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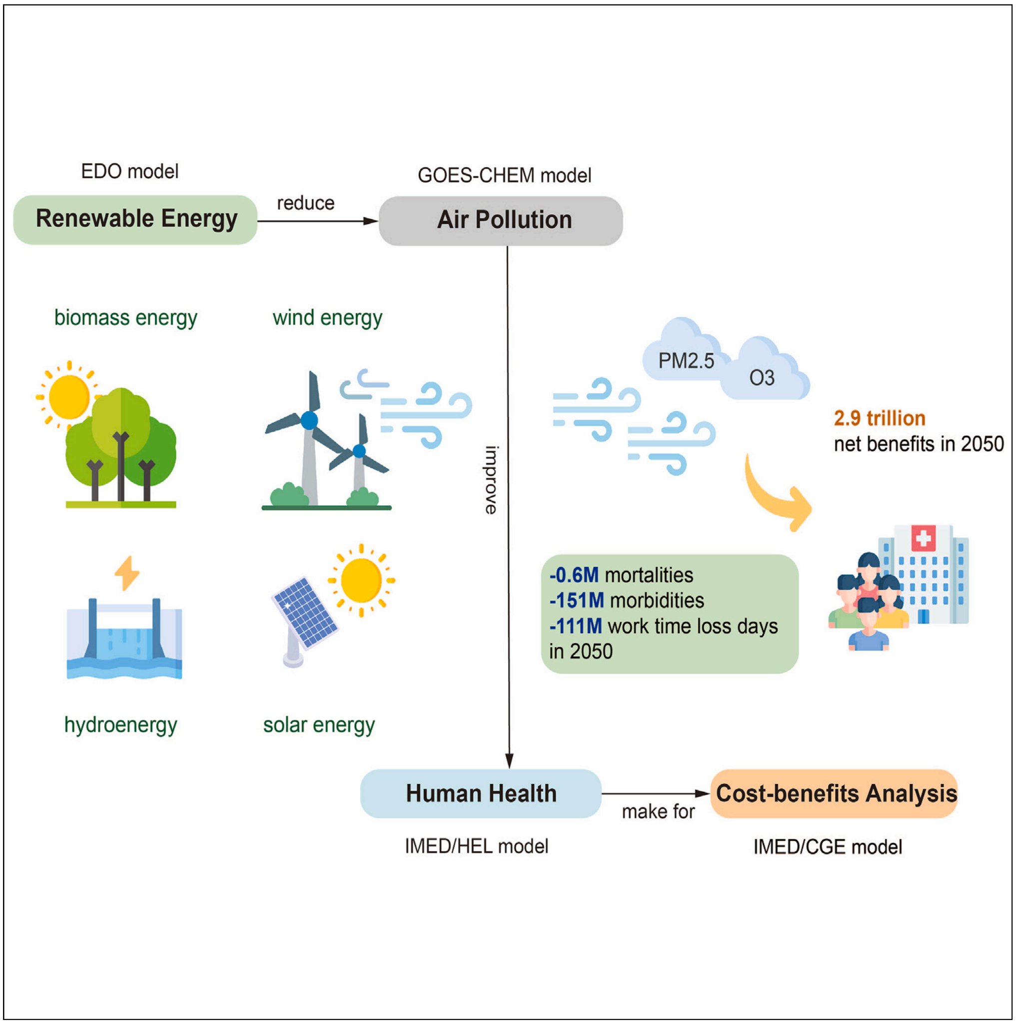

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Highlights

Developing renewable energy in China will improve air quality

Developing renewable energy can avoid air pollution-related premature deaths

Health co-benefits from deploying renewable energy in China are regionally heterogeneous

Economic benefits of renewable energy lag behind the high initial investment cost

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Large-scale renewable energy brings regionally disproportional air quality and health co-benefits in China

Yang Xie,[1,2] Meng Xu,[3] Jinlu Pu,[1] Yujie Pan,[4] Xiaorui Liu,[4] Yanxu Zhang,[5] and Shasha Xu[4,6,*]

SUMMARY

Developing renewable energy could jointly reduce air pollution, greenhouse gas emissions, and bring air pollution-related health co-benefits. However, the temporal and sub-national distributions of investment costs and human health co-benefits from renewable energy deployment remain unclear. To investigate this gap, we linked multiple models for a more comprehensive assessment of the economic-environmental-health co-benefits of renewable energy development in China. The results show that developing renewable energy can avoid 0.6 million premature mortalities, 151 million morbidities, and 111 million work-loss days in 2050. Meanwhile, the human health and economic co-benefits vary substantially across regions in China. Renewable energy can undoubtedly bring health and economic co-benefits. Nevertheless, the economic benefits lag considerably behind the high initial investment cost, first negative in 2030 (−0.6 trillion Yuan) and then positive in 2050 (2.9 trillion Yuan). Hence, renewable energy deployment strategy must be carefully designed considering the regional disparities.

INTRODUCTION

China is a leading country with the highest installed capacity of renewable energy worldwide.[1,2] Meanwhile, it faces serious air pollution, which leads to severe health impacts and economic burdens, especially in developed and populated regions.[3,4] While the power sector consumes much fossil fuels,[5] renewable energy provides a promising solution to jointly reduce fossil fuel combustion-related greenhouse gas emissions and bring air quality benefits,[6,7] thus simultaneously achieving air quality improvement in the short and medium terms and carbon neutrality in the long term.[8,9] For instance, Bloch et al. (2015) found that shifting from coal and oil to renewable energy could improve economic and environmental sustainability.[10] Therefore, national and provincial policymakers in China have shown strong interest in transitioning energy consumption toward renewable energy sources,[11] with the power sector playing a central role.[12]

Exposure to $PM_{2.5}$ and O_3 is associated with morbidity and premature human mortality,[13–15] e.g., premature deaths from cardiovascular and respiratory disease and lung cancer as revealed in epidemiological studies.[16] Previous studies have quantified future air quality changes and their effects on human health under projected emission scenarios at global and regional scales.[5,17–19] Studies quantifying the impacts of 2°C mitigation pathways on air pollution and health conclude that health co-benefits are substantial in terms of decreased exposure levels and premature mortality. In addition to significant health benefits, there are also economic gains and cost savings from improving air quality related to reduced mortality, morbidity, work time loss,[20–22] lower medical costs, and carbon saving.[19,23] For example, Markandya et al. (2018) found that the extra effort of pursuing the 1.5°C target instead of the 2°C target would generate a substantial net benefit of 0.27–2.31 trillion USD in China.[20]

Previous studies have extensively discussed the health co-benefits of China's carbon mitigation efforts through the co-reduction of air pollutant emissions.[24–26] A broad consensus is that more stringent alternative energy targets in China are worth the investment from the perspective of health co-benefits.[27] However, the temporal and sub-national distributions of investment costs and human health co-benefits from renewable energy deployment remain unclear. Here, we construct two renewable energy scenarios to better characterize the investment costs and socioeconomic benefits of developing renewable energy at the provincial level in China.

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Table 1. Minimum renewable energy portfolio modeling requirements in the power sector under two scenarios

	Scenario			
	Stated Policy		Below 2°C	
Source	2030	2050	2030	2050
Wind	11%	16%	15%	22%
Solar	7%	10%	11%	15%
Hydropower	17%	17%	18%	18%
Biomass	1%	2%	1%	2%
Renewable energy in the power sector	51%	78%	68%	85%

RESULTS

We construct two scenarios of Stated Policy and Below 2°C scenarios with different renewable energy ratios in China. **Stated Policy scenario:** This scenario assumes full and firm implementation of the energy sector and related policies, including the national fossil fuel consumption trends. The carbon emission constraint is set based on China's current carbon emission intensity target: a reduction of 40%–45% and 60%–65% in carbon intensity by 2020 and 2030, respectively. Compared with 2017, the final energy demand will increase, and coal supply will decrease quickly in 2050, while other energy demand increases by 2050, especially electricity. **Below 2°C scenario:** To limit global temperature increase below 2°C, the government reduces fossil fuel consumption and develops renewable energy in China. The CO_2 emission caps are about 9000 Mt in 2020, 8000 Mt in 2030, and 3000 Mt in 2050 in China. The main driver is the emissions reduction target for energy-related CO_2 through a strategy with renewable electricity, electrification, and sectoral transformation at the core. The total energy demand in the Below 2°C scenario is the same as that in the Stated Policy scenario before 2030 and the electrification rate is above 60% by 2050.

Table 1 shows the minimum renewable energy portfolio in the power sector under Stated Policy and Below 2°C scenarios. The share of renewable energy in the power sector, including hydropower, will be 51% in 2030 and 78% in 2050 in the Stated Policy scenario, which is higher than the prediction in a study in 2017.[28] Compared with the Stated Policy scenario, renewable energy will increase from 51% to 68% in 2030, and wind and solar increase much faster than hydropower. Renewable energy portfolio in the Below 2°C scenario in 2050 will account for 85% of the power generation, which is 7% higher than that in the Stated Policy scenario in 2050. Renewable energy prediction in this study is consistent with the government's renewable energy outlook.

Improvement of air quality

Due to the reduced fossil fuel consumption and strict environmental controlling policy in China, primary pollutants emissions will drop in the next three decades and air quality will improve after 2030. A large share of renewable energy usage can reduce CO_2 emissions and air pollutants (Figure S1). The difference in emissions between the two scenarios also increases over time. In 2030, CO_2, NOx, SO_2, and N_2O emissions under the Below 2°C scenario will be reduced by 26%, 25%, 32%, and 19%, respectively, compared with the Stated Policy scenario. Moreover, by 2050, this proportion will increase to 48%, 55%, 58%, and 43%, respectively.

Figures 1A and 1B show that developing renewable energy can reduce the $PM_{2.5}$ concentrate of China. There is also significant regional difference. $PM_{2.5}$ concentration reduction from developing renewable energy is most significant in Central China and less in West China. For instance, $PM_{2.5}$ concentration will reduce by ~10 $\mu g/m^3$ from the Stated Policy scenario to Below 2°C scenario in Beijing, Hebei, and Henan. While in Qinghai, Tibet, Xinjiang, $PM_{2.5}$ concentration barely changes between two scenarios. By contrast, O_3 pollution is still a serious problem. The impact of developing renewable energy on O_3 concentration is not obvious in both 2030 and 2050.

Air pollution-related mortality

Renewable energy development will avoid air pollution-related mortality significantly The number of premature deaths related to air pollution is most prominent in East and Central China (especially in Henan, Shandong, and Hebei), and far outnumbers the Southwest, Northwest, and Northeast regions (Figure 2A).

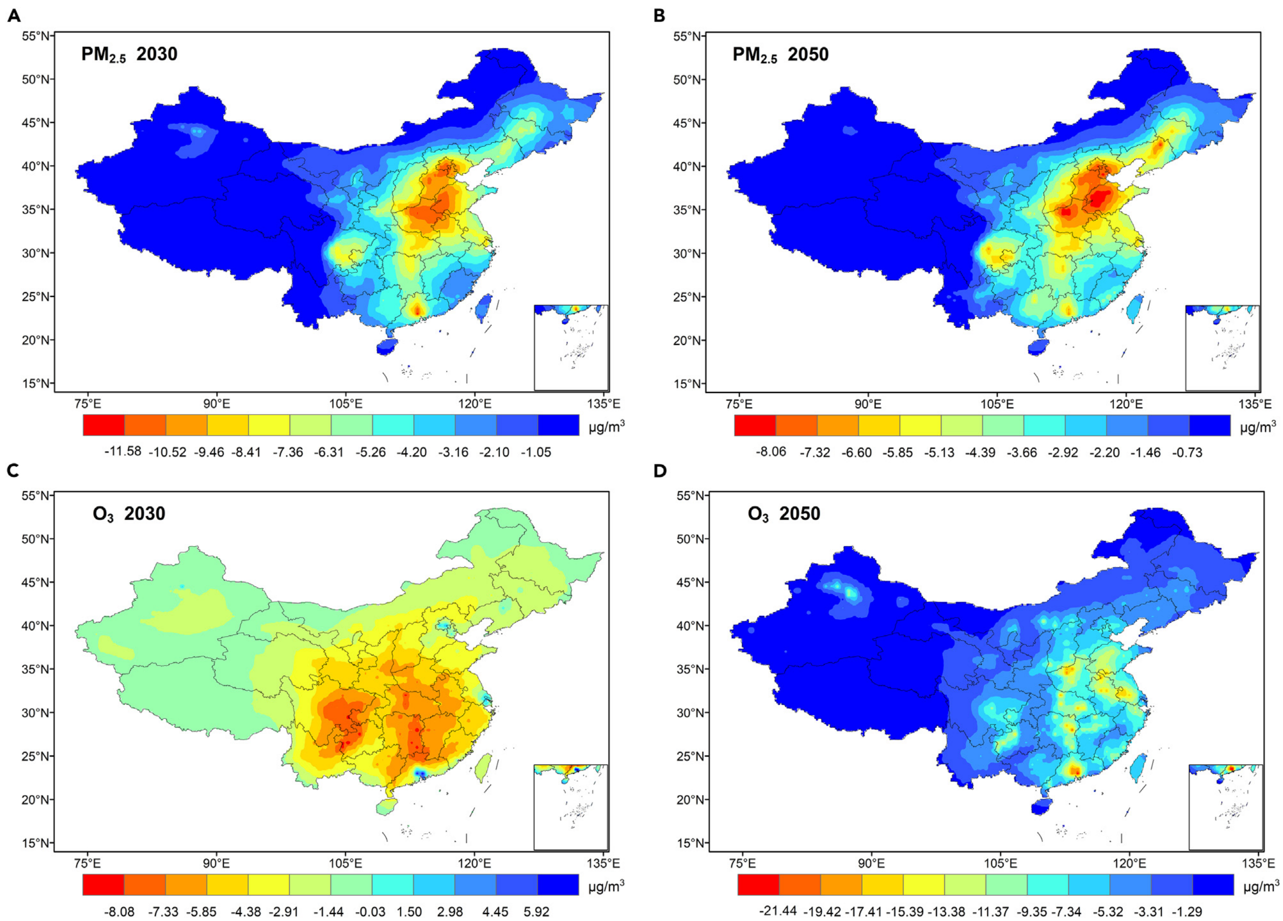

Figure 1. Air quality benefits of developing renewable energy in 2030 and 2050 in China

(A and B) show that the differences of $PM_{2.5}$ concentration under two scenarios (Below 2°C -Stated Policy) in 2030 and 2050.

(C and D) show the differences in O_3 concentration under two scenarios (Below 2°C -Stated Policy) in 2030 and 2050. The blue means that developing renewable energy can reduce the $PM_{2.5}$ and O_3 concentration; the red means that developing renewable energy can increase the $PM_{2.5}$ and O_3 concentration.

Avoided air pollution-related death in East and Central China is 0.286 (73% of total avoided air pollution-related death), and 0.441 (73%) million persons in 2030 and 2050, respectively. Therefore, developing renewable energy will significantly impact human health in both regions. Moreover, substantial provincial differences exist in the impacts of developing renewable energy on human health, as air quality can reduce air pollution-related mortality in regions with high population density and intensive energy consumption.[13] For example, in Guangdong, Shandong, and Henan (the three most populations provinces in China), 0.032 (8% of total avoided deaths), 0.035 (9%), and 0.041 (10.5%) million air pollution-related deaths in 2030 could be avoided by developing renewable energy. Due to aging society, counteract, the mortality reductions realized through much lower air pollutant emissions.[21] Noticeably, the population aging exacerbates the baseline mortality risk of $PM_{2.5}$ exposure, yielding notable reductions in air pollution-related mortality in 2050.[10] As a result, avoided air pollution-related deaths will increase significantly from 2017 to 2050 (Figure 2B). $PM_{2.5}$ concentrate is the leading cause of air pollution-related deaths (Figure 2C). After 2030, the number of avoided $PM_{2.5}$-related deaths will be 7.5 times more than O_3-related premature deaths. However, this result is likely to be slightly higher because the health burden of $PM_{2.5}$ is estimated to be around 6.2-fold more significant than O_3 on average.[29]

We estimate the air pollution-related mortality per 1,000 people in each province (Figure S2). The result shows that the air pollution-related mortality per 1,000 people in North and Central China (including Beijing, Tianjin, Hebei, Shandong, and Henan) is much higher than that in other regions. In the Stated Policy scenario, 3.3 in 1,000 people would die prematurely in 2030 due to air pollution in North China.

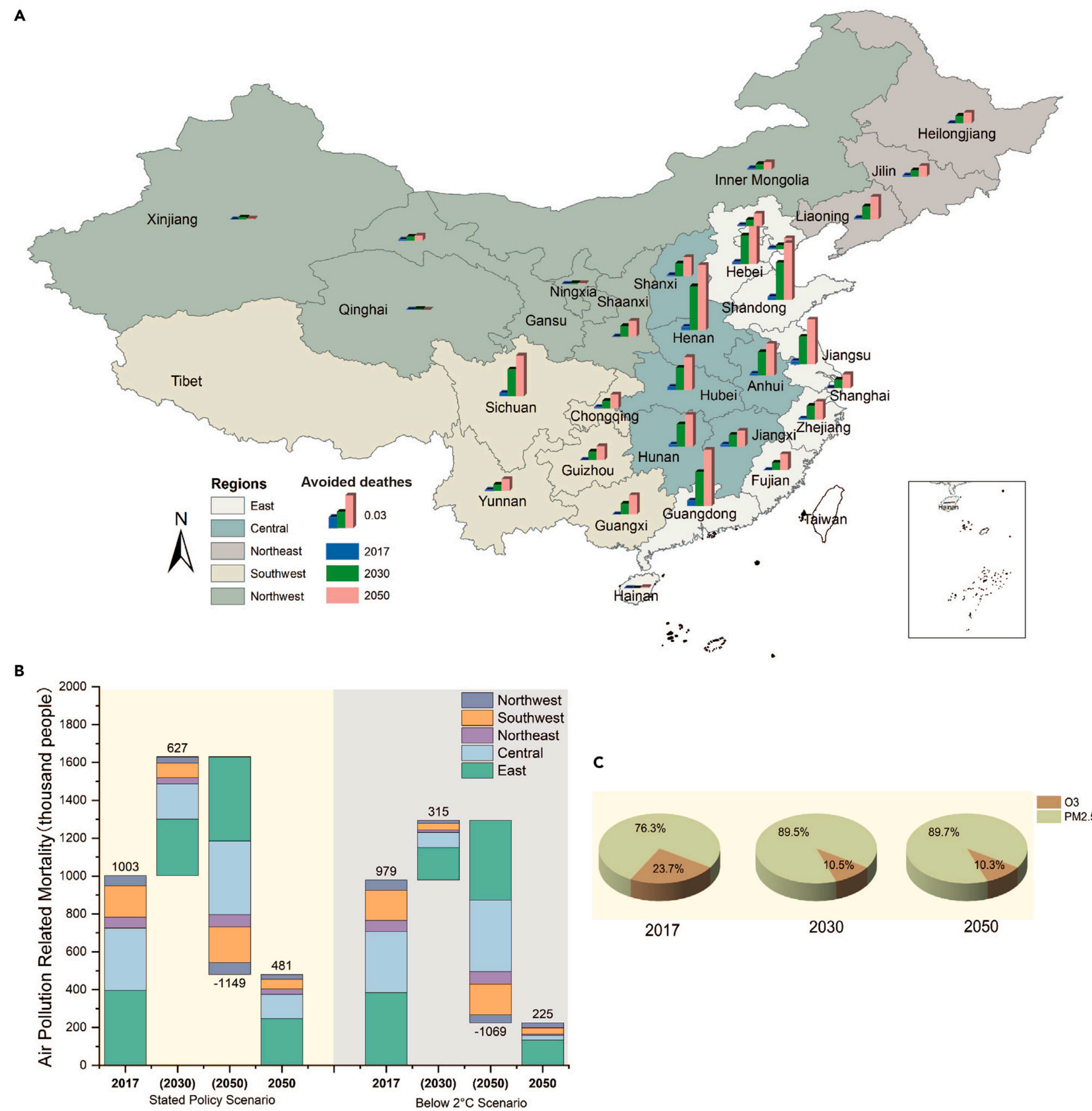

Figure 2. Avoided premature mortality by developing renewable energy in 2030 and 2050

(A) presents the avoided air pollution-related mortality in 2017, 2030, and 2050 in China.

(B) shows the cumulative avoided mortality from 2017 to 2050.

(C) depicts the proportions of avoided mortality due to $PM_{2.5}$ and O_3.

Air pollution-related morbidity and work time loss

There are regional disparities in air pollution-related morbidity and work time loss. We estimate that there were 270 million morbidities related to air pollution in 2017 (95% confidence interval (CI), −130∼610 million), which nearly 90% of them are caused by O_3 (240 million, 95% CI, −130∼600 million, Figure 3A). There are significant differences in the air pollution-related morbidity and work time loss among provinces (Figure 3). For example, there were 12 million air pollution-related morbidity in each province of Central China while only 3 million in Northeast China in 2017. Further, air pollution-related morbidity

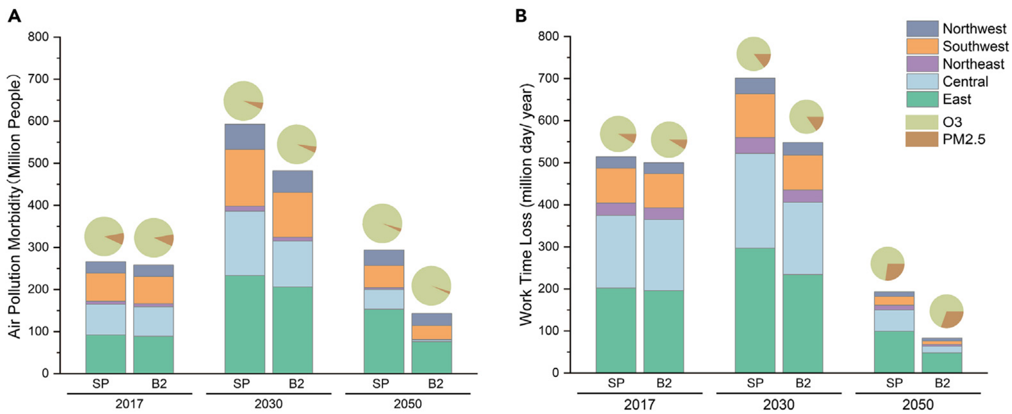

Figure 3. Air pollution-related morbidity and work time loss

(A and B) show the air pollution morbidity and work time loss reduction caused by air pollution in different scenarios. The pie chart represents the proportion of $PM_{2.5}$ and O_3 in health impacts.

in Southern provinces (11 million) was larger than in Northern provinces (5 million) in West China. In the future, the air quality-related morbidity in the Below 2°C scenario (482 million in 2030 and 143 million in 2050) is far less than that in the Stated Policy scenario (593 million in 2030 and 294 million in 2050).

Significant regional differences exist in the incidence of air pollution-related morbidity rate (Figure S3). Due to the more severe O_3 concentrate, Western regions have the highest incidence of air pollution-related morbidity. In 2030, the morbidity rate will be above 60% in most provinces of the Western regions, although the morbidity rate will decrease in the Below 2°C scenario. By contrast, the morbidity rate is less than 40% in most Eastern and Central provinces and 20% in Northeast regions.

Air pollution-related work time loss in Eastern and Central regions is much more than that in other regions. Both regions also account for an increasing proportion over time (73% in 2017, 77% in 2050 under the Stated Policy scenario). Developing renewable energy has a positive effect in reducing work time loss. In 2030, work time loss in the Below 2°C scenario is 20% less than that in the Stated Policy scenario.

Air pollution-related morbidity and work time loss will peak in China in 2030 and decline after 2030. Morbidity and work time loss in Eastern and Central regions are higher than in other regions (Eastern/Northwest/Southwest China) and have more potential to decline. For example, under the Stated Policy scenario, the Eastern regions will have an average of 23 million morbidity cases and 30 million hours of work time loss per province in 2030, which will decrease by 67% and 84% (by 7.6 million cases and 4.8 million hours) in 2050 under the Below 2°C scenario, respectively. Moreover, air pollution-related morbidity and work time loss are consistent on both temporal and spatial scales, and the measures that improve air quality have co-benefits in reducing work time loss.

Cost-benefits analysis

Developing renewable energy can bring economic benefits and costs, such as the GDP gains caused by increased employment, carbon saving by replacing fossil fuels, medical savings by reducing morbidity, fossil fuels savings, and operation and maintenance costs. Results show that the investment cost in renewable energy in 2030 will be as high as 2.3 trillion Yuan in China under the Below 2°C scenario. Although it could bring air quality and health co-benefits, the investment is much higher than benefits. However, the net benefits of developing renewable energy will increase faster after 2030 in most provinces of China (except for Inner Mongolia, Fujian, and Shaanxi) by 2050 (Figure 4A). To achieve the carbon neutrality target by 2060, the government should promote massive investment in renewable energy before their cost decline has been entirely realized.[14] Regions with large-scale onshore wind power capacities will have more potential for carbon reduction, including Northwest China (such as Gansu, Xinjiang, and Inner Mongolia). These regions will receive more investment in renewable energy and create more jobs. Meanwhile, investment in renewable energy in these regions will also bring spillover effects to other regions.

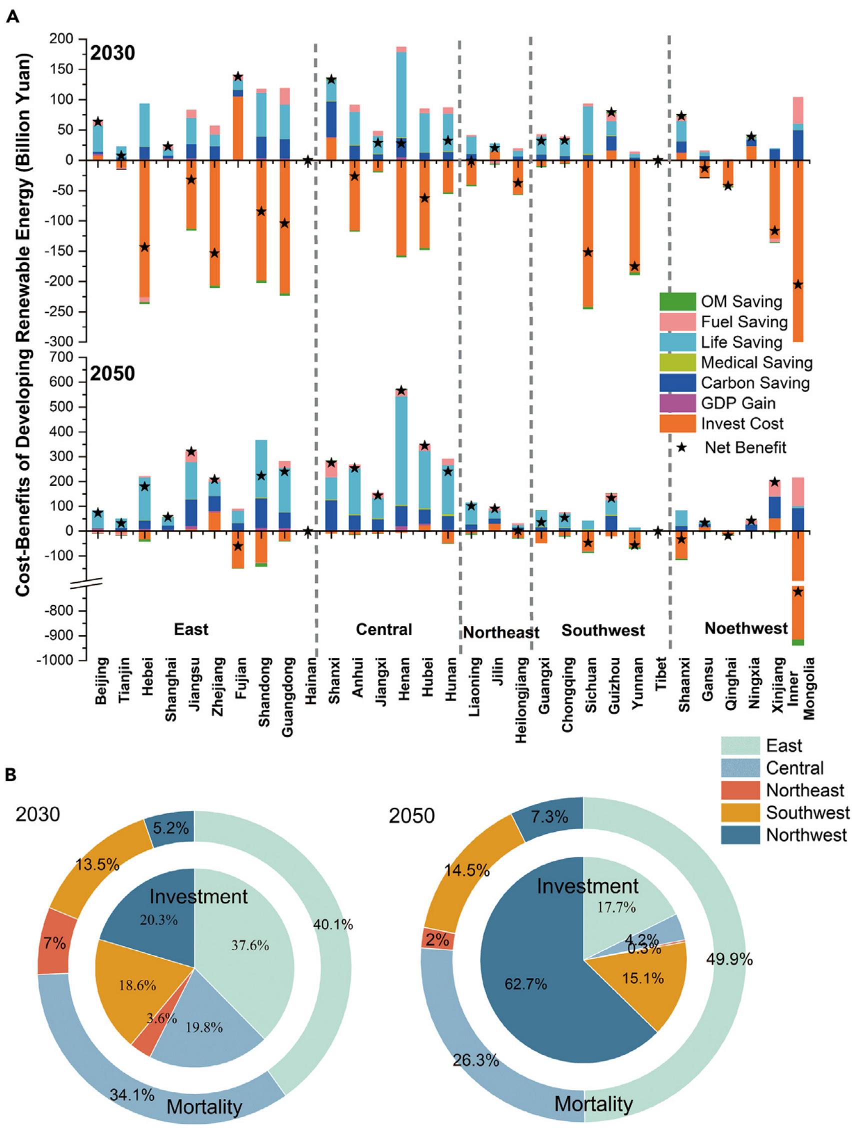

Figure 4. Cost-benefits analysis of developing renewable energy

(A) presents the investment, saving, and net benefit of developing renewable energy at the provincial in China.

(B) shows the share of future investment in renewable energy and air pollution-related mortality reduced by deploying renewable energy in five regions of China.

The net benefits of developing renewable energy are significant in Eastern China (1.6 trillion Yuan) and Central China (1.7 trillion Yuan). At the same time, investment costs will decrease by 0.6 trillion Yuan in Eastern China and 0.4 trillion Yuan in Central China in 2050. Increased net benefits primarily consist of carbon reduction benefits and life savings. Investment cost in renewable energy disproportionately reduces health impacts regionally (Figure 4B). Investment cost in the central region accounts for 20% of the total investment in 2030, but it accounts for a 34% reduction in premature death. Conversely, investment in the Northwest region accounts for 20% of total investment, which reduces premature deaths by 5%. The disproportion will be even more pronounced by 2050, with only 20% of investment cost in the Eastern and Central regions leading to a 76% reduction in premature deaths.

DISCUSSION

This study adopts an integrated model framework to quantify air pollution-related health and economic co-benefits of developing renewable energy at the provincial level in China. The results show that air quality will significantly improve when China develops renewable energy to reduce carbon emissions and to keep the temperature increase within 2°C. Developing renewable energy will have a more pronounced effect on air quality improvement in 2050 than that in 2030. Capacity solar of photovoltaic power generation level will accelerate the replacement of high carbon emission power sources,[11] which could bring air quality co-benefits and prevent millions of premature deaths.[30]

Moreover, regional differences primarily drive the disproportion of investment and health benefits to marginal emission benefits worldwide. One study has shown that if no decarbonization policies are implemented, black and high-poverty communities in the US may be burdened with higher $PM_{2.5}$ concentrations than the national average during the energy transition.[31] Dwellers in less developed counties are more vulnerable to long-term exposure to ambient $PM_{2.5}$ than those in developed counties.[13] Furthermore, there is a socioeconomic disparity in the air pollution-related mortality association in China.

This study also suggests that national renewable energy deployment needs to consider equity in air pollution concentrations across all demographic groups. Since health benefits are not directly reflected in economic growth, they are often overlooked when formulating energy deployment strategies.[32] However, from the perspective of total social and economic benefits, health benefits are also essential and must be fully considered when making decisions. Due to the large investment in the early stage of renewable energy deployment, the short-term health benefits are not significant from the income perspective, but the long-term benefits are obvious as the cumulative renewable power phases out the fossil-fired power. Therefore, short-term and long-term benefits must be considered early in formulating investment strategies.

More ambitious deployment of renewable energy will contribute massively to reducing air pollution, improving human health, and benefiting economy. One study shows that the incremental health benefit from improved air quality exceeds eight times the additional costs of CO_2 mitigation.[33] Although the benefits will not outweigh the costs in the short run, the benefits are significant and positively impact renewable energy consumption in developed and developing economies in the long run. Compared with existing research,[34] the health co-benefits will be higher than mitigation costs, even when considering all included uncertainties, implying the cost-effectiveness of China's Paris Agreement goal. Renewable energy development involves difficulties due to high upfront costs and long lags for economic benefits.[35] The government needs to launch a long-term policy to support renewable energy investment.

Meanwhile, developing renewable energy would have regionally disproportionate health and economic co-benefits, especially in Central and Eastern China. This is an inevitable result of China's "West-East Energy Transfer" project.[36] Most renewable power has been deployed in Western China and transmitted to Eastern China. For example, about 60% of wind power in 2015 was delivered from West to Central and Eastern China.[37] Specifically, most wind power produced in Inner Mongolia and Ningxia is sent to Beijing, Tianjin, Hebei, and Hunan.[38]

In addition, provinces with abundant renewable energy are often located in economically backward Western and Northern China.[28] Due to better air quality and less population density, the health benefits are not significant in the renewable energy-supplying regions. On the contrary, the health benefits of the "West-to-East Energy Transfer" are more evident in Eastern China as these provinces are with higher population density and a more developed economy.[39] Therefore, provinces with abundant renewable energy should receive more financial support, and health benefits should also be factored in when formulating energy investment strategies and electricity prices.

Limitations of the study

There are some limitations in this study. This study may overestimate the investment cost as renewable energy cost is declining quickly. Meanwhile, renewable energy will bring opportunity to the related sectors, which is not a direct cost to the economy. This study may overestimate the renewable policy cost.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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- ○ Calculating air pollutant concentrations
- ○ Quantifying health impacts of air pollution and co-benefits of health impacts

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.107459.

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AUTHOR CONTRIBUTIONS

Conceptualization, Y.X. and S.X.; Methodology, Y.X. and S.X.; Software, X.L. and Y.Z.; Investigation, Y.X. and S.X.; Data Curation, Y.X., S.X., and X.L.; Writing-Original Draft, Y.X., S.X., and J.P.; Writing-Review & Editing, Y.X., S.X., and M.X.; Visualization, J.P., S.X., and Y.P.; Supervision, Y.X.; Project Administration, S.X.; Funding Acquisition, Y.X. and S.X.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
National-level energy consumption	Statistical Review of World Energy	https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/xlsx/energy-economics/statistical-review/bp-stats-review-2022-all-data.xlsx
Provincial-level Energy Balance Table	China Energy Statistical Yearbook	http://www.stats.gov.cn/tjsj/tjcbw/
Provincial-level renewable energy production	China Electric Power Yearbook	http://www.stats.gov.cn/tjsj/tjcbw/
Input-output table	National Bureau of Statistics of China (NBS)	Input-output Tables of China
Software and algorithms		
IMED|CGE	IMED|CGE	http://scholar.pku.edu.cn/hanchengdai/imedcge
EDO	Balmorel 3.02	http://www.balmorel.com/index.php/downloadmodel
GEOS-Chem	GEOS-Chem 13.3.3	https://zenodo.org/record/5748260#.ZEelznZBy70
IMED|HEL	IMED|HEL	http://scholar.pku.edu.cn/hanchengdai/imedhel

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Shasha Xu (xushashasmile@gmail.com).

Materials availability

The study did not generate new materials.

Data and code availability

- This paper analyzes existing, publicly available. These accession numbers for the datasets are listed in the key resources table.
- All custom codes have been deposited on the related website. Links are listed in the key resources table.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

This study develops an integrated assessment approach to evaluate the air quality improvement, health, and cost-benefit of developing renewable energy in China. The research framework (Figure S4) combined the IMED|CGE (Integrated Model of Energy, Environment and Economy for Sustainable Development/Computable General Equilibrium) model, and the EDO (Estimated Dynamic Optimization) model to project the renewable energy (including hydropower, wind, solar and biomass) requirements, used the GEOS-Chem model to calculate $PM_{2.5}$ and O_3 concentrations and assessed the health impact and cost-benefit with the IMED|CGE and IMED|HEL model.

Projection of the renewable energy requirement

The IMED|CGE model is classified as a multi-sector, multi-region, recursive dynamic CGE model that covers 41 economic commodities and corresponding sectors. The base year data, regional coverage, and sectoral classification of the IMED|CGE model are flexible depending on the specific research purposes and contents. This model represents 41 sectors divided into basic, resource-requiring, land-requiring, and energy supply sectors. This technology-rich hybrid CGE model can describe a series of important energy supply technologies, such as power generation, non-fossil fuel supply, and carbon capture and storage (CCS) technology. Such treatment of technology representation would enable this model to assess the mitigation cost of carbon reduction more reasonably.[40–42] Like most modern CGE models, this model is solved yearly by Mathematical Programming System for General Equilibrium under the General Algebraic Modeling System (GAMS/MPSGE).[43] The model consists of four blocks: a production block, a market block, an income block for government and households, and an expenditure block for final demand agents. Sectoral activity is represented by a nested constant elasticity of substitution (CES) production function, in which inputs are classified into materials, energy commodities, labor, capital, and resource inputs.

Calculating air pollutant emissions

The EDO (Electricity and District Heating Optimization) model is a fundamental power and district heating system model, built on the Balmorel model (www.balmorel.com). The power system is represented at the provincial level, considering the interprovincial grid constraints and expansion options. The model includes thermal power (including CHP), wind, solar (including CSP), hydro, power storage, heat boilers, heat storage, heat pumps, etc. It also considers demand-side flexibility from industries, options for charging electric vehicles, and a fully integrated coupling with the district heating sector. The model can represent the current dispatch in the Chinese power system hourly, including technical limitations on the thermal power plants and interprovincial exchange of power; as well as the dispatch in a power market, provincial, regional, or national, based on the least-cost marginal price optimization. Key characteristics relate to the detailed representation of the variability of load and supply as well as flexibility and flexibility potentials, which can operate optimally and be deployed efficiently in capacity expansion mode. The EDO model provides the emissions of $PM_{2.5}$ and O_3 for the power sector. Calculating national emissions uses IPCC emission factors.

Calculating air pollutant concentrations

GEOS-Chem model, an atmospheric transport and chemistry model, was used to calculate the daily-maximum-8-hour-avergae ozone concentration and daily average concentration of $PM_{2.5}$. GEOS-Chem model has a horizontal resolution of 0.5-degree latitude and 0.67-degree longitude. This model domain is nested in a global model simulation with a resolution of 4-degree latitude and 0.67-degree longitude, which provides initial and boundary conditions. The size of the provinces varies drastically in China. The number of grid boxes ranges from ~600 in Xinjiang to ~10 in Beijing. We used the simple arithmetic average of the ozone concentration of all the grid boxes in a province for analysis. The model is driven by the meteorological data from the Goddard Earth Observing System (GEOS, version 5) of the NASA Global Modeling Assimilation Office (GMAO), and the meteorological data in 2008 are used for 2050 simulations.

In this study, we estimated the primary provincial emissions of $PM_{2.5}$ and O_3, and they were directly fed to the GEOS-Chem model simulations,[44] in which two concentration levels will be calculated for the years 2017, 2030 and 2050, respectively, taking into account chemical transaction and inter-regional transport. Besides, we compared our results with earlier studies and found the results are quite consistent, even though the model setup and used emission inventories slightly differ.[45,46]

Quantifying health impacts of air pollution and co-benefits of health impacts

By adopting the latest Exposure-Response Functions suitable for China, the health impacts of air pollution will be quantified, including chronic mortality, morbidity, work day loss, and value of statistical life (VSL).[47] IMED|HEL model evaluates the health impacts of $PM_{2.5}$ and ozone exposure, including six kinds of mortality and morbidity endpoints (chronic bronchitis, asthma, lower respiratory symptoms, chronic obstructive pulmonary disease, ischemic heart disease, stroke), work-loss days (WLDs), health expenditure and VSL. $PM_{2.5}$-associated mortality is calculated using the nonlinear integrated exposure-response functions and the Global Exposure Mortality Model (GEMM).[48,49] Ozone-related mortality is calculated by linear exposure-response functions.[50] The confidence intervals present the uncertainties of the exposure-response functions derived from the epidemiologic literature. The medical expenditure caused by $PM_{2.5}$ pollution is quantified with linear concentration-response functions using the health service price in Japan, based on data in Japan and per capita GDP. We adopt VSL for OECD countries and estimate future health service prices and VSL based on the per capita GDP projection with an elasticity of 0.8.[51] Total annual WLDs is the sum of WLDs due to morbidity and cumulative WLD due to mortality of the working population. The settings of the IMED|HEL model can be found in our previous studies.[52] The above health impacts will be converted into market and non-market effects. Market effects include annual per capita work loss due to morbidity and chronic mortality and additional medical expenditure, which will be used as input to the IMED/CGE model to assess the macroeconomic impacts on GDP. Non-market impacts will be evaluated by applying econometric approaches such as willingness to pay. We conduct the cost-benefit analysis by comparing the additional investment cost of renewable energy installation with the benefits of fuel cost saving, GDP gain, medical expenditure saving, operating and maintenance cost and life value saving.