon neutrality in a cost-effective way (with uncertainties) and how to choose an optimal technology pathway when incorporating health into policy making. Finally, we analysed the association between China's carbon neutrality goal and people's life expectancy, which is one of the most commonly used heath policy performance indicators worldwide, especially in China.

Implications of the available evidence

This study contributes to the growing evidence of health co-benefits from deep decarbonisation of the whole socioeconomic system, and identifies the economic and public health outcomes of China's carbon neutrality goal. We found that, by achieving China's carbon neutrality goal, China's life expectancy in 2060 could increase by 0·88–2·80 years per person compared with the reference scenario, which is equal to 5–10 years of China's efforts from the public health sector. Whether the future life expectancy improvement is closer to 0·88 or 2·80 years largely depends on the technology portfolio of the carbon neutrality pathway. We suggest avoiding an over-reliance on negative emission technologies, which leave emission space for fossil fuel combustions and industrial processes in sectors that are hard to mitigate (such as industries, transport, and building sectors), so that the air quality improvement and public health synergy of the carbon neutrality goal can be maximised. China's choice of technology portfolios to realise the carbon neutrality goal will have long-term and profound effects on China's future. Our findings can be used to inform policy makers that it is critical to make smart and careful policy design on carbon neutrality pathways.

neutrality goal, especially in light of the COVID-19 pandemic when governments value the Health in All Policies principle.[2] Choosing an appropriate, or even optimised, technology pathway to realise the carbon neutrality goal could help China to address the multiple challenges of tackling climate change, controlling air pollution, and improving public health, so that the carbon neutrality goal, air quality goal, and Healthy China goal can be achieved in a synergetic manner.

Previous studies have discussed extensively the health co-benefits of China's carbon mitigation efforts through co-reduction of air pollutant emissions. They found that the monetised health co-benefits are usually high enough to outweigh the mitigation costs.[3–7] These studies have focused on the health co-benefits of achieving China's nationally determined contribution (NDC) target or the 2°C target, which is less ambitious compared with the carbon neutrality goal. However, as the ambition of climate policy increases, mitigation costs will grow faster than health co-benefits.[3] Therefore, whether the monetised health co-benefits of the carbon neutrality goal can still cover the mitigation costs remains unclear. To date, most studies have evaluated the health effects of a small number of mitigation scenarios, which is incapable of tracking the dynamically changing relationship between mitigation costs and health co-benefits. As China is at a critical point in deciding which technology pathway to follow towards its carbon neutrality goal, policy makers should consider in full the combination of different emission trajectories (ie, the cumulative emission budget and shape of emission pathways) and technology pathways,[8] and to incorporate health impacts into the technology pathway design.[9] Finally, traditional health co-benefits studies used indicators like avoided premature deaths to quantify the public health co-benefits of climate actions, which might not be straightforward for policy makers and the public to understand the scale of the health co-benefits. Life expectancy is a key policy concern for every country in the world,[10] especially in China given that it is one of the major indicators in Healthy China goals.[11] Therefore, translating the health outcomes of carbon neutrality goals into life expectancy could better inform policy making.

The *Lancet* Countdown: Health and Climate Change in Asia brings together partners from 19 institutions from a wide range of disciplines. The 2020 China report of the *Lancet* Countdown on health and climate change works towards building an understanding of the response to the changing health profile of climate change in the region.[12] Here, we present a case study of the *Lancet* Countdown.[13] China is at a critical moment in formulating the 14th Five-Year Plan, the 2030 Carbon Peak Plan, and the 2060 carbon neutrality plan. We aimed to incorporate health co-benefits into the technology pathways to achieve China's carbon neutrality goal and to explore whether there is any suggested technology pathway that can help to achieve the carbon neutrality goal, air quality goal, and Healthy China goal in a synergetic manner. Specifically, we aimed to answer three questions. Under different combinations of emission trajectories and technology pathways, how would mitigation costs and health co-benefits dynamically change? What would be the optimal technology pathway for China to achieve the carbon neutrality goal while maximising the synergy with the air quality goal and Healthy China goal in a cost-effective manner? How would the realisation of China's carbon neutrality goal affect people's life expectancy?

Methods

Modelling framework

The modelling framework of this study consists of three modules similar to other integrated assessment models,[3,14–16] and details can be found in appendix 2 (pp 4–30).

First, we used a macroeconomic model with technology details, the China Hybrid Energy and Economic Research (CHEER) with low-carbon technology model (known as CHEER-LCT), to quantify the economic-wide mitigation costs and air pollutant emissions of different technology pathways under different carbon neutrality emission trajectories. CHEER-LCT is a dynamic computable general equilibrium model[17] with detailed description on low-carbon technologies. Eight kinds of power generation technologies are considered, including coal, gas, oil, hydro, wind, solar, nuclear, and biomass.[18,19] Three types of negative emission technology (NET) are considered, including land use, land-use change, and forestry, direct air capture, and carbon capture and storage (including for both conventional fossil fuels and for bioenergy).[20–23] Second, we used the air pollutant emission pathway as the input for a reduced complexity chemical transportation model (known as CHEER-AIR),[24,25] which is available at the province level, and we transformed the emissions[26] into particulate matter concentration in the atmosphere. Third, we used the health impacts assessment model (known as CHEER-HA), which has detailed population age structure that estimates the number and economic value of health impacts caused by exposure to $PM_{2\cdot5}$. Nine health endpoints related to $PM_{2\cdot5}$ exposures are covered, including premature mortality due to chronic exposure caused by chronic obstructive pulmonary disease, ischaemic heart disease, stroke, and lung cancer, as well as hospital admission due to respiratory disease, hospital admission due to cardiovascular and cerebrovascular disease, emergency room visits, bronchitis, and premature deaths from acute exposure. We calculated the health damage of the air pollutant concentration through concentration-response functions[27] and monetised the damage through two parameters: value of a statistical life (VSL) and cost of illness. We translated the premature deaths of different age groups into loss of life expectancy through life expectancy distributions by age.[28]

	Current legislation	Maximum feasible reduction
Reference scenario with no carbon emission constraints	Reference–CLE	Reference–MFR
Nationally determined contributions	NDC–CLE	NDC–MFR
Carbon neutrality goal		
Led by renewable energies	RE–CLE	RE–MFR
Led by negative emission technologies	NET–CLE	NET–MFR

Carbon mitigation targets are given in rows, air pollution control measures are given in columns. NDC=nationally determined contributions. CLE=current legislation. MFR=maximum feasible reduction. RE=carbon neutrality pathways led by renewable energies. NET=carbon neutrality pathways led by negative emission technologies.

***Table:* Scenario definitions for stringency levels of carbon mitigation targets versus air pollution control measures**

The time horizon of this modelling study is 2020–60. In addition to uncertainties caused by emission trajectories and technology portfolios, we also considered the uncertainties embodied in the models, including the air pollutant emission factors, the VSL, the four shape parameters of the concentration-response functions, and baseline incidences of four premature death endpoints.

Scenarios

We established scenarios from two dimensions (table): the stringency levels of carbon mitigation targets and the stringency levels of air pollution control measures. All these scenarios share the same socioeconomic development narrative, Shared Socioeconomic Pathway 2 (SSP2), which is an intermediate development framework that is widely used as a reference scenario for future projections.[29,30]

In the carbon mitigation target dimension, we modelled four representative scenarios with different carbon emission trajectories (figure 1A). Details about the emission trajectories can be found in appendix 2 (p 1). The first two are the reference (ie, no climate policy) scenario and the NDC scenario. We also modelled two representative carbon neutrality scenarios that share

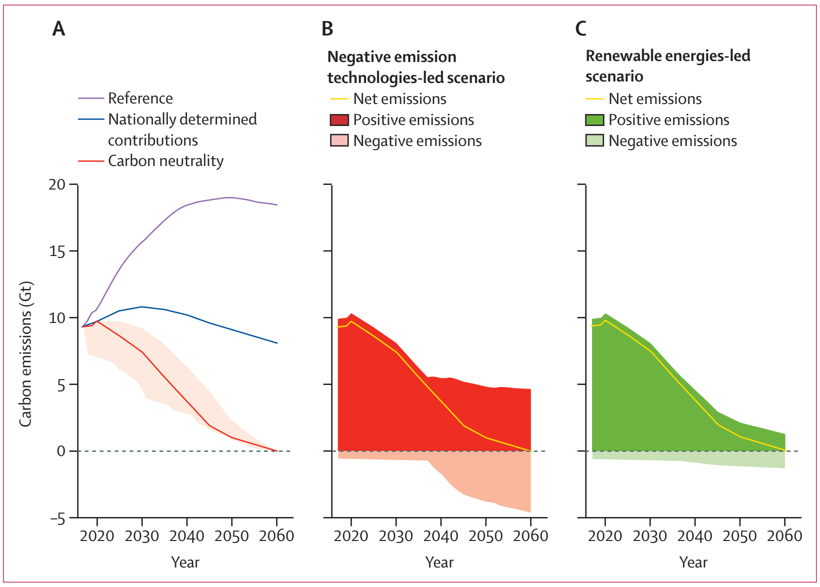

Figure 1: **Carbon emission trajectories of all scenarios**

(A) Net carbon emission trajectories of all scenarios. The orange line represents a representative carbon neutrality emission trajectory. The orange shadow represents other possible carbon neutrality emission trajectories (95% CI). The positive and negative emissions of two representative carbon neutrality scenarios led by either negative emission technologies (B) or renewable energies (C). The net emissions in panel B and C are the same as the orange line in panel A. There are emissions absorbed by land use, land-use change, and forestry in all scenarios.

the same net emission trajectory. The negative emissions provided by negative emission technologies, such as bioenergy carbon capture and storage, are generally regarded as an essential step to achieving the carbon neutrality goal; therefore, we designed the NET-led scenario to explore the maximum usage of negative emission technologies under constraints of resources and technology costs (figure 1B). However, air pollutants emitted from biofuels will become a threat for public health,[9] even though it is assumed that all bioenergy carbon capture and storage plants and other carbon capture and storage plants install end-of-pipe emission control devices. The use of negative emission technologies will also leave space for co-emitted air pollutants from fossil fuel combustions in industry, transport, and household sectors.

We designed an RE-led scenario in which the negative emission technologies are replaced by renewable and low carbon energies as much as possible, although a certain amount of negative emissions are preserved (figure 1C). We also considered various technology pathways wherein the share of renewable energies and negative emission technologies fluctuates between the RE-led scenario and the NET-led scenario, to investigate how the mitigation costs and health co-benefits change dynamically when choosing different technology portfolios.

In the air pollution control dimension, we considered two scenarios that project the future level of end-of-pipe control to capture the uncertainties caused by air pollutant emission factors. The current air pollution legislation (CLE) scenario represents the air pollutants reduction level to achieve the Beautiful China goal by 2035, which requires enhancing air pollution control measures to meet the national ambient air quality standards target of 35 μg/m³.[31] The maximum feasible reduction (MFR) scenario requires using the best available technologies to meet the WHO Interim-3 standard of 15 μg/m³ by 2050.[31] The calibration process of the SO_2, NO_x, $PM_{2.5}$, and NH_3 emission factors in the CLE and MFR scenarios can be found in appendix 2 (pp 6–7).

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Achieving the carbon neutrality goal would bring about profound change in China's energy structure and sectoral emission distributions. Overall, the major carbon reductions are contributed by improved energy efficiency, electrification, and deployment of renewable energies (figure 2A). Emissions offset by negative emissions in 2020–60 are 4% (23 Gt) in the RE-led scenario and 15% (77 Gt) in the NET-led scenario (figure 2B). The cumulative primary energy consumption from 2020 to 2060 in RE-led and NET-led scenarios would be 33–40% (945–1150 Gtce) lower than the reference scenario (figure 2C). The respective shares of non-fossil fuels in the primary energy structure would be 7% in the reference scenario and 43% in the NDCs scenario in 2060; however, the shares would reach as high as 63% in NET-led scenarios and 86% in RE-led scenarios (figure 2C). Solar and wind energy would take up the biggest share of non-fossil fuel energy. Fossil fuels should be almost phased out of the power generation sector by 2060 in all carbon neutrality scenarios (figure 2C). In 2060, electric power generated by biomass with carbon capture and storage would account for 11% (1294 Twh) of total power generation in the NET-led scenario, whereas this ratio would only be 5% (687 Twh) in the RE-led scenario (figure 2C). In the RE-led scenario, the emissions from industry sectors such as cement, steel, and transport are mainly reduced through electrification, while they are mainly offset by carbon capture and storage of fossil fuels and bioenergy in the power sector in the NET-led scenario (figure 2B–C).

To achieve China's carbon neutrality goal, the cumulative emissions would reduce by 66–79% (477–577 Gt) from 2020 to 2060, and the total cumulative discounted gross domestic product loss compared with the reference scenario is 40–125 trillion CNY (a 5% discount rate) with varied emission trajectories and technology portfolios. The total costs of achieving the carbon neutrality goal is 2·46–7·67 times the costs of achieving the NDCs target (priced at 16 trillion CNY), which requires a fundamental improvement of energy structure, production efficiency, and consumer behaviours. Mitigation costs are mainly

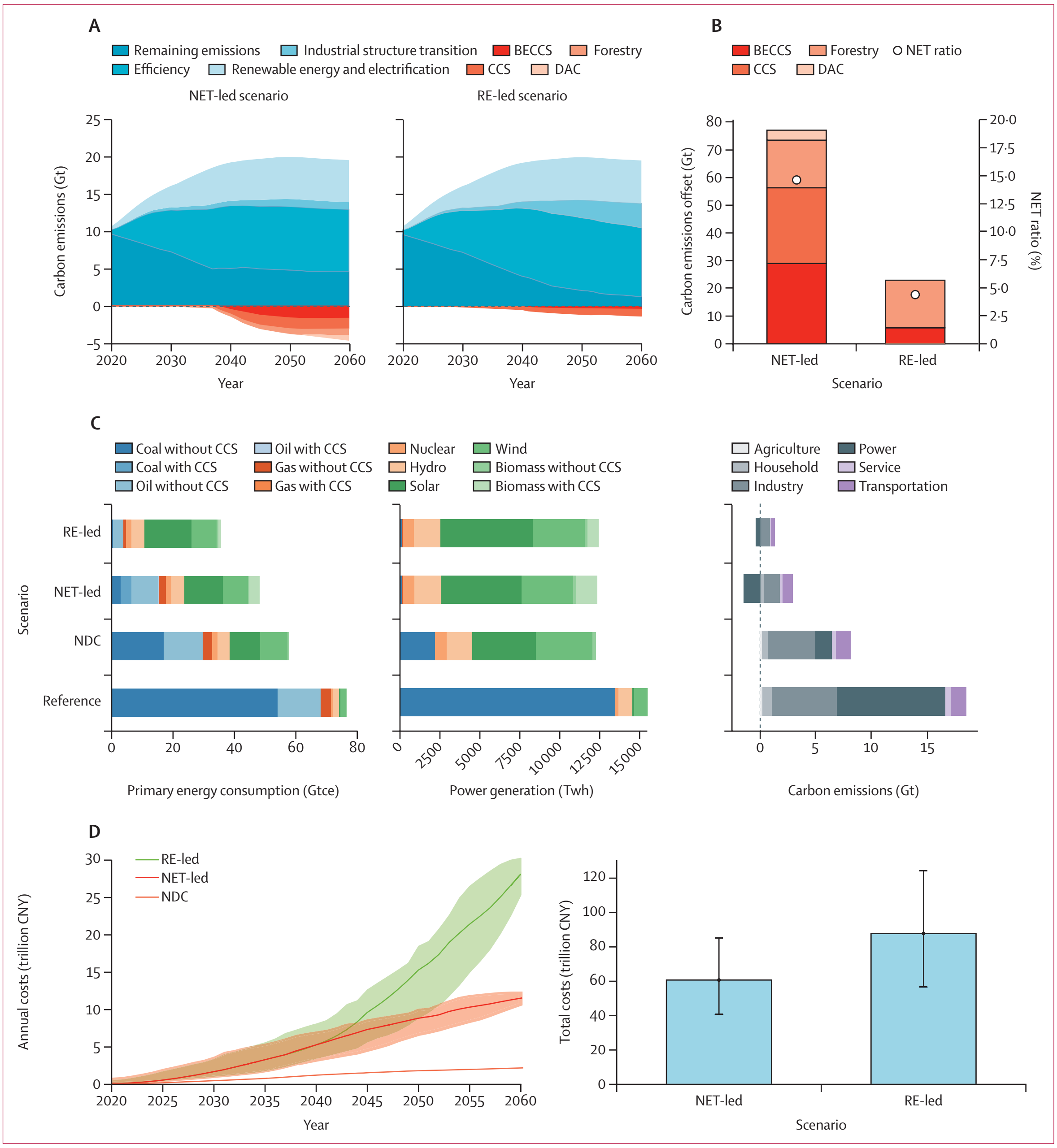

Figure 2: **A roadmap and costs for China to achieve carbon neutrality**

(A) Sources of mitigation in the NET-led scenario and the RE-led scenario from 2020–60. (B) Total contribution of negative emission technologies from 2020 to 2060. (C) Primary energy consumption structure, power generation mix, and sectoral carbon emissions of different scenarios in 2060 in China. (D) Annual mitigation costs and total discounted mitigation costs from 2020 to 2060 of different policy scenarios, with a discount rate of 5%. Mitigation costs for each scenario are quantified as the gross domestic product loss compared with that of the reference scenario. Shadows and error bars represent the 95% CI caused by emission trajectories. NET ratio=the share of emissions offset by negative emission technologies in total carbon mitigations from 2020 to 2060. BECCS=bioenergy carbon capture and storage. CCS=carbon capture and storage. DAC=direct air capture. NDC=nationally determined contributions. RE-led=carbon neutrality pathways led by renewable energies. NET-led= carbon neutrality pathways led by negative emission technologies.

affected by technology portfolio and emission trajectories, where costs will decrease as more negative emission technologies are deployed and carbon budgets are higher. In the scenarios with identical technology portfolio and different emission trajectories, the variation of cumulative mitigation costs versus the scenarios with representative emission trajectory can be up to 35–40%. Meanwhile, the cumulative mitigation cost of NET-led scenario is about 31% lower than that of the RE-led scenario (88 [56–125] trillion CNY *vs* 61 [40–85] trillion CNY; figure 2D). The mitigation costs of the two representative carbon neutrality scenarios are the same between 2020–38 and start to

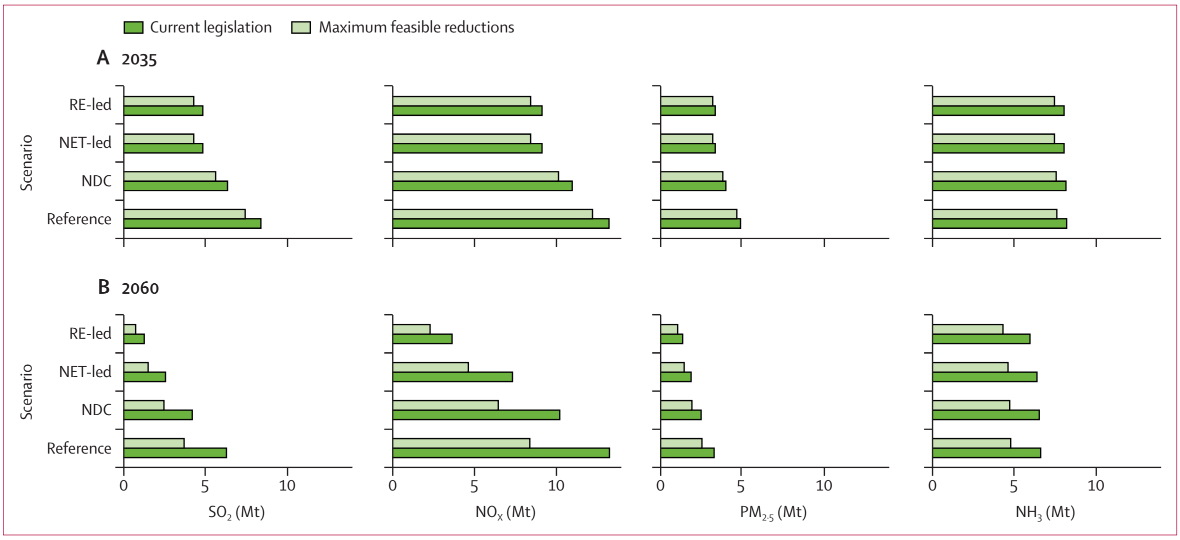

Figure 3: **Air pollutant emissions in 2035 (A) and 2060 (B) under different climate target and air pollution control scenarios**
NDC=nationally determined contributions. NET-led=carbon neutrality pathways led by negative emission technologies. RE-led=carbon neutrality pathways led by renewable energies. SO_2=sulphur dioxide. NO_X=nitrogen oxides. NH_3=ammonia. $PM_{2.5}$=fine particulate matter.

diverge after that because negative emission technologies start to enter the market from 2038 (figure 2D), which alleviates the pressure for industry and transportation sectors to decarbonise through electrification.

Owing to the low-carbon energy transition required to achieve the carbon neutrality goal, the air pollutant emissions in China also decrease dramatically. The SO_2, NO_X, $PM_{2.5}$, and NH_3 emissions of carbon neutrality scenarios in 2060 reduce by 59–79%, 45–72%, 43–59%, and 3–10%, respectively, compared with the reference scenario, considering the varying technology pathways and stringencies of air pollution control (figure 3). In both the RE-led and NET-led scenarios, the air pollutants emission from power generation in 2060 are almost zero due to the phase-out of fossil fuels. However, there are still notable NO_X emissions from industry sectors (mainly cement and steel), transportation sectors (such as air, freight, and passenger transport), households (eg, gas or biomass boilers), and NH_3 emissions from the agriculture sector, which has become a major source of secondary $PM_{2.5}$.

Figure 4 shows the $PM_{2.5}$ concentrations in 2035 and in 2060 under different climate target and air pollution control scenarios. Despite the non-negligible contribution of improvements in end-of-pipe control measures, sole dependence on them cannot help all Chinese provinces meet the 2005 WHO guideline standards of 10 µg/m^3 (subfigures of NDC–MFR in 2060). In the short term (until 2035), the combinations of strong climate and air pollution control policies could lead to substantial improvement of air quality across China. The respective population-weighted national mean $PM_{2.5}$ concentrations are 26·31 µg/m^3 in the reference-MFR scenario and 18·70 µg/m^3 in the RE-MFR and NET-MFR scenarios in 2035 (appendix 2 p 37). Because the structural difference between the NET-led and RE-led scenarios only emerges after 2038, the air quality under two carbon neutrality scenarios do not differ in 2035. In the long term (until 2060), national average $PM_{2.5}$ concentrations are 6·10 µg/m^3 in the RE-MFR scenario and 9·57 µg/m^3 in the NET-MFR scenario, marking a great improvement caused by carbon neutrality goals and stringent air pollutant control measures. However, not all provinces are able to meet the WHO guideline standard in the NET-MFR scenario. The number of provinces that could meet the WHO guideline standard in 2060 is 5, 9, 19, and 30 in the reference-MFR, NDC-MFR, NET-MFR, and RE-MFR scenarios, respectively. This finding indicates that even with the most stringent air pollution control measures, the reliance on negative emission technologies (subfigures of NET-MFR) is not enough for all provinces to meet the 10 µg/m^3 standard. By contrast, the air quality of all provinces in the carbon neutrality pathway led by developing renewable energies will meet the WHO guideline (10 µg/m^3) from 2059. Hence, only with the full development of renewable energies can every province in China meet the WHO air quality guideline standards through carbon neutrality goal.

The cumulative premature deaths avoided from 2020–60 would be 27 (22–36) million in the NET-led scenario and 37 (29–50) million in the RE-led scenario, accounting for 31–34% and 42–46% of premature deaths in the reference scenario, respectively (appendix 2 p 38). The 95% CI considers the uncertainties caused by emission trajectories, stringencies of air pollution control, and parameters in the CHEER-HA model. The detailed number of premature deaths for each scenario and health damages from acute exposures can be found in appendix 2 (pp 38–39). As life expectancy is a major health policy goal, the loss of life expectancy per person due to $PM_{2.5}$ exposures in each scenario is also quantified

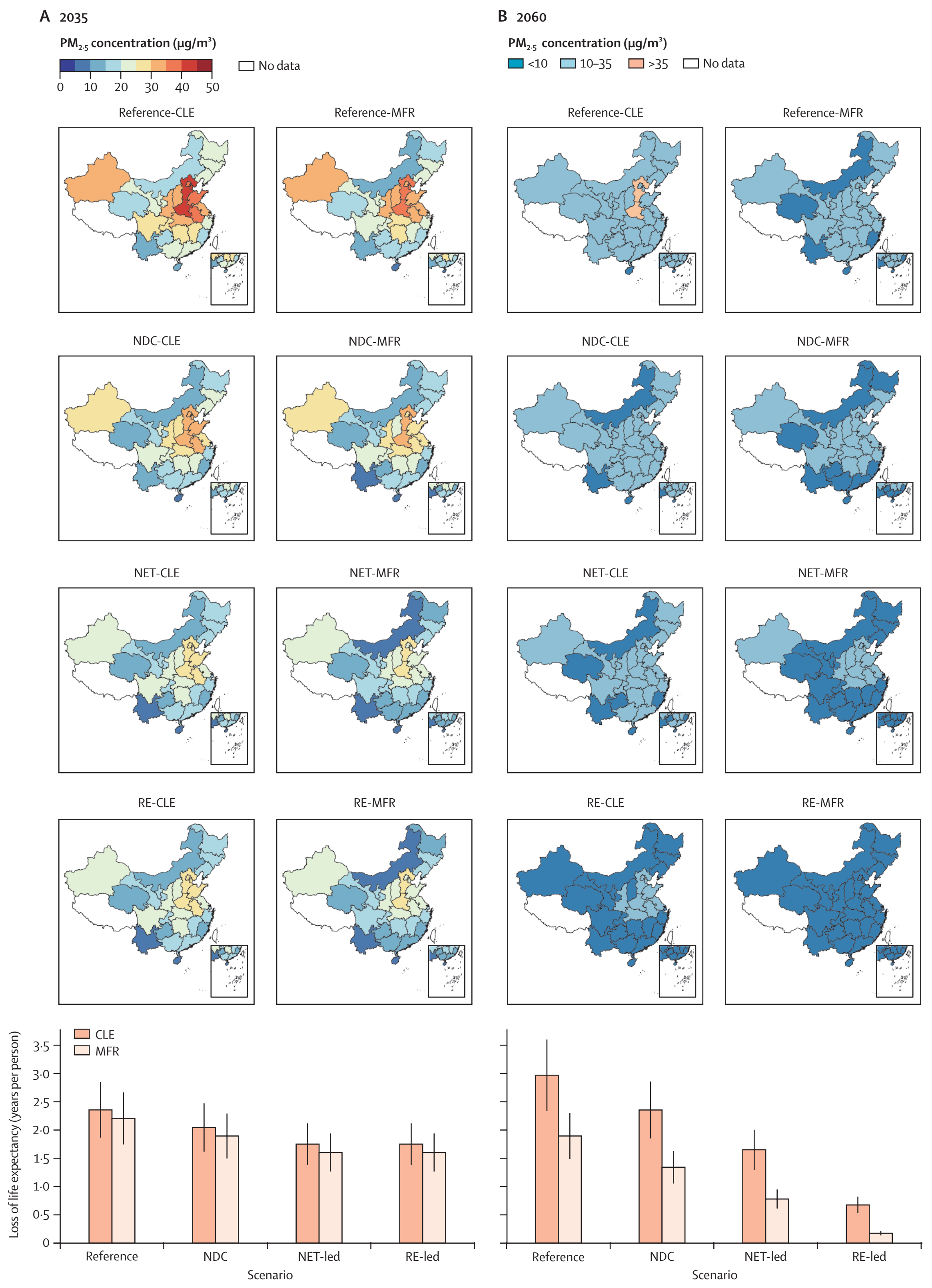

***Figure 4:* Population-weighted $PM_{2·5}$ concentrations and life expectancy loss in 2035 (A) and 2060 (B) under different climate target and air pollution control scenarios**

China's national air quality standard is 35 μg/m³. The 2005 WHO guideline standard is 10 μg/m³. The error bars represent uncertainties caused by the concentration-response function parameter, baseline incidence of health endpoints, and the emission trajectory. South China Sea islands are inset. NDC=nationally determined contributions. RE-led=carbon neutrality pathways led by renewable energies. NET-led=carbon neutrality pathways led by negative emission technologies. CLE=current air pollution legislation. MFR=maximum feasible reductions.

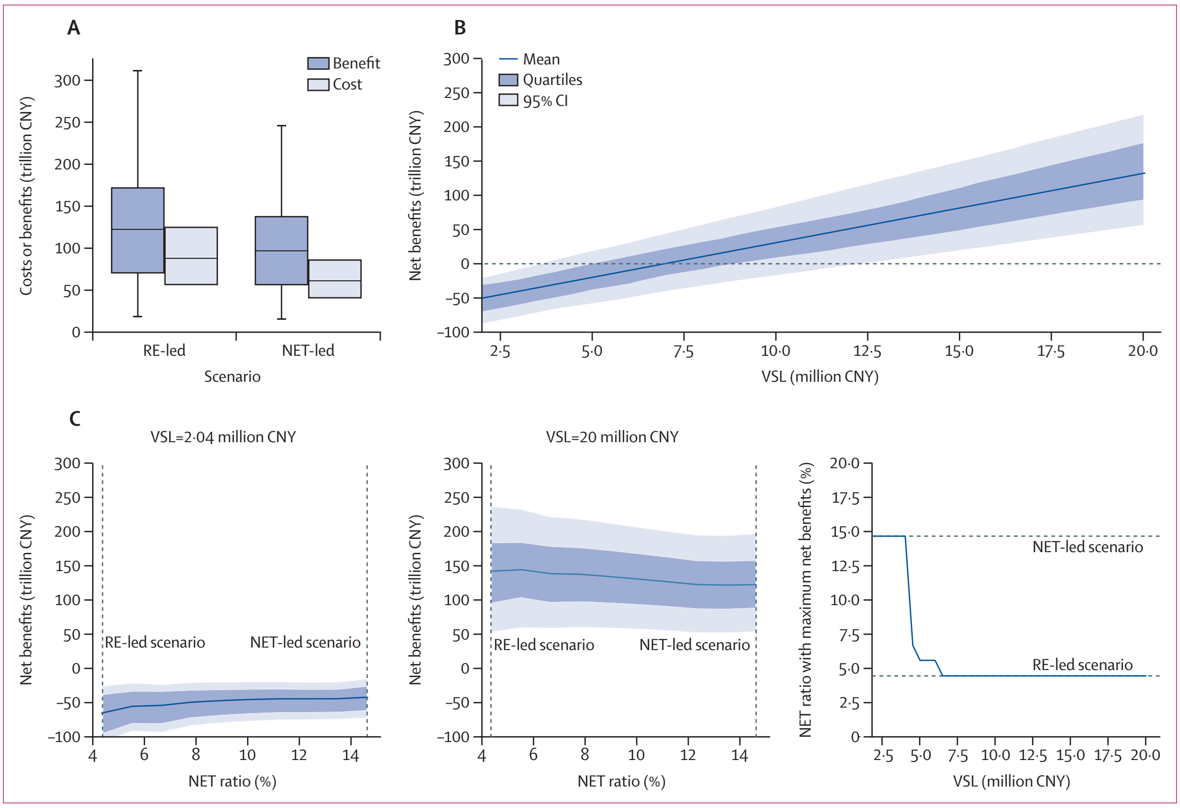

Figure 5: **Co-benefits versus mitigation costs**

(A) The monetised co-benefits and mitigation costs of the RE-led scenario and the NET-led scenario considering all sources of uncertainties, except for technology portfolios in this study (emission trajectories, air pollutants emission factors, the value of VSL, the four shape parameters of the concentration-response functions, and baseline incidences of four premature death endpoints). The health co-benefits and mitigation costs are shown as median (horizontal line), quartile (box), and 95% CI (vertical line). (B) The net benefits of carbon neutrality pathways with respect to VSLs, considering uncertainties caused by emission trajectories, technology portfolios (NET ratios), air pollutants emission factors, the four shape parameters of the concentration-response functions, and baseline incidences of four premature death endpoints. (C) The impacts of VSL on optimal technology portfolios, considering all other sources of uncertainties in this study, including emission trajectories, air pollutant emission factors, the four shape parameters of the concentration-response functions, and baseline incidences of four premature death endpoints. How net benefits change when NET ratios increase are shown for low or high VSL values, along with the NET ratio with maximum net benefits when VSL value changes. NET-led=carbon neutrality pathways led by negative emission technologies. NET ratio=the share of total emissions offset by negative emission technologies in total carbon mitigations from 2020 to 2060. RE-led=carbon neutrality pathways led by renewable energies. VSL=value of a statistical life.

(appendix 2 p 38). In the reference scenario with no climate policy, the loss of life expectancy per person due to $PM_{2\cdot5}$ exposure in 2060 is 2·97 (2·34–3·59) years in the reference–CLE and 1·89 (1·49–2·27) years in reference–MFR scenario, considering the uncertainties in CHEER-HA models and emission trajectories (figure 4). In the carbon neutrality scenarios, the loss of life expectancy decreases by the lowest 0·88 (the lowest estimation in NET-MFR) to the highest 2·80 (the highest estimation in the RE-CLE) years per person in 2060 compared with the reference scenarios, which is almost equivalent to China's 5–10 years (2005–15 or 2010–15) of past achievements in life expectancy growth.[32] The public health gain by switching from NET-led pathway to RE-led pathway (0·47–1·19 years) is even larger than switching from the NDC scenario to carbon neutrality scenario (0·44–0·85 years), which again shows the significance of choosing an appropriate carbon neutrality pathway to optimal public health.

We monetised the health co-benefits and compared them with the mitigation costs for the RE-led and NET-led scenarios (figure 5A). Both the health co-benefits and mitigation costs are smaller in the NET-led scenario. Similarly, as the share of emissions offset by negative emission technologies in total carbon mitigations (NET ratio) increases, both the health co-benefits and mitigation costs will decrease (appendix 2 p 39). Hence, it is not possible to conclude whether relying on renewable energies or negative emission technology is a truly better pathway.

Many factors would influence the comparison results (appendix 2 pp 30–31), including the emission trajectories, the technology pathways, shapes of concentration-response functions, the baseline incidence rates of health endpoints, use of end-of-pipe air pollution control measures, and the VSL. Uncertainties of health co-benefits are larger than those of mitigation costs, mainly due to large range of VSL we choose (2·04–20 million CNY). As VSL increases, the possibility of net benefits being positive increases, as does the value of net benefits. When VSL is higher than 12·5 million CNY (39% of the Organisation for Economic Co-operation and Development value[33]), even if we consider all sources of uncertainties in this study, the lower bound of net benefits will be higher than zero (figure 5B). This result implied that it is possible to achieve carbon neutrality in a cost-effective way.

To analyse how the change of VSL affects the choice of an optimal technology portfolio, we analysed how net benefits change with varying NET ratios given different levels of VSL, and then calculated the optimal NET ratio with the maximum net benefits according to different VSL values (figure 5C). When VSL is low enough, the decrease of monetised health co-benefits is smaller than the decrease of mitigation costs as NET ratio increases and the net benefits will increase, hence making the NET-led pathway the optimal pathway with maximum net benefits. However, when VSL is high enough, net benefits will decrease as NET ratio increases, hence making the RE-led pathway the optimal pathway. Specifically, when VSL is higher than 6·2 million CNY, the RE-led pathway is the optimal pathway; when VSL is smaller than 3·9 million CNY, the NET-led pathway is the optimal pathway. When VSL is 3·9–6·2 million CNY, the optimal NET ratio gradually decreases from 14% to 5%. To summarise, our analysis on optimal NET ratio showed that, if the focus is on health co-benefits, a carbon neutrality pathway with more renewable energies is preferable.

Discussions

Achieving China's carbon neutrality goal in 2060 will have profound and long-lasting effects for the Chinese economy and public health and even globally.[34] Our modelling analysis showed that, by deep decarbonisation of the energy structure and the whole economy, China could achieve carbon neutrality with avoidance of 22–50 million premature deaths for 2020–60, hence avoiding life expectancy loss by 0·88–2·80 years per person in 2060. Under the more stringent end-of-pipe air pollution control scenarios (ie, the MFR scenarios), the air quality of all provinces in the carbon neutrality pathway led by developing renewable energies will meet the WHO guideline (10 μg/m^3) from 2059. The total mitigation costs for 2020–60 are 40–125 trillion CNY (discount rate 5%), varying mainly due to the choice of technology pathways and emission trajectories. If China decides to strongly promote renewables and electrifications rather than relying on negative emission technologies to offset carbon emissions as much as possible, the health co-benefits will be higher due to the co-emitted air pollutants avoided, with an increase in mitigation costs at the same time. However, if the VSL is higher than 12·5 million CNY (39% of the Organisation for Economic Co-operation and Development value), the monetised health co-benefits will cover the mitigation costs, and the carbon neutrality pathway will be cost-effective even when considering all uncertainties we have discussed.

Our study has several limitations. First, although we have taken uncertainties from various sources into our studies, it is unfeasible to fully explore the uncertainties from every section of our studies due to long chain of our models (eg, the parameter uncertainties of computable general equilibrium model [ie, CHEER-LCT] and air quality model). However, we have taken the most sensitive parameters into account. Second, we only included health damages related to $PM_{2·5}$ concentrations, neglecting the impacts caused by other pollutants (such as ozone). Third, despite some moral and ethical concerns regarding monetising of the premature deaths based on a gross domestic product-based value,[35] we chose not to analyse this ethical issue and instead used VSL as a signal to imply the significance of health perspective in policy making. Finally, although the air pollutant control costs are not considered in our model, the technical costs of end-of-pipe control measures are generally small compared with the transition costs of deep decarbonisation, hence our conclusions are not likely to be jeopardised.

In summary, the findings of our modelling analysis highlight the significance of understanding the economic and public health outcomes of different carbon neutrality pathways. For policy makers in China—especially at this critical moment of low carbon transition, recovery from the COVID-19 pandemic, and formulation of the 14th Five Year Plan, the 2030 Carbon Peak Plan, and the 2060 carbon neutrality plan—it is important to carefully and smartly design the optimal carbon neutrality pathway according to its long-term effects on the economy and public health. Taking health co-benefits into account suggests that a carbon neutrality pathway is best, which avoids over-reliance on negative emission technologies to offset carbon emissions. This approach will compress the space to the minimum for fossil fuel combustion and other co-emission sources. Developing renewable energies and promoting electrification in transport, household, and industry sectors will maximise the synergy between the carbon neutrality goal, air quality goal, and Healthy China goal.

Contributors

All authors contributed to the study design. ShiZ and KA did the literature review and data collection, with contributions from JL, YW, SW, and ShaZ. ShiZ and KA did the modelling, with contributions from JL, YW, ShaZ, WC, CW, and PG. ShiZ, KA, WC, CW, and PG analysed and interpreted the results. ShiZ, WC, and KA accessed and verified the underlying data and wrote the first drafts of the manuscript. All authors had full access to all the data in the study and finalised the manuscript for submission according to comments from authors and reviewers. WC had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Detailed data and results can be found in appendix 2 (pp 31–40). The sources of data are listed in appendix 2 (pp 31–33). More data can be provided upon request to the corresponding authors.

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