

THE LANCET Planetary Health

Supplementary appendix

This appendix formed part of the original submission and has been peer reviewed.
We post it as supplied by the authors.

Supplement to: Shen G, Zhang Y, Jiang K, et al. Region-specific solutions for clean cooking and heating in rural China: a cost-benefit analysis. *Lancet Planet Health* 2026. <https://doi.org/10.1016/j.lanplh.2026.101439>

APPENDIX:

Region-Specific Cost-Effective Solutions for Clean Cooking and Heating in rural China

Guofeng Shen^{1,2,3}, Yuanzheng Zhang¹, Ke Jiang¹, Ajay Pillarisetti⁴, Wenjun Meng⁵, Qirui Zhong¹, Huizhong Shen⁶, Hefa Cheng¹, Shu Tao^{1,2,6}, *

1. College of Urban and Environmental Sciences, Peking University, Beijing 100871, China
2. Institute of Carbon Neutrality, Peking University, Beijing 100871, China
3. Center for Environment and Health, Institute of Tibet Plateau, Peking University, Beijing 100871, China
4. Division of Environmental Health Sciences, University of California Berkeley, Berkeley, California 94720, United States
5. Aerosol Chemistry Department, Max Planck Institute for Chemistry, 55128 Mainz, Germany
6. School of Environmental Science and Engineering, Southern University of Science and Technology, 518055 Shenzhen, China

* Corresponding author: Prof. Shu Tao, Email: taos@pku.edu.cn, Tel: 86-10-62751938

All authors declare no completing financial interests.

A1. Heating demand analysis and baseline temperature

China has several zones with much different climate conditions, and not all regions have space heating demands in winter. Even in areas with heating demands in cold seasons, there are substantial differences in the heating duration and intensity. Usually, the traditional division of heating and non-heating areas is that on the north or south of Qinling-Huaihe line;¹ however, in reality, areas that require space heating are not limited to the traditional northern heating areas. For example, in high-altitude mountainous areas in the south, especially in the southwest, rural residents also need to heat homes in winter as the temperature decreases with the increased altitude. The heating duration also varies largely across different regions. For instance, it is usually half of a year or longer in Heilongjiang province, while in Henan and southern Shandong provinces, the heating duration is usually only two or three months.² As for the convenience of government and management, many regions often officially set the start and end dates for heating each year. Such management is limited to urban areas that provide centralized heating. Except for few areas, rural residents generally make their own decision on heating activities based on weather conditions and their needs objectively.

Usually, when the temperature is below a certain temperature, residents would start the space heating. This specific temperature is defined as the baseline temperature for heating in many studies and policies.³ In many studies, the baseline temperature is fixed, like 5 °C, but in fact, the baseline temperature would change with changes in the living conditions and comfort requirements, that is, the heating baseline temperature would increase with the increase of household income and heating expenditure affordability. Some surveys observed that since the 1990s, with the continuous improvement of residents' living standards, the number of rural households from the traditional non-heating areas of Central and East China but using electric devices for heating has significantly increased.⁴⁻⁵

By setting different baseline temperature (-5, 0, 5, and 10 °C), spatial pattern of the heating degree days (HDDs), the sum of the difference between the daily average temperature and the baseline heating temperature, are characterized and compared (**Figure s1**). When the baseline temperature increased from -5 °C to 10 °C, the heating duration and the area of heating zone expectedly increased. Though many household energy studies adopted 5 °C as the heating baseline temperature, as seen from the spatial characteristics, under this baseline temperature, nearly the entire country has high heating demands, except for Hainan province and few areas in the southeast coastal regions. This is not consistent with realistic experience. In developing or less-developed areas, it is reasonable to expect that residents may have a lower baseline temperature for heating, that is the heating activity would start at relatively colder days. As seen

from the spatial pattern, a baseline temperature of 0 °C can well reflect the actual situation of rural heating demand in China. Most regions on north of the Qinling-Huaihe line and the Qinghai Tibet Plateau (QTP) are main heating areas, while some central and eastern regions on south of the line also have heating needs in a few days, mostly the HDD < 33 °C. Thus, in constructing a clean heating plan, the baseline heating temperature was set 0 °C.

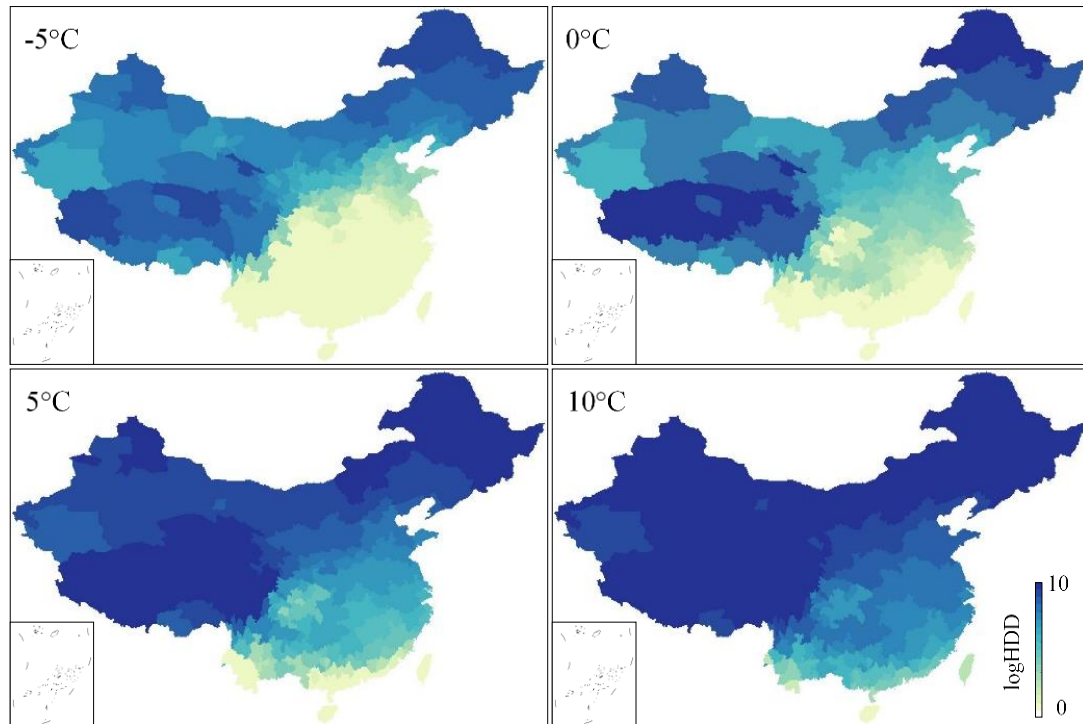


Figure s1: Spatial distributions of the Heating Degree Days (HDDs) under different baseline temperatures of -5°C, 0°C, 5°C, and 10°C.

In the baseline temperature of 0 °C, the HDs vary from zero to about 220 days/year, with an obvious pattern of longer in the north and the west compared to the south and the east. Longer HDs in the north are due to cold climate conditions in the high latitudes, and that in the west are associated with cold temperature in high altitude QTP regions. In the relationship between HDD and HD at the second-administration city level, in which a positive but not non-linear relationship was observed. Generally, in areas with longer HDs, there would be more increase of the HDD as those areas are much colder compared to areas with short HDs, resulting in the deviation from linearity. Among areas with much long HDs, like more than 110 days per year in rural China, there are two different curves observed, being corresponding to areas in the high latitude and high altitude, respectively. For the former, like the situation in other areas, HDDs increase with the increase of HD exponentially in general, while in the latter which is mainly in the QTP, the increase in the HDD with the increase of HD is smaller showing a likely linear

relationship. In areas with short HDs, like ~ 15 days per year, they are mainly in the north of the southern provinces like Guangdong, Yunnan, Hainan, and Taiwan provinces where nearly no heating is needed based on the baseline temperature of 0°C , but in the south of the typical Qinling-Huaihe line separating the heating and non-heating zones in the country. These areas are considered as short-term heating regions where the HD is less than two weeks per year and the HDDs are generally below 33°C . Given the relatively few HDs (mostly only 1–3 days, as seen in **Figure s2**) and the low price of rural residential electricity, annual heating expenses for these residents are not substantial.⁶ Additionally, existing infrastructure can accommodate electricity-based heating in the short-term heating region due to low overall demand. In fact, even with no subsidy policy, a clean heating approach using electricity has been observed in these regions, although the adoption rate varies depending on household income.⁷ Areas with HDs exceeding 15 days, defined as the long-term heating region in this study, encompass nearly all regions north of the Q-H line and the QTP. In these regions, HDDs increase rapidly with HDs, indicating stronger heating demands and the need for more intensive policy measures and subsidies to facilitate clean heating transitions. In regions characterized by steep terrain and low population density, the per capita cost of infrastructure can be particularly high due to construction difficulties and low utilization rates.⁸ Despite significant spatial variation, there is a negative correlation between terrain slope and population density (**Figure s3**). Based on the spatial distribution of costs and household incomes, regions suitable for promoting clean heating through electricity or natural gas are mainly in plain areas in North and Northeast China. Previous studies have shown that electricity has substantial advantages in terms of total costs compared to piped natural gas.

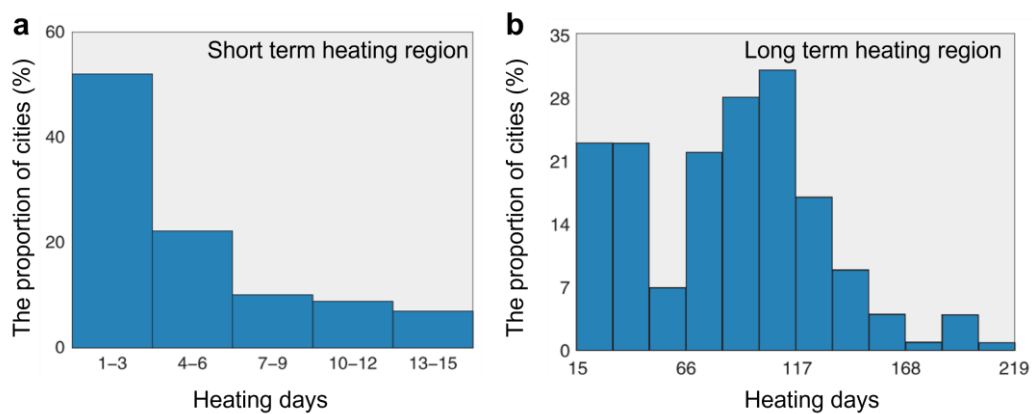


Figure s2: Proportion of cities with different heating days in (a) short-term heating regions and (b) long-term heating regions.

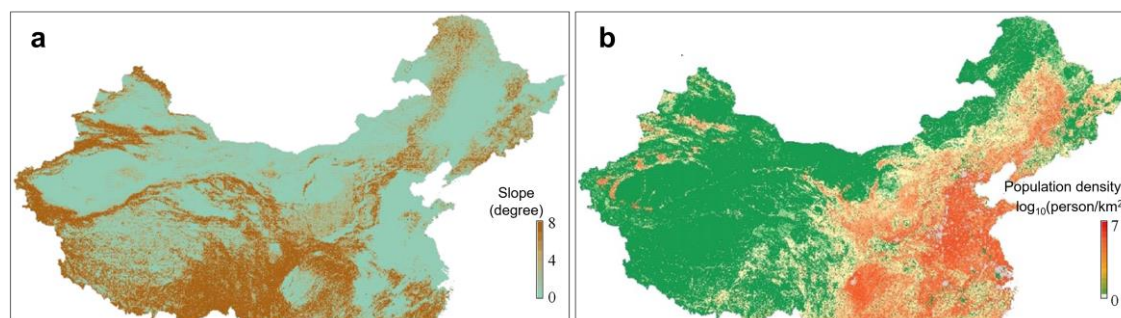


Figure s3: Slope (a) and population density (b) in the long-term heating region.

References cited here:

1. Chen, Y., Ebenstein, A., Greenstone, M., & Li, H. Evidences on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. *PNAS* 2013; 110(32): 12936-12941.
2. Duan, X., Zhao, X., Wang, B., Chen, Y., & Cao, S. Handbook of the Chinese exposure factors. Science Press, Beijing 2014.
3. Mehregan, M., Naminezhad, A., Vakili, S., & Delpisheh, M. Building energy model validation and estimation using heating and cooling degree days (HDD-CDD) based on accurate base temperature. *Energy Sci. Engineer.* 2022; 10: 3638-3649.
4. Zhao, J., Long, B., Yuan, W., Liu, S., Li, K. Analysis of central heating necessity in south China based on air temperature and apparent temperature. *J. Meteorol. Environ.* 2021, 37: 41-47 (In Chinese)
5. Li, R. Research on the influence mechanism of heating energy-saving product application in south China. MSc Thesis. 2020 (In Chinese).
6. Bai Y, Miao Q, Yuan J, Chang D, Dong Z. Research on rural clean heating pricing mechanism in northern China: the perspective of residents' consumption. *Ecological Economy* 2023; 39: 149-155 (In Chinese).
7. Wang, Z., Li, C., Cui, C., Liu, H. & Cai, B. Cleaner heating choices in northern rural China: Household factors and the dual substitution policy. *J. Environ. Manag.* 2019; 249: 109433.
8. Meng, W., Zhu, L., Liang, Z., *et al.* Significant but Inequitable Cost-Effective Benefits of a Clean Heating Campaign in Northern China. *Environ. Sci. Technol.* 2023; 57: 8467-8475.

A2. Design of clean cooking and heating scenarios

There are significant differences in cooking and heating behaviors, necessitating distinct clean solutions for each. Cooking activities involve all residents and occur throughout the year, whereas heating demand is limited to the cold seasons in several but not all regions of the country.

Transitions to clean cooking may occur spontaneously, driven by factors like the socioeconomic development.¹⁻² Therefore, clean cooking solutions are potentially more straightforward, more flexible, and can be promoted at the household level. In fact, for urban residents, electricity has been primarily used for steaming staple foods and heating water, while natural gas is often used for preparing side dishes. In rural areas, liquefied petroleum gas (LPG) serves as an alternative to natural gas for cooking side dishes, since it does not require pipeline infrastructure and it usually meets traditional Chinese cooking methods and habits. Additionally, considering convenience and lower energy prices, electric cooking should be the preferred solution. Currently, even households primarily reliant on solid fuels often use electric rice cookers for staple foods and electric water heaters for boiling water. In fact, induction cookers, microwave ovens, and other appliances commonly used for cooking side dishes in urban areas can gradually be promoted in rural regions as alternatives to traditional solid fuels. The clean cooking scenario in this study is implemented at the household level. The standard household clean cooking model in this study is, for households still relying on solid fuels for cooking, the study designs two scenarios based on varying proportions of clean energy transitions: C1, where 50% of these households switch entirely to clean energy, and C2, where 100% of these households make the transition to clean energy.

Clean heating transitions, contrastingly, heavily depend on government intervention and subsidies due to high up-front and recurring cost. Large-scale clean heating programs require high capacity, reliable grids or natural gas pipelines and necessitate greater investment in infrastructure. As such, clean heating solutions need to be adapted to local conditions, promoted centrally, and synchronized regionally. For the clean heating solutions, as mentioned above, the study first analyzed the heating demand differences across regions on a national scale and calculates the heating days (HDs) for different regions using 0°C as the baseline temperature. The study primarily focuses on regions with more than 15 HDs per year (long-term heating region) and designs appropriate clean heating solutions. Based on previous research, electric heating is more advantageous than natural gas heating in terms of cost and safety. Therefore, the clean heating solution for the long-term heating region in this study is to replace traditional solid fuels with electric heating. However, since rural electric grids in China generally do not provide the minimum rated power capacity (6-10kW) required for electric heating, a large-scale implementation of electric heating in rural areas would necessitate comprehensive grid

renovation.

Considering the per-household investment cost, grid renovation in each municipality is extended from areas with the highest population density to those with lower population densities. Following the method of Meng et al.,³ a K-means clustering algorithm is employed to simulate the additional power infrastructure construction and grid renovation. As the grid renovation gradually extends to lower-population density areas, the overall per-household investment cost increases. Based on the current baseline heating scenario (H0), different per-household investment caps —namely 4000, 6000, 8000, 10000, and 12000 RMB — are set as different clean heating scenarios (H1-H5). When the grid renovation reaches the lower-density areas and the total per-household investment cost to hit the investment cap, the renovation is halted, thus determining the coverage area and households benefiting from the grid renovation and clean electric heating.

Moreover, given the high cost and low marginal benefit of upgrading electric grids in sparsely populated mountainous areas, the study further proposed using locally appropriate clean heating options in these areas. One such option is to use processed biomass briquettes replacing traditional heating fuels. Thus, scenarios H6-H9 were designed, with each scenario representing the introduction of 10%, 20%, 40%, and 40% processed biomass in areas where the per-household grid upgrade cost is 8000 RMB. The difference between H8 and H9 lies in the spatial distribution of biomass implementation, that is in H8, biomass implementation is distributed evenly across the area, whereas in H9, biomass implementation follows the spatial distribution of biomass production, considering the spatial heterogeneity of biomass substitution.

References:

1. Shen, G., Xiong, R. Tian, Y., et al., Substantial transition to clean household energy mix in rural China. *Nat. Sci. Rev.* 2022; 9: nwac050.
2. Li, C., Li, M., Zhang, L., et al., Energy-poverty-inequality SDGs: a large -scale household analysis and forecasting in China. *PNAS* 2025; 122: e2408167121
3. Meng, W., Zhu, L., Liang, Z., *et al.* Significant but Inequitable Cost-Effective Benefits of a Clean Heating Campaign in Northern China. *Environ. Sci. Technol.* 2023; 57: 8467-8475.

A3. Modelling of ambient and indoor PM_{2.5}

Residential emissions of CO₂ and major air pollutants at baseline and in each scenario, including PM_{2.5}, NO_x, SO₂, NH₃, BC, OC and CO, are calculated based on the fuel consumption and corresponding emission factors (EFs). GEMS currently contains emissions for a variety of air pollutants and greenhouse gases spanning from 1700 to 2021, with a spatial resolution of 0.1°×0.1°.¹ After energy substitution, the fuel consumption and emissions are recalculated with EFs remaining in each scenario. When replacing solid fuels with electricity, additional emissions from power plants are calculated based on increasing fuels consumption for producing the electricity needed and corresponding EFs for fuels used in power plants.

The study uses reduced-form models to estimate changes in ambient PM_{2.5} concentrations associated with anthropogenic emission changes, with the influence of meteorological conditions by the probability function.²⁻³

For the baseline and each transition scenario, the ambient PM_{2.5} concentration could be calculated by the reduced-form model as equation (1):

$$C(PM_{2.5,S}) = Model [E_{PM_{2.5,S},total}, E_{NO_x,S,total}, E_{SO_2,S,total}, E_{NH_3,S,total}, E_{CO,S,total}] \quad (1)$$

when $C(PM_{2.5,S})$ represents the grid ambient PM_{2.5} concentration in the scenario S, and $E_{p,S,total}$ represents grid total emissions of the pollutant p in the scenario S as the inputs of the model.

The probability function characterized the fluctuations in ambient PM_{2.5} concentration from the baseline level which is determined by the emissions. As shown in Figure s4, in most areas the variations in PM_{2.5} due to meteorological conditions were within 20%, and in the densely eastern plain region, the variations were less than 10%. Thus, the influence of meteorological conditions on ambient PM_{2.5} and outdoor exposure was small, compared to the changes associated with emission changes. In addition, as the outdoor air quality change contributed less to the overall exposure than the indoor exposure, the uncertainty and potential biases in ambient PM_{2.5} levels from the reduced-form model were small in the total exposure and health impact analysis.

The model was evaluated and validated for robustness by comparing results with the ground-based observations at both global and national scales, and those from Atmospheric Chemical Transport Modelling. Details of evaluation are presented in previous publications³⁻⁵ and **Figure s5**. The model performs well in both northern and southern regions over the historical time series. The output results of the reduced-form model have been compared and validated against data from monitoring stations in China, sufficiently demonstrating that the reduced-form model can support PM_{2.5} simulation and prediction of its temporal and spatial characteristics at the

national and regional scales.

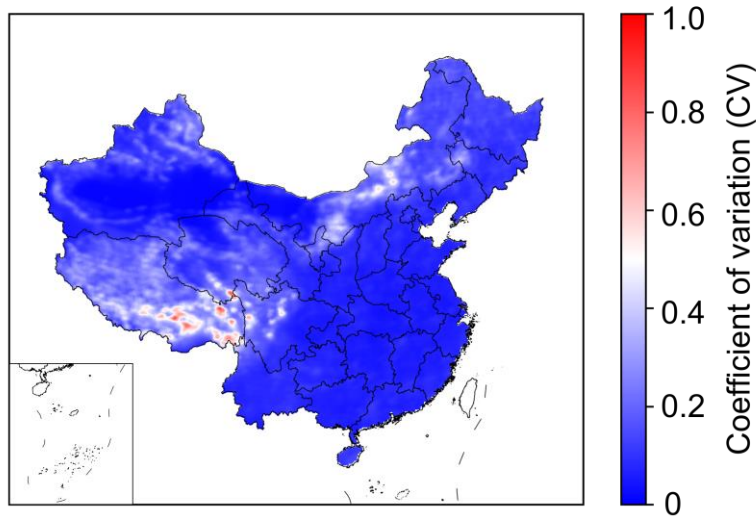


Figure s4: Coefficient of variation (CV) in the ambient $PM_{2.5}$ due to meteorological conditions. The ambient basic levels are from the multivariable regression models with the inputs of emission amounts of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors, while the CVs in the figure indicates the fluctuation in the pollution levels due to the influence of meteorological conditions.

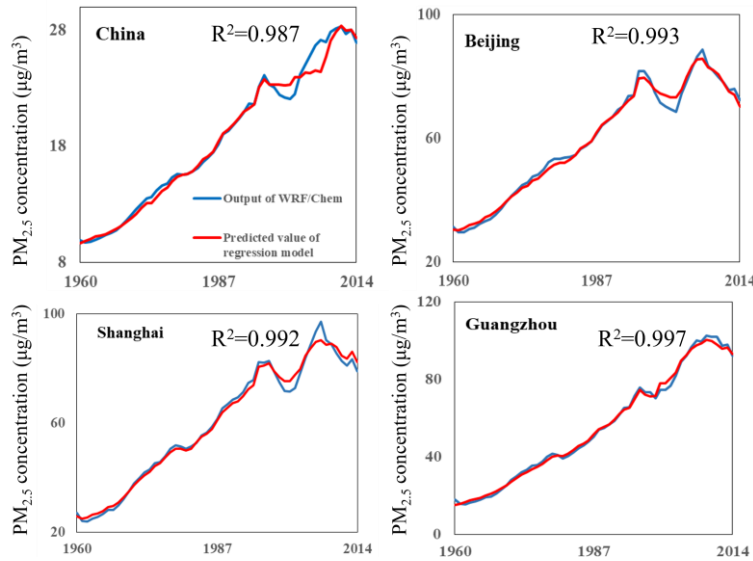


Figure s5: Comparison of the reduced-form model results against the WRF-Chem simulation outputs for the whole country, and those in three cities of Beijing, Shanghai, and Guangzhou from the north, central, and south China, respectively.

The contribution of rural residential emissions to $PM_{2.5}$ concentration need to be attributed to evaluate the effect of transition scenarios. The emissions could be first attributed to different sectors as equation (2):

$$E_{p,S,total} = E_{p,S,res} + E_{p,S,other} \quad (2)$$

Where $E_{p,S,res}$ are the rural residential emissions of pollutant p , respectively, and $E_{p,S,other}$ represents the total emissions apart from $E_{p,S,res}$. Based on the normalized marginal attribution method with a marginal reduction ratio α ($\alpha = 20\%$), the contribution of rural residential emissions to ambient $PM_{2.5}$ could be calculated as equation (3):

$$C(PM_{2.5,S,res}) = C(PM_{2.5,S}) \times \frac{Model[E_{p,S,total}] - Model[E_{p,S,total} - \alpha \times E_{p,S,res}]}{\sum_{sector \in \{res, other\}} (Model[E_{p,S,total}] - Model[E_{p,S,total} - \alpha \times E_{p,S,sector}])} \quad (3)$$

In addition, the residential emissions could also be attributed to cooking and heating activities as:

$$E_{p,S,res} = E_{p,S,cooking} + E_{p,S,heating} \quad (4)$$

Based on the same method, the $PM_{2.5}$ concentration due to residential emissions could be further attributed to rural cooking emissions and heating emissions as equation (5): $C(PM_{2.5,S,act}) =$

$$C(PM_{2.5,res}) \times \frac{Model[E_{p,S,total}] - Model[E_{p,S,total} - \alpha \times E_{p,S,act}]}{\sum_{act \in \{cooking, heating\}} (Model[E_{p,S,total}] - Model[E_{p,S,total} - \alpha \times E_{p,S,act}])} \quad (5)$$

when $act \in \{cooking, heating\}$.

Unlike ambient $PM_{2.5}$, the indoor $PM_{2.5}$ concentration is calculated differently using a statistical approach⁶⁻⁸ with the updated indoor air quality database by Chen et al., (2018).⁹ The indoor $PM_{2.5}$ concentration is calculated differentially based on the use of solid fuels versus clean energy. For households using solid fuels, statistical data from the literature classified by fuel type, stove type, and other criteria are utilized to represent indoor $PM_{2.5}$ levels. In contrast, for households that exclusively use clean energy, the indoor $PM_{2.5}$ concentration primarily arises from outdoor infiltration, which can be calculated using the outdoor $PM_{2.5}$ concentration along with an infiltration coefficient algorithm as equation (6) introduced by Xiang et al.¹⁰:

$$F_{inf} = \frac{AER_{open} \times P_{open}}{AER_{open} + K} \times \frac{t_{open}}{t_{open} + t_{closed}} + \frac{AER_{closed} \times P_{closed}}{AER_{closed} + K} \times \frac{t_{closed}}{t_{open} + t_{closed}} \quad (6)$$

When F_{inf} is the infiltration factor of $PM_{2.5}$ that represents the ratio of indoor $PM_{2.5}$ concentration to ambient $PM_{2.5}$ concentration under stable conditions; AER is the air exchange rate of $PM_{2.5}$; P is the penetration factor of $PM_{2.5}$; K is the primary sedimentation rate of $PM_{2.5}$; t is the duration for the different door and windows status (open or closed). Household energy information is from nationwide surveys which have accounted for stacked energy use¹¹⁻¹². Then for each county, the average $PM_{2.5}$ indoor level was calculated by weighting the $PM_{2.5}$ concentration of each energy group by the time-sharing fraction of each respective energy

source.

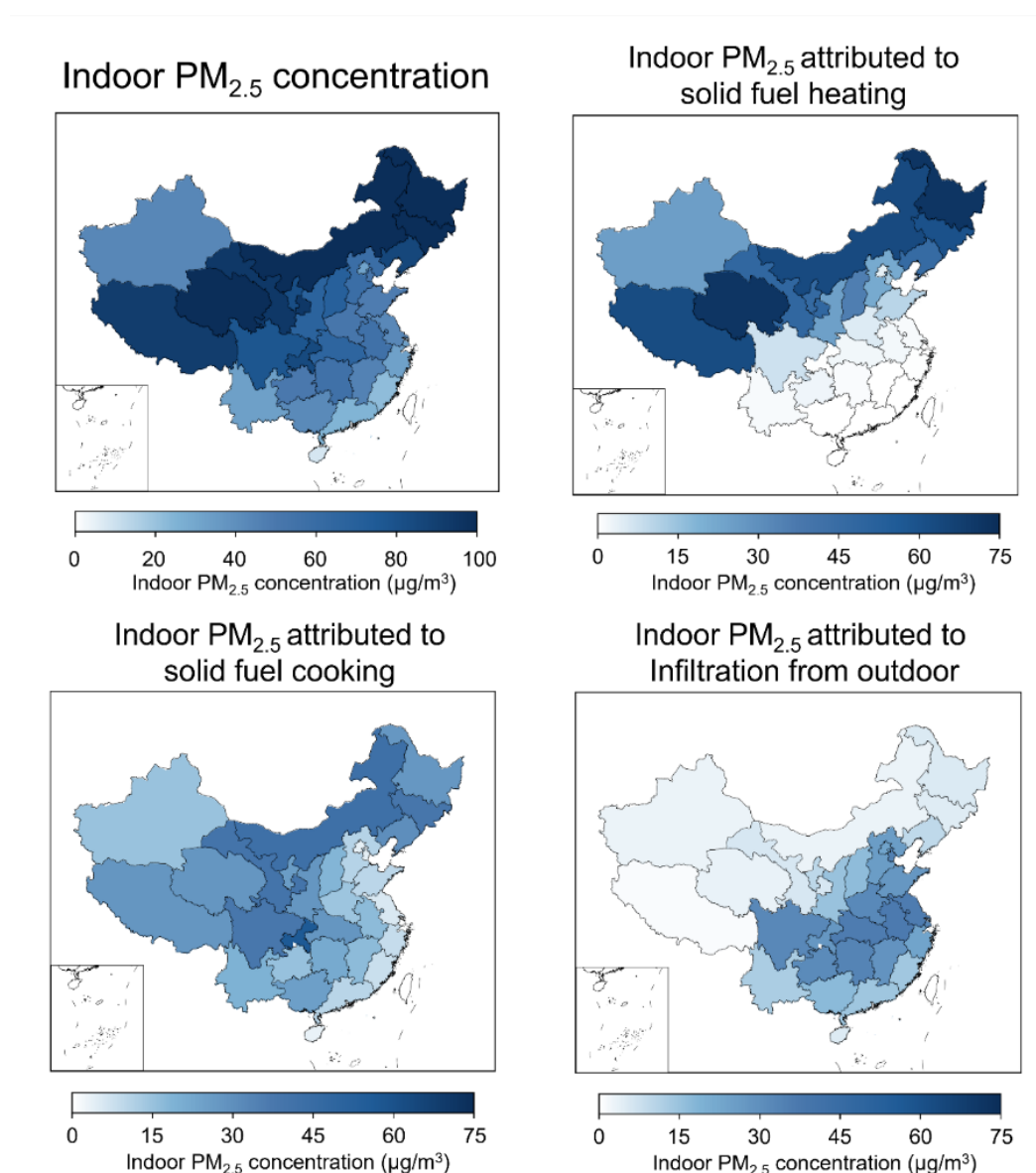


Figure s6: Spatial distribution of indoor PM_{2.5} concentrations and their contributions from solid-fuel combustion for heating and cooking, as well as infiltration from outdoors.

The modelled indoor PM_{2.5} concentration, together with contributions from indoor solid fuel combustion and outdoor infiltration, are illustrated in **Figure s6**. The model reproduces a pronounced north–south gradient, with higher concentrations in northwestern China and lower concentrations in the southeast. This spatial pattern is consistent with field measurements of indoor PM_{2.5}, supporting the model’s internal validity in capturing regional contrasts¹³⁻¹⁴. Contribution of solid-fuel heating to indoor PM_{2.5} reasonably followed the spatial distribution of heating demand. It is most pronounced in Northeast China and the Tibetan Plateau, where longer heating seasons and higher heat requirements prevail. The contribution to the annual

mean indoor concentration could reach up to 74.4 (59.6–83.6) $\mu\text{g}/\text{m}^3$ in Heilongjiang, the northernmost province. In contrast, the cooking-related contribution is more spatially uniform and is primarily determined by the local share of solid fuels used for cooking, exhibiting a clear west–east gradient, being higher in the west and lower in the east, which is consistent with the difference in economic development. The contribution from infiltration of outdoor air is mainly governed by ambient $\text{PM}_{2.5}$ and the percentage of clean energy use, with relatively high infiltration-driven contributions concentrated in southern regions.

References cited here: :

1. Global Emission Modeling System (GEMS). <https://gems.pku.edu.cn>. Accessed Nov. 2025.
2. Meng, W., Cheng, Y., Shen, G. et al. The Long Hazy Tail: Analysis of the Impacts and Trends of Severe Outdoor and Indoor Air Pollution in North China. *Environ. Sci. Technol.* 2024; 58: 8326–8335.
3. Zhong, Q., Ma, J., Shen, G., et al. Distinguishing Emission-Associated Ambient Air $\text{PM}_{2.5}$ Concentrations and Meteorological Factor-Induced Fluctuations. *Environ. Sci. Technol.* 2018; 52: 10416–10425.
4. Zhong, Q., Tao, S., Ma, J., et al., $\text{PM}_{2.5}$ reductions in Chinese cities from 2013 to 2019 remain significant despite the inflating effects of meteorological conditions. *One Earth* 2021; 4(3): 448–458.
5. Yu, X., Zhong, Q., Zhang, W., et al., Direct and inverse reduced-form models for reciprocal calculation of BC emissions and atmospheric concentrations. *Environ. Sci. Technol.* 2021; 55: 10300–10309
6. Yun, X., Shen, G., Shen, H. et al., Residential solid fuel emissions contribute significantly to air pollution and associated health impacts in China. *Sci. Adv.* 2020; 6: eaba7621.
7. GBD 2021 HAP collaborators. Global, regional, and national burden of household air pollution, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *The Lancet.* 2025; 405: 1167–1181.
8. Mestl, H. E. S. et al. Urban and rural exposure to indoor air pollution from domestic biomass and coal burning across China. *Sci. Total Environ.* 2007; 277: 12–26.
9. Chen, Y. et al. Estimating household air pollution exposures and health impacts from space heating in rural China. *Environ. Int.* 2018; 119: 117–124.
10. Xiang, J. et al. Reducing Indoor Levels of “Outdoor $\text{PM}_{2.5}$ ” in Urban China: Impact on Mortalities. *Environ. Sci. Technol.* 20149; 53: 3119–3127.
11. Tao, S., Ru, M., Du, W., et al. Quantifying the rural residential energy transition in China from 1992 to 2012 through a representative national survey. *Nature Energy* 2018; 3: 567–573.
12. Shen, G., Xiong, R. Tian, Y., et al., Substantial transition to clean household energy mix in rural China. *Nat. Sci. Rev.* 2022; 9: nwac050.
13. Zhang A, Liu Y, Zhao B, et al. Indoor $\text{PM}_{2.5}$ concentrations in China: A concise review of the literature published in the past 40 years. *Building and Environment* 2021; 198: 107898.

14. Du W, Li X, Chen Y, Shen G. Household air pollution and personal exposure to air pollutants in rural China – A review. *Environmental Pollution* 2018; 237: 625–38.

A4. Premature death calculation

To quantify human exposure to PM_{2.5}, this study first categorized the population by time-activity modes and residential energy utilization types. For time-activity mode, the outdoor and indoor dwell time of residences with different ages, sexes, regions and seasons are derived from the Exposure Factors Handbook of Chinese Population.¹ Due to varying exposure levels in different rooms (such as kitchens and living rooms), indoor activity time is further categorized based on room types, utilizing data from available literature studies.²⁻³ The proportion of residents' indoor stay time is divided into kitchen, living room, and other rooms.

Based on time share information as mentioned above, individual exposure to PM_{2.5} could be calculated by equation (7):

$$exposure = \sum_{i,s} C_{i,s} \times t_{i,s} \times \frac{d_s}{\sum_s d_s} \quad (7)$$

Where i is the environment (outdoor, kitchen, living room, and other room), s is the season (heating season or non-heating season), d_s represents the total days of the season s , $C_{i,s}$ represents the PM_{2.5} concentration, $t_{i,s}$ is the share of dwell time in different environments. Based on the weighted proportions of different population groups, the average PM_{2.5} exposure level for the population within a grid could be calculated by equation (8):

$$EXP = \sum exposure_{a,m,f,l} \times F_{a,m,f,l} \quad (8)$$

where a is the age range, m is the gender, f is the fuel type, l is the location of stove, F is the fraction of specific population in the grid.

Population weighted exposure (PWE) on a national scale, used as the primary indicator of exposure levels in this study, could be calculated by equation (9):

$$PWE = \frac{\sum_g EXP_g \times Pop_g}{\sum_g Pop_g} \quad (9)$$

where g represents the grid within the country, Pop denotes the population, and the summation aggregates all grids across the entire country.

PM_{2.5}-induced premature deaths are calculated based on the PWE and the latest integrated non-linear exposure-dose function (IER) from the Global Burden of Disease (GBD).⁴ Considering five related diseases that include: acute lower respiratory infections (ALRIs), chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), lung cancer (LC) and cerebrovascular disease (Stroke), the IER can be used to calculate the population attributable fraction (PAF) for each disease based on PM_{2.5} exposure. PAF refers to the percentage of total deaths from a disease that are attributable to PM_{2.5} exposure. Using basic mortality rate data in

2019 provided by GBD and supplemented with data from China Statistical Yearbook, ⁵⁻⁶ we constructed a provincial-level basic mortality rate database for each disease, differentiated by urban and rural areas. Thus, the number of premature deaths attributable to PM_{2.5} exposure can be calculated by equation (10):

$$Death = \sum_{g,a,d} Pop_{g,a} \times MR_{g,a,d} \times PAF_{g,a,d} \quad (10)$$

where g is the grid, a is the age range, d is the disease, MR is the basic mortality rate of the province where the grid g is located.

References cited here:

1. Duan, X. Exposure Factors Handbook of Chinese Population. (China Environmental Science Press, 2013).
2. Mestl, H. E. S. et al. Urban and rural exposure to indoor air pollution from domestic biomass and coal burning across China. *Science of The Total Environment* 377, 12–26 (2007).
3. Chen, Y. et al. Estimating household air pollution exposures and health impacts from space heating in rural China. *Environment International* 119, 117–124 (2018).
4. Cohen, A. J. et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *The Lancet* 389, 1907–1918 (2017).
5. National Bureau of Statistics of China. China Statistical Yearbook 2020. (China Statistics Press, 2020).
6. Murray, C. J. L. et al. Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet* 396, 1223–1249 (2020).

A5. Cost and health benefit quantification

The cost of clean heating transition was the sum of costs for the initial capital construction and installation, purchase and regular maintenance of heating device, daily electricity consumption, and the avoided costs of coal. For the biomass substitution option, biomass fuel costs are also included. Following Meng et al., (2023),¹ the cost of grid device for renovation depends on the coverage area; the grid installation cost considers both the installation of indoor equipment and cable laying expenses; household heating device costs are based on the market price of air-source heat pumps; maintenance costs are set at 5% of the initial renovation cost; electricity costs are calculated based on residential electricity prices and household electricity demand, which is determined by the number of heating days and daily heating hours. The costs of clean cooking only include the cooking device, energy cost, and coal-related cost savings. The cooking device costs are determined by market prices, while cooking energy consumption is based on appliance power, the calorific value and efficiency of liquefied petroleum gas (LPG), and daily cooking duration. Coal savings are included in the cost analysis, though they contribute as a negative value.

The total investment costs are broken down to analyze the government and household cost burdens. The additional costs to be borne by residents include the purchase of heating equipment, electricity expenses, and supplementary costs for biomass pellets. Heating equipment is subsidized by the government at a rate of at least 20% in accordance with existing policies, with a coefficient of variation (CV) of 15% adopted to account for uncertainty. The remaining costs, including those for power grid construction, installation, and operation and maintenance, are jointly borne by the government and enterprises.

The results at the national scale, averaged across households, are presented as the annualized cost over 20 years using a 4% discount rate with a sensitivity range of 2-10% in the cost-benefit analysis. As shown in **Figure s7**, the costs, benefits, as well as the benefit-to-cost ratios are generally less sensitive to the different discount rates here, with the relative differences in their mean values in 11%, 2%, and 13%, respectively.

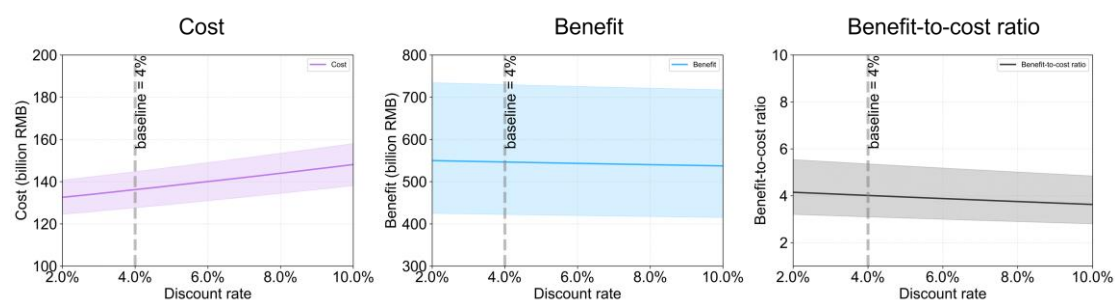


Figure s7: Changes in the costs, benefits, and the benefit-to-cost ratios in response to the

discount rate from 2% to 10%. Results shown are for the clean cooking C2 scenario and clean heating scenario H3. Scenario C2, where all such households complete the transition to clean cooking, and for clean heating scenarios H3, the per-household investment cap for power grid renovation is 8,000 RMB.

For health benefit monetization, following Meng et al., (2023) and Yan et al., (2022),¹⁻² we adopted the value of a statistical life (VSL) and used the income to adjust the standard VSL to the value of different regions and time using the following equations with the income elasticity of 0.5, VSL values are critical for calculating these benefits, and a mean of 4.50 million RMB per capita is adopted with a range of 3.34-6.24 million RMB in the sensitivity analysis.²⁻³

$$VSL_{p,t_0} = VSL_{n,t_0} \times \left(\frac{Income_{p,t}}{Income_{n,t_0}} \right)^{0.5} \quad (11)$$

$$VSL_{p,t} = VSL_{p,t_0} \times \left(\frac{Income_{p,t}}{Income_{p,t_0}} \right)^{0.5} \quad (12)$$

VSL values are critical for quantifying these benefits. For example, in scenario C2, the benefit-to-cost ratio can vary from 5.46 (3.90-7.18) to 10.21 (7.29-13.41). Despite uncertain VSL values, the sensitivity analysis confirms that clean renovation yields substantial net benefits with the benefit-to-cost ratios >1.0 (**Figure s8**). Note that the VSL values employed here are assumed to be identical across all age groups, despite the inherent variability in actual VSL. If distinct VSL values were applied to different age groups, the absolute values of aforementioned cost-benefit ratios may differ; however, the core conclusion, that the proposed intervention remains cost-effective, would remain unchanged.

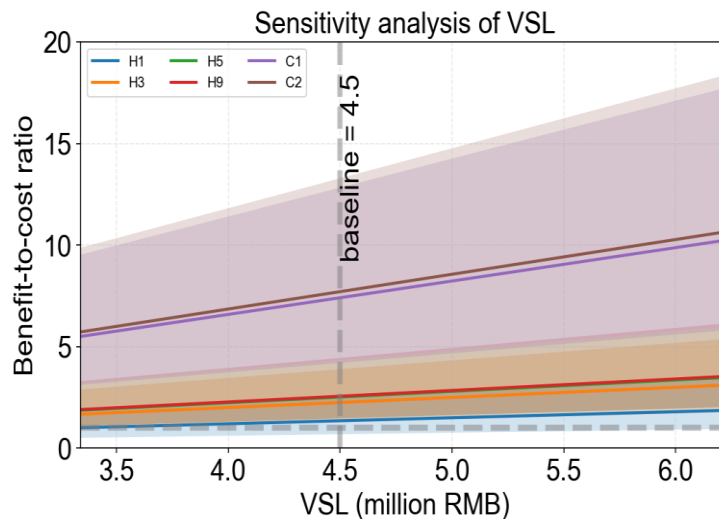


Figure s8: Sensitivity analysis of the benefit-to-cost ratios using different values of a statistical life (VSL) under different scenarios.

References cited here:

1. Meng, W., Zhu, L., Liang, Z., et al. Significant but Inequitable Cost-Effective Benefits of a Clean Heating Campaign in Northern China. *Environ. Sci. Technol.* 2023; 57: 8467-8475.
2. Yan M, Xie Y, Zhu H, Ban J, Gong J, Li T. The exceptional heatwaves of 2017 and all-cause mortality: An assessment of nationwide health and economic impacts in China. *Science of The Total Environment* 2022; 812: 152371.
3. Jin Y, Andersson H, Zhang S. Do preferences to reduce health risks related to air pollution depend on illness type? Evidence from a choice experiment in Beijing, China. *Journal of Environmental Economics and Management* 2020; 103: 102355.

A6. Burden of transition costs in different regions

The additional investment required accounts for less than 1.5% of general expenditures, and <1.0% in most provinces. As seen in **Figure s9**, Hebei and Shandong provinces have the highest ratios, at 1.3% and 1.1% respectively, while the ratios of other provinces are all below 0.8%. This will not impose a significant burden on government finances. However, it should be noted that this represents the annualized cost; the burden of one-time investment in construction remains relatively substantial, which requires joint efforts from the government and enterprises to advance.

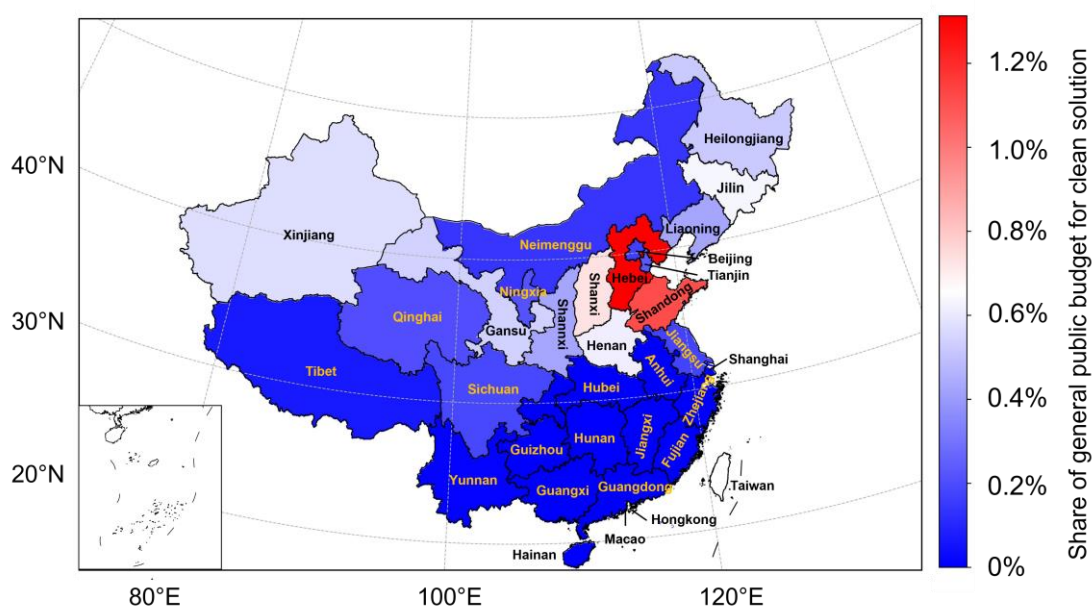


Figure s9: Percentages of the estimated general public budget for clean heating solution in different regions. The case is clean heating scenario H3 where per-household investment cap is 8,000 RMB. The expenses from the government include those related to heating renovation, installation and maintenance, and a 20% subsidy on heating equipment purchases to each household.

Significant increases in renovation rates with additional investment are observed in the North China Plain, Northeast Plain, Xinjiang, and the Gansu Corridor (**Figure s10**), while other areas, such as the QTP and the Inner Mongolian Plateau, being characterized by complex terrain or low population density, are less suitable for such large-scale power grid renovation. However, these regions often have abundant biomass resources, which could serve as an alternative energy source after processing. Processed biomass derived from brushwood or straw can effectively utilize local resources and partially address the issue of agricultural straw disposal. While the direct combustion of brushwood and straw generates substantial air pollution, the use

of processed pellets or briquettes, in combination with improved clean stoves, can significantly reduce air pollutant emission.

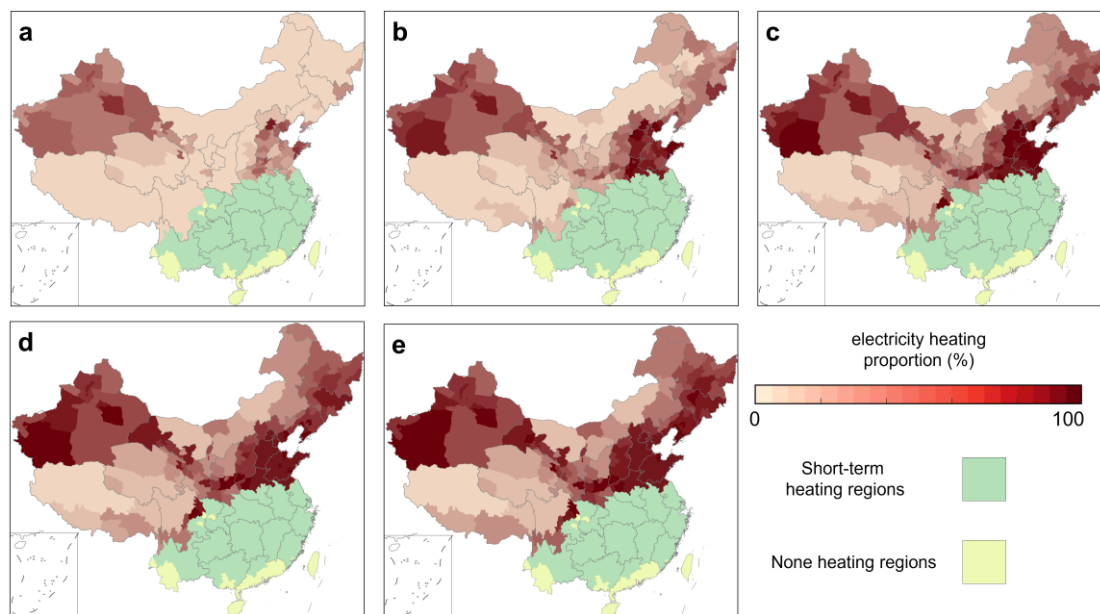


Figure s10: Spatial distribution of the proportion of clean electric heating in long-term heating region under per-household investment caps of (a) 4000, (b) 6000, (c) 8000, (d) 10000, and (e) 12000 RMB, that correspond to the scenarios H1 to H5, respectively.

A7. Changes in emissions and ambient air quality under different scenarios

Clean cooking and heating can significantly reduce both indoor and outdoor pollutant emissions while also lowering carbon emissions (**Figure s11**). For clean cooking scenarios, replacing solid fuels with clean modern energy either at levels of 50% or 100% would result in linear reductions in the emissions of most air pollutants, except for NO_x that remains about 5% emissions. For heating emissions, as mentioned above with the increased investment cap from 4,000 to 12,000 RMB/household (Scenarios H1 to H5), there would be more homes switching to clean heating, and consequently more air pollutant reductions. The marginal emission reduction would be smaller from H1 to H5. Among different clean transition scenarios, it is estimated that primary PM_{2.5} emission would be reduced from 724 (612-967) Gg at baseline to 351 (309-470) Gg in H3, or by about 52%. In H3, hazardous air pollutant emissions in most areas could be effectively reduced. The remaining emissions in the next round of clean heating plan would primarily be from the Northeast and Southwest regions of China. After H3, if these other regions adopted biomass pellets for space heating, primary PM_{2.5} would be further reduced to ≥ 256 (205-312) Gg, depending on the coverage of new biomass heating.

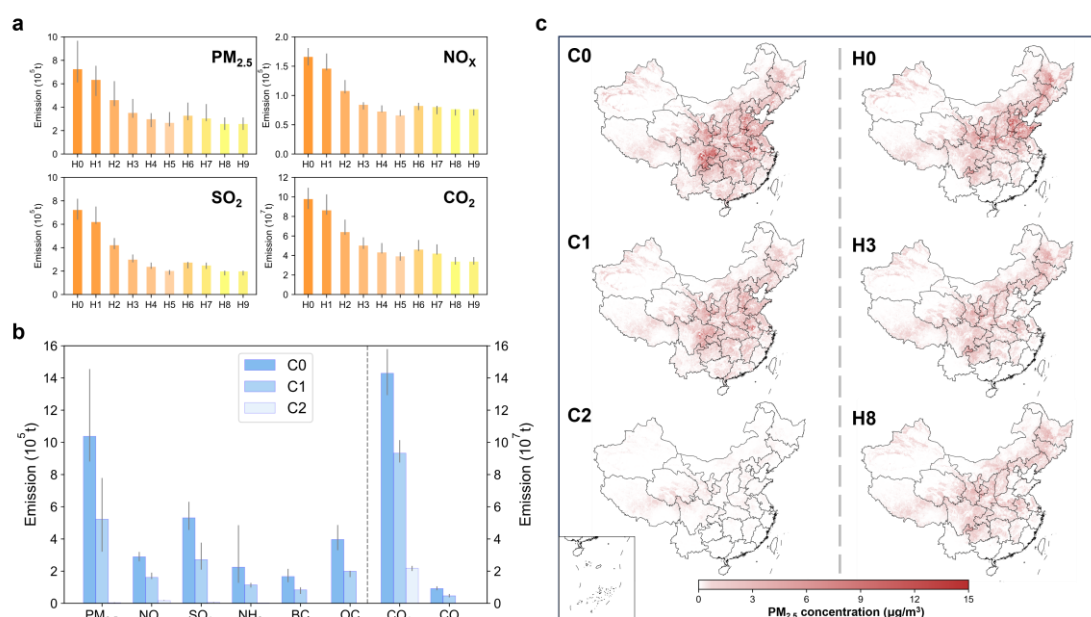


Figure s11: Pollutant emission changes in different clean heating (a) and cooking (b) scenarios; and the modelled ambient PM_{2.5} concentration distributions (c) in different scenarios. Cooking scenarios C0-the baseline in 2019, C1 - 50% of these households switch entirely to clean energy, and C2- 100% of these households make the transition to clean energy; Clean heating scenarios H0 and H3- a clean heating innovation under the investment cap of 0 and 8000 RMB per household, respectively, and H8- based on H3 with the rest, 40%, distributed evenly across the area, will adopt biomass pellets with improved stoves for space heating.

Rural residential emissions contribute about 13% ($2.0 \mu\text{g}/\text{m}^3$) to annual average national ambient $\text{PM}_{2.5}$ concentration ($15.5 \mu\text{g}/\text{m}^3$), with cooking and heating activity contributions of approximately 1.09 (0.97 - 1.18) $\mu\text{g}/\text{m}^3$ and 0.91 (0.68 - 1.12) $\mu\text{g}/\text{m}^3$, respectively. For the scenario of universal clean cooking, ambient $\text{PM}_{2.5}$ due to rural residential cooking emissions would reduce from the 1.09 (0.97 - 1.18) $\mu\text{g}/\text{m}^3$ to 0.08 (0.07 - 0.09) $\mu\text{g}/\text{m}^3$ (**Table s1**).

Table s1: National average ambient $\text{PM}_{2.5}$ concentration ($\mu\text{g}/\text{m}^3$) contributed by residential emissions under different scenarios. H0-H9 represent the contributions of heating emissions under different heating scenarios, while C0-C2 represent the contributions of cooking emissions under different cooking scenarios. The values in the central table indicate the total residential contribution of each scenario combination. Data showns are the median values with the interquartile ranges from the Monte Carlo simulation.

		H0:	H1:	H2:	H3:	H4:	H5:	H6:	H7:	H8:	H9:
	Heating	0.91	0.82	0.68	0.57	0.51	0.47	0.55	0.53	0.49	0.48
	Cooking	(0.68-1.12)	(0.58-1.09)	(0.48-0.91)	(0.40-0.76)	(0.36-0.68)	(0.33-0.63)	(0.39-0.73)	(0.37-0.71)	(0.35-0.65)	(0.34-0.64)
C0: 1.09 (0.97-1.18)		2.00	1.91	1.77	1.66	1.6	1.56	1.64	1.62	1.58	1.57
		(1.79-2.30)	(1.69-2.25)	(1.58-2.05)	(1.49-1.90)	(1.44-1.81)	(1.40-1.76)	(1.47-1.87)	(1.45-1.84)	(1.42-1.79)	(1.41-1.77)
C1: 0.66 (0.59-0.72)		1.57	1.47	1.34	1.23	1.17	1.12	1.21	1.19	1.14	1.14
		(1.36-1.85)	(1.27-1.80)	(1.17-1.62)	(1.09-1.47)	(1.04-1.37)	(1.00-1.30)	(1.07-1.43)	(1.06-1.40)	(1.01-1.33)	(1.02-1.33)
C2: 0.08 (0.07-0.09)		0.99	0.90	0.76	0.65	0.59	0.55	0.63	0.61	0.57	0.56
		(0.77-1.21)	(0.67-1.19)	(0.57-1.00)	(0.49-0.85)	(0.45-0.77)	(0.42-0.72)	(0.48-0.82)	(0.46-0.80)	(0.43-0.75)	(0.43-0.73)

For clean heating transitions, significant reductions in ambient $\text{PM}_{2.5}$ could be also expected. In H3, annual mean $\text{PM}_{2.5}$ due to rural residential heating emissions would be reduced from 0.91 (0.68 - 1.12) $\mu\text{g}/\text{m}^3$ to 0.57 (0.40 - 0.76) $\mu\text{g}/\text{m}^3$, by about 37%, and with the remaining homes changing to cleaner biomass fuels in advanced stoves, ambient $\text{PM}_{2.5}$ would decline further to 0.48 (0.34 - 0.64) $\mu\text{g}/\text{m}^3$. From scenarios H1 to H5, the ambient $\text{PM}_{2.5}$ does not linearly reduce, but shows gradually decreasing marginal benefit. Spatial distributions of ambient $\text{PM}_{2.5}$ due to heating emissions change under different transition scenarios, as the clean heating switch starts in densely populated plain areas in the North China and then in sparsely populated areas and some mountain villages (**Figure s11**).

Transitions for both cooking and heating energies would have more significant reductions in pollutant emissions and consequent air quality improvement. In the present framework, ambient

PM_{2.5} would reduce from 2.00 (1.79-2.30) µg/m³ to about 1.14 (1.02-1.33) µg/m³ in the case of electric heating with 8,000 RMB/household investment while the remaining 40% of the households use new advanced biomass heating and 50% of all households adopt and use clean cooking (*scenarios* H8&C1). If all switched to clean cooking, the ambient PM_{2.5} would be 0.56 (0.43-0.73) µg/m³, with a reduction of 1.43 µg/m³ (71.5%). Such reduction is substantial and significant.

A8. Changes in indoor air quality

Providing cleaner household energy has significant impacts on indoor air quality and may substantial health benefits. Indoor solid fuel burning, even in vented stoves, leaks considerable amounts of air pollutants directly indoors, a process known as indoor fugitive emissions. About one fourth of primary particles enter the indoor environment with vented stoves burning solid fuels, with more fine than coarse particles released indoors.

Changes in indoor PM_{2.5} under different scenarios for the whole country, and those in the heating and non-heating region, are listed in **Table s2**. Indoor PM_{2.5} in the long-term heating regions is around 63 (56-72) µg/m³. By promoting clean heating, the indoor PM_{2.5} could be effectively reduced to 42 (37-47) µg/m³ in scenario H3, and further to 35 (31-40) µg/m³ in scenario H5. From H3, when the remaining use biomass fuels in improved stoves for heating, indoor PM_{2.5} would be also reduced to some extent, but the degree is small in comparison to the switch to electric heating. Clean heating in the short-term heating and non-heating regions had much smaller impacts on annual mean indoor PM_{2.5}, as the indoor PM_{2.5} in those regions are largely affected by the cooking emissions and from outdoor air.

Unlike clean heating, that mainly affects annual mean indoor PM_{2.5} in the long-term heating regions, clean cooking transitions can result in substantial reductions in indoor PM_{2.5} across the whole country. Clean cooking reduces indoor PM_{2.5} in all regions, but indoor PM_{2.5} can remain elevated, between 15 – 50 µg/m³, depending on region and due to impacts of emissions from indoor heating and/or infiltration of polluted outdoor air. Again, the combination of clean cooking and heating can reduce indoor PM_{2.5} to lower levels that consequently reduces total exposure and yields significant health benefits.

Table s2: Indoor PM_{2.5} concentration (µg/m³) under different scenarios.

Scenario \ Region	Long-term heating region	Short-term heating region	None heating region	National
H0	63 (56-72)	47 (41-55)	29 (25-36)	52 (46-59)
H1	59 (52-67)	47 (41-55)	29 (25-36)	50 (44-57)
H2	49 (43-56)	47 (41-55)	29 (25-36)	46 (40-52)
H3	42 (37-47)	47 (41-55)	29 (25-36)	43 (38-48)
H4	37	47	29	41

	(32-42)	(41-55)	(25-36)	(36-46)
H5	35 (31-40)	47 (41-55)	29 (25-36)	40 (35-45)
H6	41 (36-46)	47 (41-55)	29 (25-36)	43 (38-48)
H7	40 (35-45)	47 (41-55)	29 (25-36)	42 (37-47)
H8	39 (35-44)	46 (40-54)	29 (25-36)	42 (37-47)
H9	38 (34-43)	46 (41-54)	29 (25-36)	41 (37-46)
H0 & C1	54 (48-61)	40 (36-44)	23 (20-26)	44 (40-49)
H0 & C2	48 (43-54)	33 (30-37)	17 (15-19)	38 (34-43)
H3 & C1	39 (35-43)	40 (36-44)	23 (20-26)	38 (34-42)
H3 & C2	33 (30-37)	33 (30-37)	17 (15-19)	31 (28-34)

A9. Exposure levels after the transition

Overall exposure to PM_{2.5}, taking into the consideration both indoor and outdoor exposure, would reduce from 50.2 (40.4-63.5) $\mu\text{g}/\text{m}^3$ in the baseline to 41.9 (34.2-52.3) $\mu\text{g}/\text{m}^3$ in the clean heating scenario H3, or by about 16.5%. Indoor exposure dominates the total exposure, with its relative contributions being over 95% in most cases (**Figure s12**); thus, under different scenarios, changes in total exposure in either the magnitude of reduction or in its spatial distribution, closely mirror changes in indoor exposure.

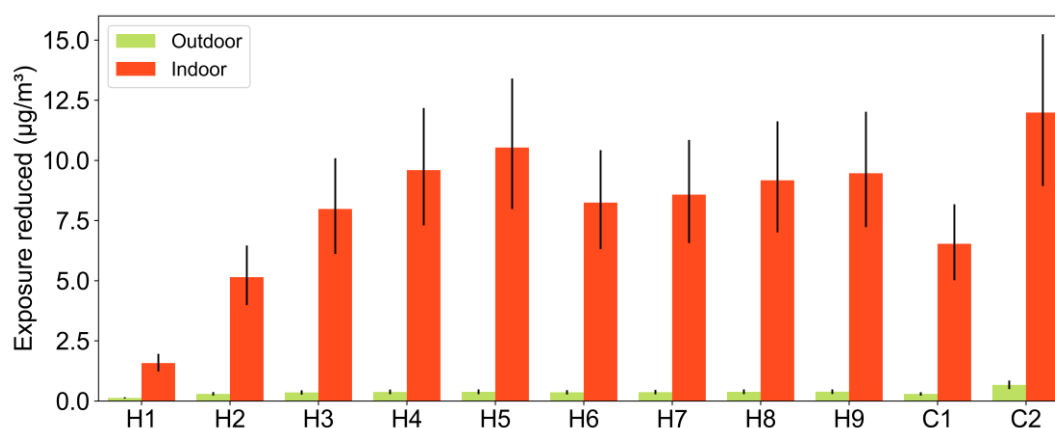


Figure s12: Reduced indoor and outdoor PM_{2.5} exposure levels in different scenarios compared to the baseline H0. Scenario C1, where half of the remaining households relying on traditional solid fuels for cooking switch to clean cooking; and Scenario C2, where all such households complete the transition to clean cooking. For clean heating, scenarios H0 – H5: Differentiated by per-household investment caps for power grid renovation, set at 0 RMB, 4,000 RMB, 6,000 RMB, 8,000 RMB, 10,000 RMB, and 12,000 RMB respectively; Scenarios H6 – H9: Based on an 8,000 RMB per-household grid renovation investment cap (consistent with Scenario H3), where 10%, 20%, 40%, and 40% of households not covered by the renovated grid adopt processed biomass as an alternative clean heating source.

Compared to the baseline scenario, where only 18.9% of the population has PM_{2.5} exposure below the national standard (35 $\mu\text{g}/\text{m}^3$), scenario H3 represents a significant improvement, achieving compliance for 34.5% of the population (**Figure s13**). From H3, when the rest changed to relatively clean biomass fuels for heating, the further reduction in the total PM_{2.5} exposure was small, but there would be more significant impacts when coupled with clean cooking interventions. With totally clean cooking, total PM_{2.5} exposure would be further reduced to 32.0 (26.9-37.9) $\mu\text{g}/\text{m}^3$ in H3 & C2 from 41.9 (34.2-52.3) $\mu\text{g}/\text{m}^3$, compared to the baseline of 50.2 (40.4-63.5) $\mu\text{g}/\text{m}^3$. Under the clean transition in H3 & C2, 56.7% of the population could meet the national air quality standard (**Figure s13**). The improvement was larger in the long-term heating region, where the total PM_{2.5} exposure reduces from the 60.0 (47.0-78.0) $\mu\text{g}/\text{m}^3$ to 40.6 (32.0-52.0) $\mu\text{g}/\text{m}^3$, by about 34%.

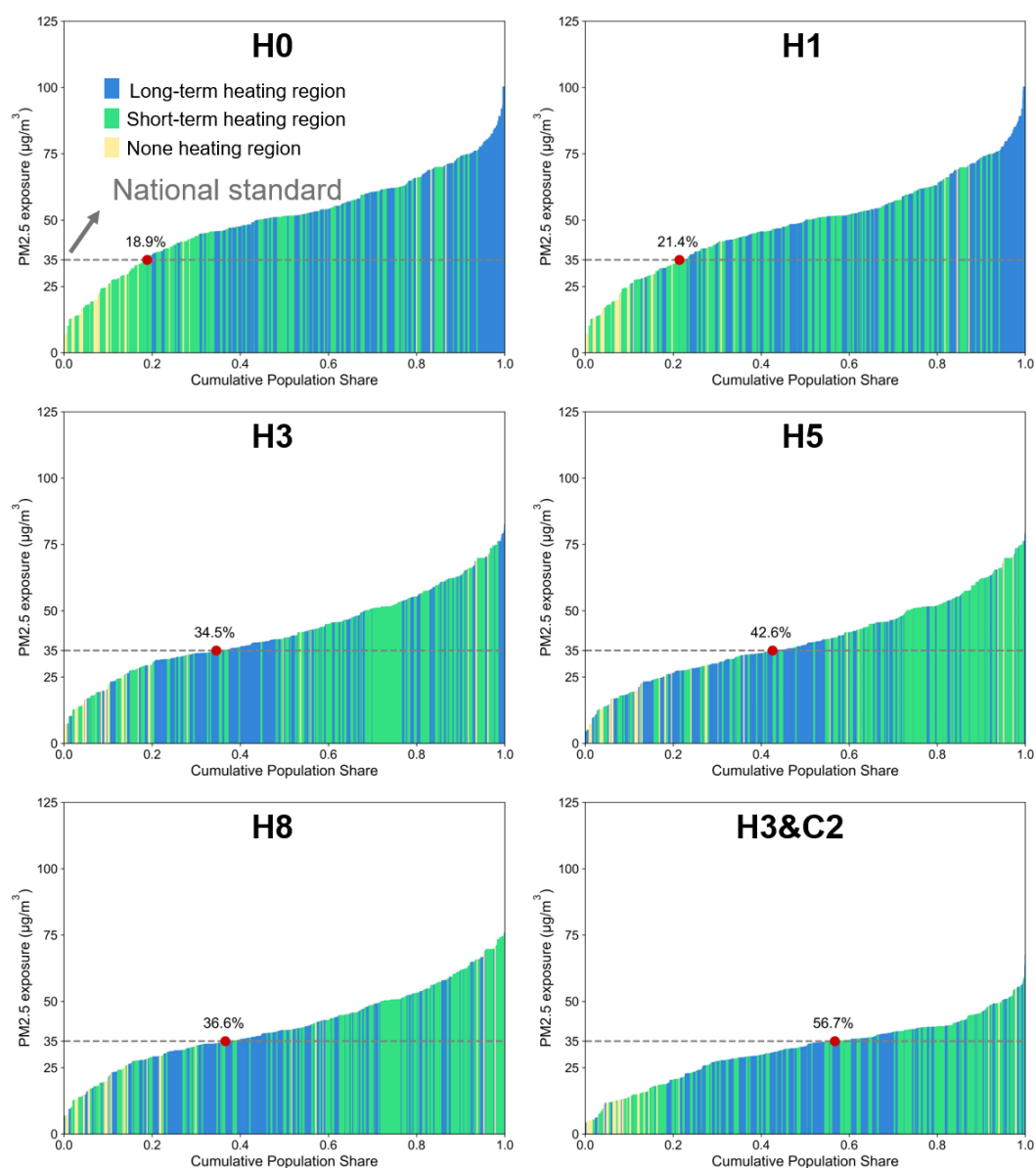


Figure s13: Differences in population $\text{PM}_{2.5}$ exposure levels across different scenarios. The color of the bars represents the regions to which the municipalities belong. The cumulative proportion of the population with $\text{PM}_{2.5}$ exposure below the national air quality standard ($35 \mu\text{g}/\text{m}^3$) is indicated in the figure.

A10. Health impact assessments

Lower PM_{2.5} exposure is undoubtedly important to protect human health. Clean heating can avoid large amounts of premature deaths in both long- and short-term heating regions. In the short-term heating region, the benefit is from reduced PM_{2.5} exposure due to improved outdoor air quality. There would be about 42 (31-55) and 60 (44-79) thousand premature deaths avoided in clean heating scenarios H3 and H5 compared to the baseline. The marginal health benefits decreased with the increasing cost of the electric heating intervention, consistent with changes in PM_{2.5} exposure.

Clean cooking by 50% or the entire country would avert 37 (28-48) and 79 (56-103) thousand premature deaths, comparable to the benefits of the clean heating intervention. Clean cooking interventions would have health benefits in both heating and non-heating regions, but at different degrees. In C1, the premature deaths avoided from the non-heating, short- and long-term heating region were 3.2 (2.1-4.5), 15.3 (11.7-19.4) and 18.8 (13.6-24.7) thousands, respectively. This is closely associated with distinct population densities there, and the non-linear relationship between the PM_{2.5} exposure and health outcomes.

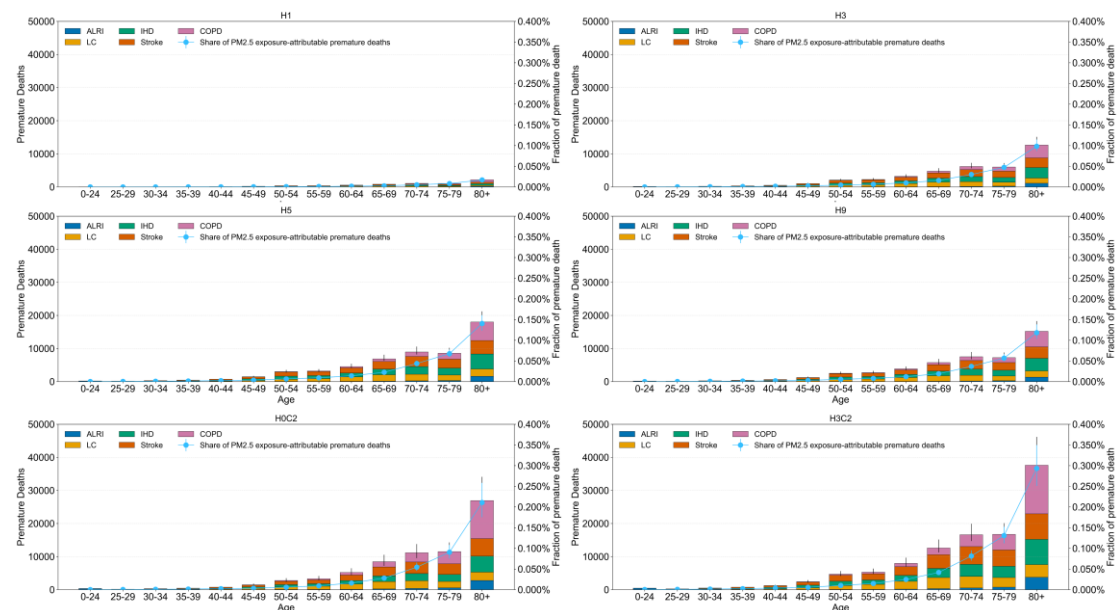


Figure s14: Number of premature deaths avoid (bar) and their proportion relative to the total population (dot) due to reduced PM_{2.5} concentrations across different scenarios and age groups.

For different age groups (**Figure s14**), among the elderly aged over 65 years about 31 (27-35) thousand premature deaths were avoided in H3, accounting for 75 (74-79) % of the total premature deaths averted. When combined with the C2 clean cooking scenario, the national number of premature deaths would decrease by 112 (97-130) thousand, while premature deaths

among those aged over 65 would be about 87 (75-101) thousand. For the elderly, the main diseases avoided are chronic obstructive pulmonary disease (COPD) and stroke, from which the premature deaths averted were 49 (42-59) thousand, accounting for 57 (54-59) % of the total. The health benefit of clean transition is particularly significant for the elderly aged over 80 years, for whom the premature deaths avoided can account for 1.0 (0.9-1.1) ‰ and 2.9 (2.5-3.5) ‰ of the total population in the H3 and H3C2 scenarios, respectively.

Note that even after the clean intervention in H3C2, the ambient PM_{2.5} remains high posing significant health concerns. As illustrated in **Figure s15**, the ambient PM_{2.5}-associated premature deaths remains approximately 446 (411-484) thousand, and for the elderly aged 65 and above, the premature death rate was nearly 4.4 (4.1-4.9) ‰ relative to the total population in this age group.

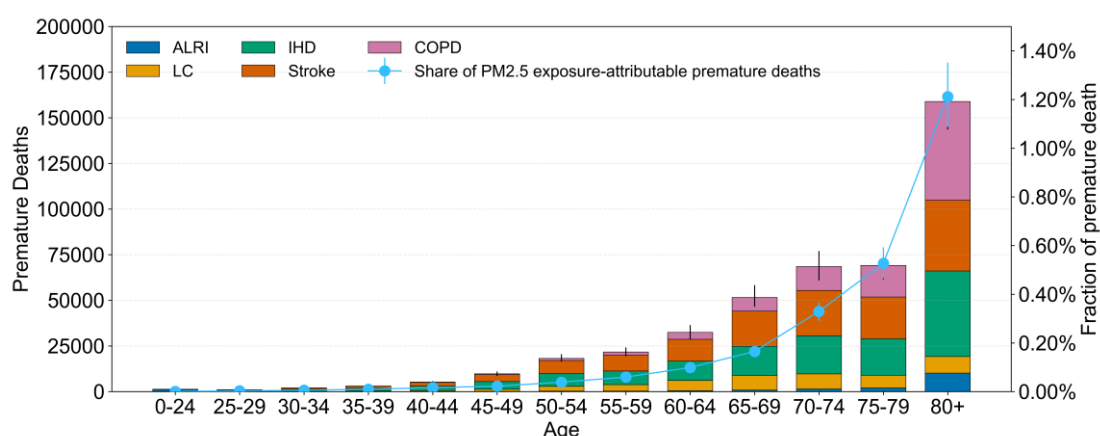


Figure s15: Premature deaths attributable to remaining PM_{2.5} exposure (bars) and their proportion relative to the total population (dots) under scenario H3C2 across different age groups. Scenario C2, where all such households complete the transition to clean cooking, and for clean heating scenarios H3, the per-household investment cap for power grid renovation is 8,000 RMB.

A11. Cost-benefit analysis

The cost of clean heating solution consists of several factors, including power grid equipment, grid installation, household heating devices, device maintenance, electricity consumption, and coal saving. The cost difference across scenarios is primarily attributable to grid investment. Regional differences for the total population covered also induces slight disparity in other costs, such as devices and energy. For example, higher investments may increase the proportion of residents who have heating demand, subsequently resulting in greater per household electricity consumption on a national scale. From H1 to H5, the cost of the clean heating transition increases from 1490 (1184-1805) to 1890 (1648-2122) RMB/household, with the cost in grid equipment and installation increasing from 340 (266-405) RMB to 840 (738-950) RMB/household. Due to the high efficiency of electric heating and current high coal prices, clean heating transitions exhibit economic advantage in terms of energy cost, resulting in a 30 (24-47) RMB/household per heating season savings in H1 to 120 (102-157) RMB/household. Along with the increasing investment cap and coverage households, the total cost expectedly increases faster, but with decreased marginal benefits. The total annual cost for covering the clean heating transition of 75% rural residents in long-term heating region is 88.1 (75.4-101.2) billion RMB in H3. When the total annual cost increase to 112 (98-126) billion RMB in H5, the coverage proportion only increases to 86%. The application of processed biomass slightly increases the cost by 80 (68-93) RMB/household from H3 to H8, because processed biomass is more expensive than dirty coal.

The cost of clean cooking is largely determined by devices and energy. The electric appliances needed for clean cooking include a rice cooker, an induction stove, and an electric water heater, whereas a gas tank and gas stove are also needed for LPG utilization. Considering the total service life, the annual cost of cooking devices is only 90 (85-94) RMB/household with a price distribution. The annual energy costs, including both LPG and electricity, are 1011 (944-1086) RMB/household, of which electricity and LPG contribute 500 (487-515) and 600 (553-653) RMB/household, respectively; displacement of coal saves 89 RMB/household. Since clean cooking is implemented on a household basis, the total annual cost is proportional to the households covered, which is 24.3 (22.7-26.1) billion and 48.6 (45.4-52.3) billion RMB in scenarios C1 and C2, respectively. Considering both cooking and heating, the total annual cost will reach 136 (121-153) billion RMB when adopting H3&C2 clean solution, which accounts for 0.14% (0.12%-0.15%) of national GDP (99 trillion RMB in 2019) and 0.57% (0.50%-0.64 %) of national fiscal expenditure (24 trillion RMB in 2019). In contrast, environmental protection expenses invested by the central government was 33 billion RMB in 2023. Given this large substantial cost, comprehensive clean cooking and heating transitions likely need to be gradually promoted over many years, and rely on investment through multiple channels including central finance, local government, and residents' expenses.

Given the significant premature death avoided by clean residential energy transitions, the health benefit is larger than the cost in each scenario for cooking and heating. The ratio of benefits to costs increases by the scale and types of transitions and the total investment, from 1.34 (0.68-2.61) in H1 to 2.51 (1.46-4.32) in H5. The biomass alternative could also increase the benefit efficiency to some extent. Compared to clean heating, the benefit of clean cooking is much more significant (**Table s3**). One important reason here is clean cooking solutions do not rely entirely on infrastructure investment.

The inter-provincial differences in cost effectiveness are significant (**Table s3**). Costs vary across different regions, and benefits also differ nationwide due to variations in exposure reductions, population size and age structure. For heating renovation, it is most effective in areas with longer strong heating demands such as Xinjiang, Inner Mongolia, and three provinces in the eastern China. For instance, in Heilongjiang province, the benefit-to-cost ratio can be as high as 8.98 (6.80-11.8). In densely populated areas like Shandong and Hebei provinces in the north China plain, the benefit-to-cost ratios are all larger than 1.0. But it is noted that in some areas like Jiangsu province in the south, though a large population live there, the heating duration is much short, thus the clean heating receives small health benefits compared to relatively high costs in electricity power grid renovation.

For cooking, the benefit-to-cost ratio would be as high as 30.6 (22.4-40.3) in Beijing, being the highest across the country. This is because cooking energy sources in the area are already clean, the cost in clean cooking transition is lower resulting in high benefit-to-cost ratios after the transition. In areas like Shaanxi and Shanxi provinces where coals were largely used for cooking, the clean transition significantly reduces costs of coals, that also leads to higher benefit-to-cost ratios. Relatively small cost-effective is observed in Tibet where the clean cooking cost is high as they usually use free biomass fuels now, and the health saving amount is small as a relatively small amount of people live there. The spatial explicit cost-benefit analysis suggested that for clean heating, as the per-household investment increases, the benefit-cost ratio shows an upward trend in most provinces (**Figure s16**).

Different age groups bear distinct health burdens and accrue varying health benefits under the proposed framework, the cost-benefit outcomes are expected to differ across groups, with the elderly age group demonstrating the highest cost-effectiveness (**Figure s17**).

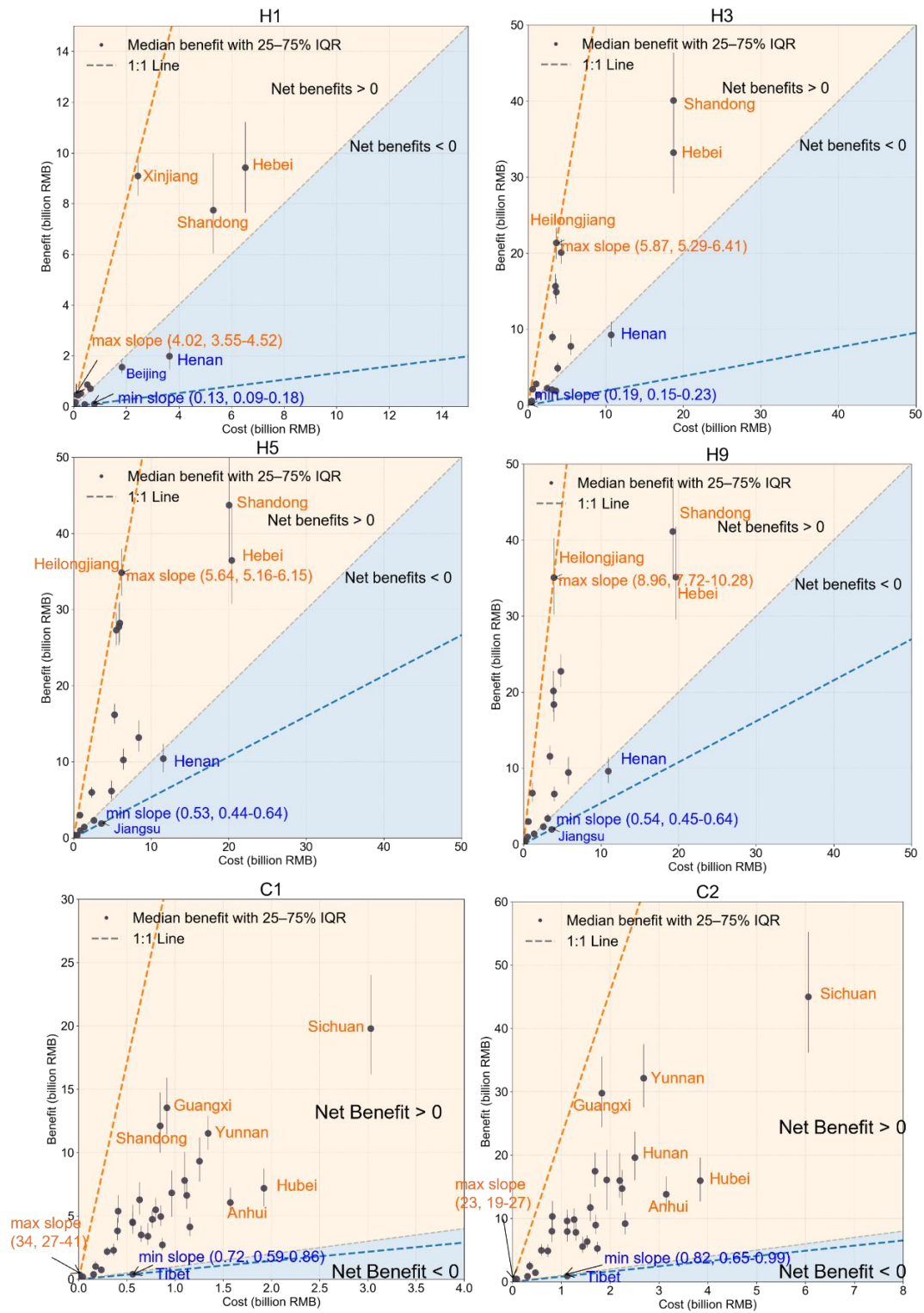


Figure s16: Cost-benefits analysis of the clean heating (scenarios of H1, H3, H5, and H9) and clean cooking (scenarios C1 and C2) transitions across different provinces

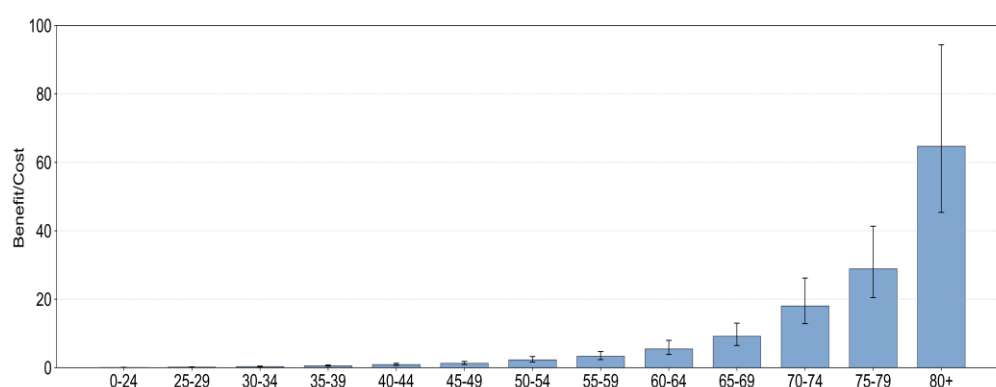


Figure s17: Benefit–cost ratios of clean transition across different age groups under scenario H3C2.

Table s3: Cost-benefit ratios for different provinces in different cooking and heating scenarios. Data shown are the median values with the interquartile ranges. There is not data for Hong Kong, Macao, and Taiwan province. Scenario C1, where half of the remaining households relying on traditional solid fuels for cooking switch to clean cooking; and Scenario C2, where all such households complete the transition to clean cooking. For clean heating, scenarios H1, H3 and H5: Differentiated by per-household investment caps for power grid renovation, set at 4,000 RMB, 8,000 RMB, and 12,000 RMB respectively; Scenarios H9: Based on an 8,000 RMB per-household grid renovation investment cap (consistent with Scenario H3), where 40% of households not covered by the renovated grid adopt processed biomass as an alternative clean heating source.

	H1	H3	H5	H9	C1	C2
Anhui	/*				4.24 (3.08,5.77)	4.85 (3.50,6.66)
Beijing	1.04 (0.74,1.43)	1.20 (0.85,1.67)	1.14 (0.81,1.59)	1.15 (0.82,1.60)	44.87 (31.62,62.02)	30.57 (22.44,40.25)
Fujian	/*				9.31 (6.96,12.48)	10.61 (7.78,14.36)
Gansu	1.31 (1.02,1.70)	2.47 (1.97,3.18)	2.64 (2.12,3.39)	2.86 (2.27,3.68)	5.13 (3.90,7.01)	4.65 (3.51,6.43)
Guangdong	/*				6.97 (5.20,9.25)	7.77 (5.70,10.53)

	H1	H3	H5	H9	C1	C2
Guangxi		/*			15.76 (11.73,20.94)	17.25 (12.51,23.29)
Guizhou		/*			6.37 (4.72,8.57)	6.78 (4.97,9.29)
Hainan		/*			6.28 (4.35,9.70)	7.46 (5.05,11.15)
Hebei	1.37 (0.99,1.88)	1.82 (1.36,2.51)	1.85 (1.38,2.55)	1.79 (1.34,2.48)	10.73 (7.67,15.19)	8.30 (6.25,11.59)
Henan	0.52 (0.34,0.81)	0.88 (0.65,1.21)	0.92 (0.69,1.28)	0.87 (0.65,1.20)	7.63 (5.35,10.83)	7.75 (5.51,10.96)
Heilongjiang	2.27 (1.74,2.98)	5.96 (4.72,7.59)	5.83 (4.64,7.43)	8.98 (6.80,11.76)	10.36 (7.39,15.32)	10.83 (7.59,16.25)
Hubei		/*			4.49 (3.28,6.14)	4.99 (3.60,6.86)
Hunan		/*			8.20 (6.05,11.19)	8.62 (6.28,11.88)
Jilin	3.49 (2.68,4.52)	4.17 (3.31,5.32)	4.71 (3.74,5.97)	4.80 (3.65,6.26)	8.21 (5.78,12.17)	7.32 (5.08,10.98)
Jiangxi		/*			4.09 (3.06,5.62)	4.54 (3.36,6.34)
Jiangsu	0.15 (0.09,0.23)	0.66 (0.48,0.91)	0.66 (0.48,0.91)	0.65 (0.47,0.89)	6.22 (4.22,8.96)	5.05 (3.51,7.16)
Liaoning	1.92 (1.41,2.59)	4.41 (3.40,5.64)	5.13 (4.01,6.55)	4.94 (3.78,6.36)	14.18 (10.36,20.19)	13.66 (9.93,19.24)
Neimenggu	/*	3.02 (2.30,3.93)	2.93 (2.25,3.79)	6.58 (4.72,9.09)	6.32 (4.68,8.83)	7.07 (5.11,10.05)

	H1	H3	H5	H9	C1	C2
Ningxia	/*	1.13 (0.86,1.48)	1.11 (0.84,1.46)	1.80 (1.32,2.38)	2.42 (1.84,3.32)	2.72 (2.07,3.77)
Qinghai	2.44 (1.96,3.12)	3.57 (2.88,4.59)	3.41 (2.74,4.36)	4.44 (3.47,5.77)	3.13 (2.35,4.27)	3.04 (2.26,4.18)
Sichuan	/*	0.76 (0.61,0.99)	1.43 (1.06,1.97)	1.17 (0.90,1.60)	7.48 (5.46,10.45)	8.52 (6.16,12.03)
Shannxi	/*	1.24 (0.96,1.65)	1.56 (1.22,2.04)	1.58 (1.19,2.12)	8.21 (6.18,10.90)	8.75 (6.44,11.63)
Shandong	1.51 (1.09,2.16)	2.36 (1.80,3.20)	2.42 (1.85,3.31)	2.32 (1.78,3.15)	16.54 (12.25,23.48)	11.98 (9.04,16.15)
Shanghai		/*			6.87 (4.89,9.88)	7.25 (5.29,9.80)
Shanxi	0.20 (0.13,0.30)	1.51 (1.10,2.03)	1.68 (1.24,2.24)	1.71 (1.21,2.34)	3.45 (2.58,4.69)	3.36 (2.50,4.61)
Tianjin	1.34 (0.95,1.83)	1.35 (0.94,1.87)	1.34 (0.93,1.84)	1.28 (0.90,1.77)	16.62 (11.30,23.89)	13.60 (9.27,19.16)
Xinjiang	3.59 (2.85,4.59)	4.83 (3.88,6.14)	4.90 (3.87,6.28)	4.74 (3.77,6.02)	6.66 (5.17,8.75)	4.45 (3.41,5.88)
Tibet	/*	0.19 (0.14,0.28)	0.77 (0.62,0.98)	1.78 (1.10,2.57)	0.77 (0.55,1.05)	0.87 (0.60,1.23)
Yunnan	/*	1.29 (1.03,1.65)	1.35 (1.09,1.72)	1.60 (1.20,2.14)	8.50 (6.60,10.97)	11.93 (8.92,15.52)
Zhejiang		/*			10.01 (7.30,13.81)	10.61 (7.65,14.62)
Chongqing		/*			7.51 (4.83,10.77)	8.82 (5.52,13.12)
National	1.34	2.24	2.52	2.55	7.41	7.70

H1	H3	H5	H9	C1	C2
(0.68, 2.61)	(1.27, 3.88)	(1.46, 4.32)	(1.43, 4.40)	(4.05, 13.85)	(4.17, 14.70)

* No clean heating renovation or the health benefits are very small with the premature deaths averted being less than 1.

A12. Inequality in exposure and transition cost

Note that the exposure inequality, as measured by the Gini coefficient, did not show significant changes at the national scale across different scenarios (**Figure s18**). This indicates that although the clean transition strategies are primarily targeted at specific regions, they do not necessarily exacerbate exposure inequality.

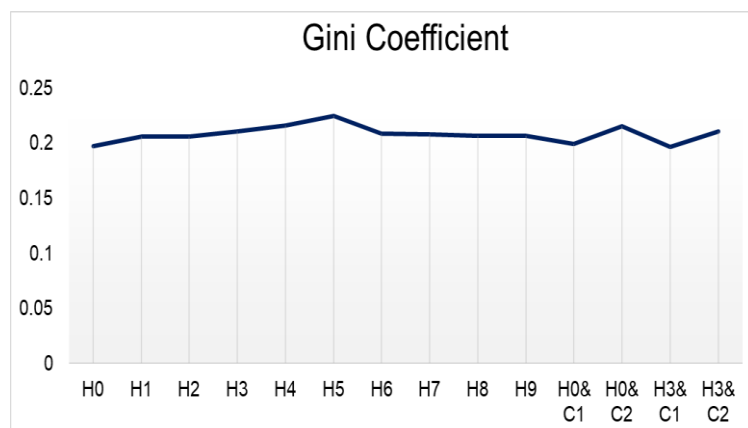


Figure s18: the Gini coefficient of population PM_{2.5} exposure levels across different scenarios.

However, disparities in cost burdens and health-saving benefits among different income groups are substantial. In the scenario H3, the transition cost is relatively low for poor households (with an annual per capita income of <10,000 yuan), at 146 (139-180) RMB/cap, while for households with an income of >10,000 yuan per-capita, the per capita transition cost is very similar, around 180 RMB/cap (**Figure s19**). In the scenario H9, the expenditures across different groups are more comparable. However, this indicates an unequal burden among households with different income levels. The low-income groups have to spend an additional 2% of their annual income on clean renovation, while for groups with an annual income of >20,000 yuan, the burden from clean renovation accounts for only 0.85%. This inequality in burden suggests that in clean renovation efforts, more subsidies should be provided to poor households, especially those in remote mountainous areas. Nevertheless, in terms of health benefits from the transition, low-income households gain the most, with 484 (357–972) RMB/cap and 537 (436–1068) RMB/cap under scenarios H3 and H9, respectively. This is mainly because low-income households rely heavily on solid fuel for heating, suffering largely from hazardous air pollutants from the inefficient burning. Clean renovation plays an equally important, if not more significant, role in protecting the health of low-income groups. For high-income groups, although the health benefits are less than those for low-income groups, they still outweigh their expenditures.

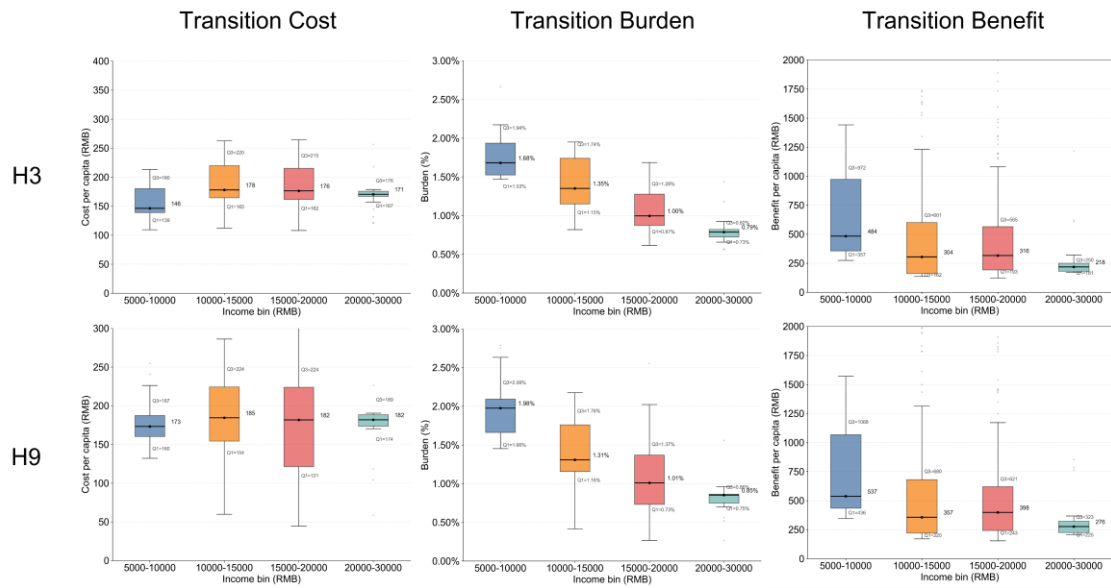


Figure s19: Additional expenses per-capita, burdens, and health benefits for homes at different income levels under the scenarios H3 and H9. scenarios H3: per-household investment caps for power grid renovation at 8,000 RMB, and H9: based on an 8,000 RMB per-household grid renovation investment cap (consistent with Scenario H3), where 40% of households not covered by the renovated grid adopt processed biomass as an alternative clean heating source.

A13. Future changes in the cost burden of the clean innovation.

To analyze future cost burden, the intermediate levelized cost of electricity (LCOE) of 0.067 USD from Wang et al. (2023) and a grid feed-in tariff ratio of 1.5 were adopted.¹⁻² The current power generation mix is projected to be fully replaced by renewable energy sources such as wind and solar at a rate of 25% per decade to calculate price changes. Coal and biomass fuel prices are assumed to remain constant at their 2019 baseline values. Changes in household income were projected based on GDP growth under the SSP2 scenario and an XGBoost regression model of per capita income vs. GDP.³

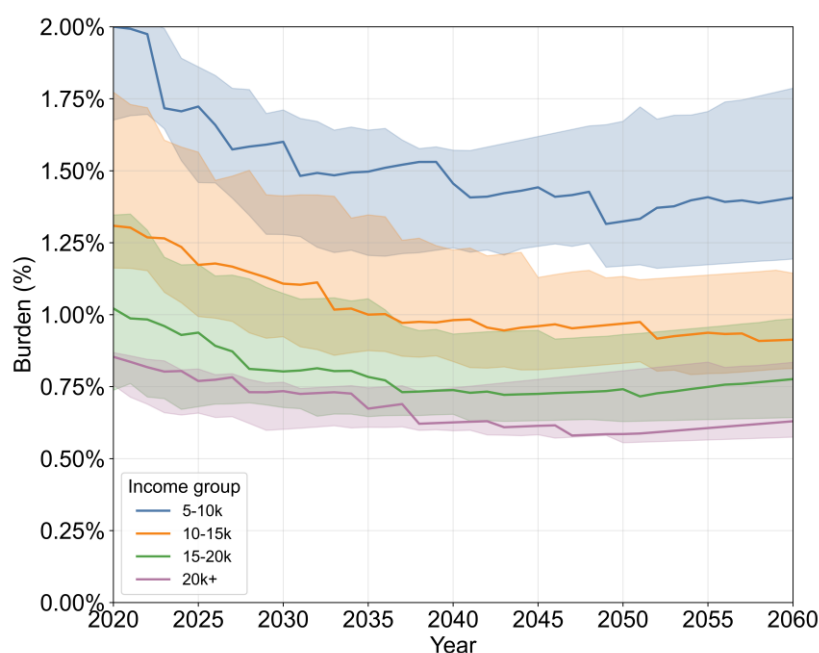


Figure s20: Changes in the increased burden of clean renovation on rural residents due to changes in energy prices and household incomes under the H9 scenario and SSP2 socioeconomic scenario

Generally, the burden of clean renovation on rural residents is expectedly to have a downward trend from 2020 to 2060, primarily driven by increasing household incomes amid economic development, as seen in **Figure s20**. For example, the burden on residents in the "10–15k" income group will decline steadily from 1.3 (1.1–1.8) % in 2020 to 0.9 (0.8–1.1) % in 2060, reaching a very low level. However, due to the deployment and promotion of carbon neutrality goals and low-carbon power generation, rising electricity prices will to some extent exacerbate the clean energy burden. For instance, although the burden on the low-income group, at 5,000–10,000 yuan per-capita, initially declines rapidly, the total burden fluctuates as electricity prices rise, eventually stabilizing at approximately 1.4%. Nevertheless, the reduction in household burden and its maintenance at a low level indicate the long-term sustainability and affordability of clean energy solutions, effectively protecting human health within an affordable range.

For the benefit-to-cost ratio, under the electricity price change, it is found that the ratio is relatively less sensitive to the changed electricity price, as shown in **Figure s21**, in the price range of 0.40 to 0.65 RMB/kwh, the benefit-to-cost ratio change slightly, from 4.01 (0.31-5.36) to 3.68 (2.84-4.92). This suggested that even under the modest long-term fluctuation in electricity price, the clean household energy renovation is significantly cost-effective.”.

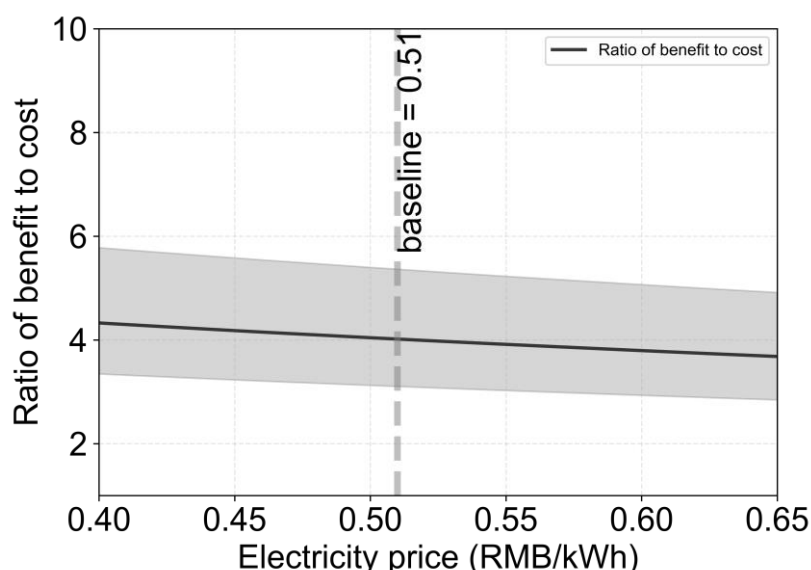


Figure s21: Changes in the benefit-to-cost ratio under the electricity price change in the clean cooking scenario C2 and clean heating scenario H3. Scenario C2, where all such households complete the transition to clean cooking, and for clean heating scenarios H3, the per-household investment cap for power grid renovation is 8,000 RMB.

References cited here:

1. Wang Y., Wang R., Tanaka K., et al. Accelerating the energy transition towards photovoltaic and wind in China. *Nature* 2023; 619: 761–7.
2. Yuan J, Ai Y, Zeng Y, Liu Q, Ouyang M. Research on China's coal-fired power generation cost and on-grid tariff policy. *Coal Economic Research*. 2018, 38(11): 43-48
3. Tong J., Buda S., Cheng J., et al. National and provincial population and economy projection databases under Shared Socioeconomic Pathways (SSP1-5)v2[DS/OL]. V4. Science Data Bank, 2024[2025-10-23]. <https://cstr.cn/31253.11.sciencedb.01683>. CSTR:31253.11. sciencedb.01683.

A14. Pelletized biofuel deployment practice in rural China

Within this framework, approximately 25.5% of the population in long-term heating zones would remain uncovered by electric heating under the H3 scenario, with most concentrated in central mountainous regions (**Figure s22**). If biomass pellets are adopted, even by only 40% of these uncovered households (Scenario H9), an additional 9,040 (6,620–11,840) premature deaths could be averted. This accounts for 21% (18%-25%) of the premature deaths avoided under Scenario H3, indicating substantial health benefits from context-specific solutions tailored to real-world conditions for populations not covered by electric heating.

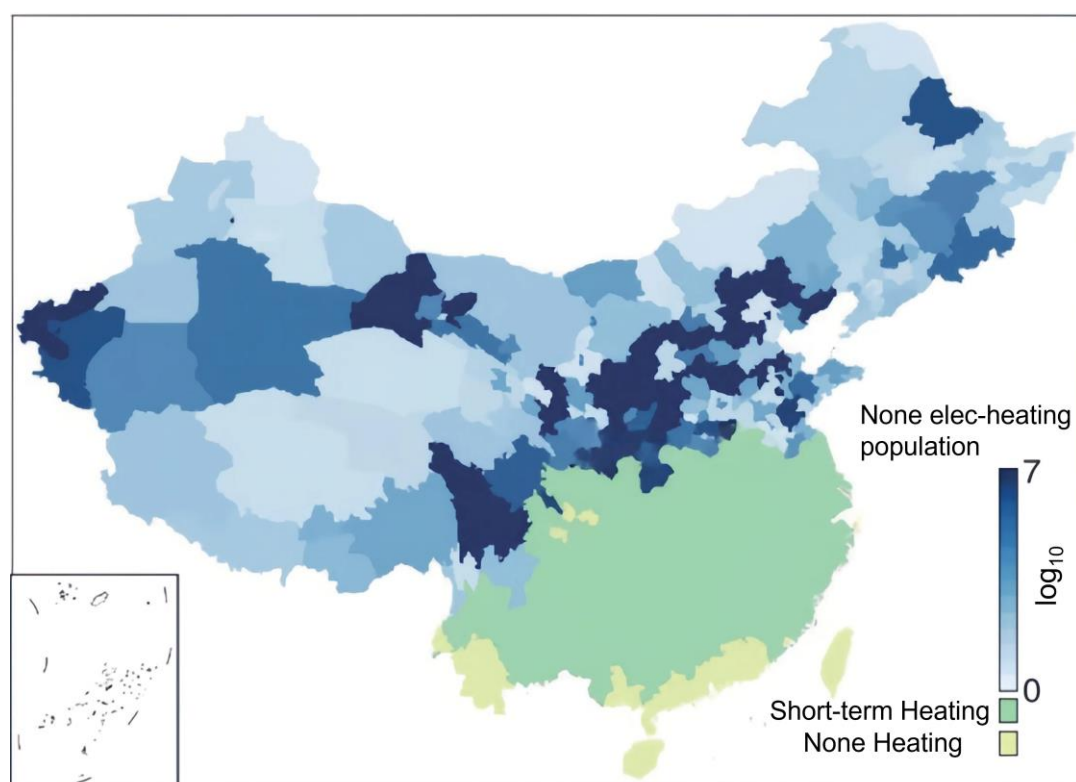


Figure s22: Distribution of the population not covered by electric heating renovation in the H3 scenario.

Relative to H3, in most central provinces the cost of averting one additional premature death under H5 (increasing retrofit investment to 12,000 RMB) is far higher than under H9 (40% biomass supplementation), and this cost ratio can reach 10-fold or more in places such as Inner Mongolia and Tibet (**Figure s23**). This is mainly because many of these areas are dominated by mountainous and hilly terrain, which limits the population that can be reached by additional grid renovation investment, whereas biomass substitution is comparatively a more cost-effective option. By contrast, in the eastern plains, such as Shandong and Hebei provinces, and in Xinjiang, where the terrain is relatively flat but biomass resources are scarce, further grid renovation yield greater benefits. Therefore, the results suggest that combining electrification with pelletized biomass is generally more cost-effective than relying on a single technology, and the optimal mix should be tailored to local terrain, infrastructure, and biomass availability.

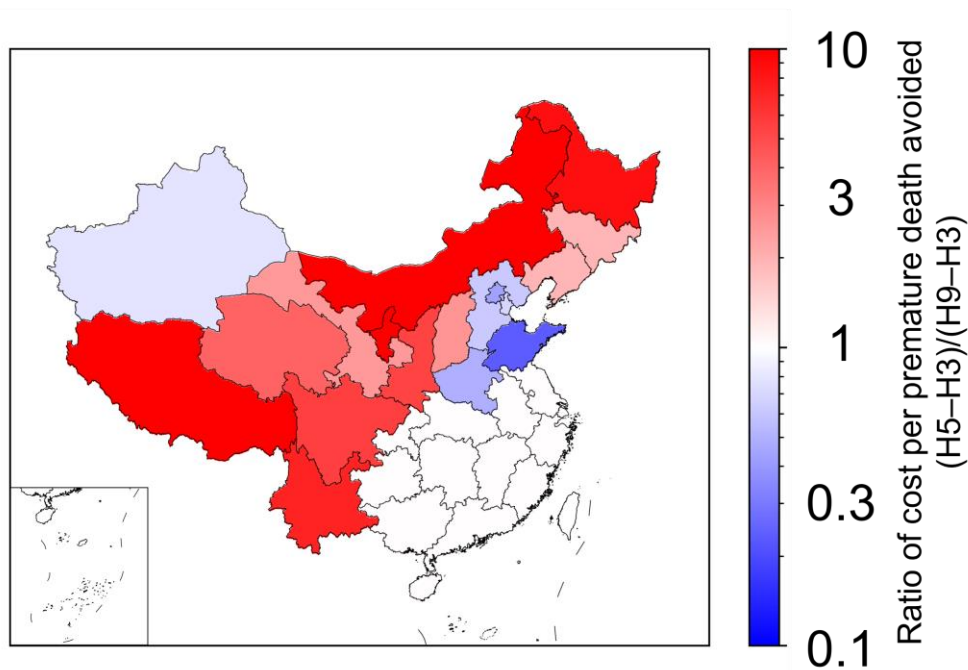


Figure s23: The Ratio of costs per additional deaths averted in the scenarios H5 and H9 compared to the H3 scenarios in different provinces. In H3 and H5, the per-household investment caps for power grid renovation are 8,000 RMB and 12,000 RMB, respectively, while in scenario H9, apart from 8,000 RMB per-household grid renovation investment cap (consistent with Scenario H3), 40% of households not covered by the renovated grid adopt processed biomass as an alternative clean heating source. All unrenovated short-term heating regions were set to 1 (white, treated as no data), as well as Jiangsu province, because its number of premature deaths avoided under scenario H9 relative to H3 was less than 1.0.

Compressed fuels and improved combustion technologies like gasification can increase burning and thermal efficiency, consequently reducing energy consumption and air pollutant emissions in comparison to raw biomass burned in traditional stoves. There are variations in pollutant emissions from burning new biomass fuels due to fuel properties, stove types, and combustion conditions; however, emission experiments indicate reductions in most air pollutants such as primary PM_{2.5}, carbon monoxide, volatile organic compounds, black carbon, etc. Emissions of some species of concern, including nitrogen oxides (NO_x) and ultrafine particles, might not be reduced to the same extent on the basis of per useful energy emissions. With improved thermal efficiency, fuel consumption amount would decrease, resulting overall in lower emissions from the residential sector as a result of heating activities.

There are rich biomass resources in rural China, but biomass collection, storage, and distribution are often cited as concerns in discussions of the large-scale utilization and sustainable use of new biomass fuels. Building fuel collection and processing plants at the village level could be feasible and achieve profitability after determining costs of fuel collection, processing, distribution, and operation costs of the plant. Rural villagers can purchase new biomass from plants or obtain it through fuel exchange. This model has been adopted in several

pilot projects; as seen in **Table s4**. The successful empirical practice leads to employment opportunities in rural areas, conducive to promoting farmers' income growth and rural development.

Table s4: Practice of biomass pellet heating in rural China

Region	Core Resources	Technical Model	Operational & Organizational Model	Key Economics
Yantai, Shandong	Abundant pruning branches from apple and cherry trees (e.g., ~100,000 tonnes/year in Chaoshu Town)	Dispersed heating using "biomass pellets + high-efficiency hydronic stoves", also catering for cooking and kang (heated bed)	Innovative "Village-level Processing Station" model. Farmers deliver raw materials for paid processing or sale, creating a localized micro-cycle.	Post-subsidy, average annualized cost per household is ~¥4,100, lower than the previous raw coal heating cost
Yangxin, Shandong	"Hometown of Chinese Duck Pear"; pear branches, straw, livestock manure with annual potential pellet production of ~1 million tonnes	Diversified pathways focusing on dispersed stoves, complemented by distributed boiler systems and biomass cogeneration	Established a countell-level platform company for unified operations ("collection by farmers, processing by enterprises, local utilization")	Significantly lower upfront and operational costs compared to "coal-to-electricity" or "coal-to-gas" alternatives, offering high cost-effectiveness
Hebi, Henan	Well-developed agriculture, annual biomass resources like straw reach 260-300 thousand tonnes	"Straw briquette fuel + intelligent biomass hydronic stoves" prioritized in remote mountainous areas, meeting heating and cooking needs	Government coordination. Enterprises provide integrated services (equipment + installation + fuel + after-sales), supported by pellet processing plants	Post-subsidy, initial equipment cost ~¥1,000/household; average winter fuel cost per household between ¥540-960
Fei County, Linyi, Shandong	Vast agricultural residues & wood processing waste (annual availability ~1.1 million	Multi-level utilization system from household stoves to distributed boilers and biomass	Leveraging large-scale projects for centralized, industrial-scale consumption of biomass.	Annual consumption of ~1.2 million tonnes of biomass feedstock, forming a complete industrial chain

Region	Core Resources	Technical Model	Operational & Organizational Model	Key Economics
	tonnes)	cogeneration		
Northeast China (e.g., Fuxin, Liaoyuan)	Abundant forestry and agricultural resources	Dispersed biomass pellet fuel systems & centralized biomass boilers	Promoted as a key alternative to coal in cold, low-population-density areas under provincial policy guidance.	Dispersed biomass technology accounts for 27% of clean heating renovations, establishing it as a primary method

References cited here:

1. Li, Z. Q. et al. Application and discussion of biomass heating in rural areas of Yantai. Construction Science and Technology 16, 12-14 (2023). (in Chinese)
2. Zhai, C. X. Yangxin biomass clean heating as a national model. Agricultural Knowledge 10, 50 (2018). (in Chinese)
3. National Development and Reform Commission (NDRC). *Clean Winter Heating Plan in Northern China (2017-2021)* (2017). <https://www.iea.org/policies/7906-clean-winter-heating-plan-in-northern-china-2017-2021>
4. China Heat IC. Case Study Report 2021 | Typical Clean Heating Cases: Policy Mechanisms in Hebi Pilot City (2022). <https://www.chic.org.cn/Home/Index/detail?id=1399>
5. Wang, Y. et al. Innovation and application of decision-making technology in the Hebi model of clean heating. Construction Science and Technology 06, 69-73 (2022). (in Chinese)
6. National Development Network. Feixian, Shandong: Prioritizing Biomass Energy Development with Multi-Energy Complementation to Protect the Environment (2021). <https://baijiahao.baidu.com/s?id=1719376813982858430&wfr=spider&for=pc>
7. Liaoning Provincial Government. Implementation Plan for Carbon Peak in Urban and Rural Construction of Liaoning Province (2023). https://www.ln.gov.cn/web/zwgkx/lnsrnzfgb/2023n/qk/2023n_deseq/bmwj/2023102609064412416/index.shtml

A15. Impacts on DALYs

While the present study focused on the health benefits on premature deaths averted, the morbidity impacts would undoubtedly add excess health benefits associated with clean energy transition. **Figure s24** shows the estimated Disability-Adjusted Life Years (DALYs), including the years of life lost (YLL) due to premature mortality and years lived with disability (YLD) due to non-fatal health conditions saved under different scenarios. DALYs provide an aggregate measure that conceptually captures both mortality and morbidity burdens.

In the H9, there would be 1.10 (0.84-1.40) millions DALYs saved, and in the clean cooking scenario C2, the DALYs saved would be about 1.51 (1.12-1.92) millions, with most significant benefits associated with impacts on chronic diseases such as chronic obstructive pulmonary disease (COPD), ischemic heart disease (IHD), and Stroke, that comprised up to 78% (70-85%) and 76% (69-83%) of the DALYs in these two scenarios.

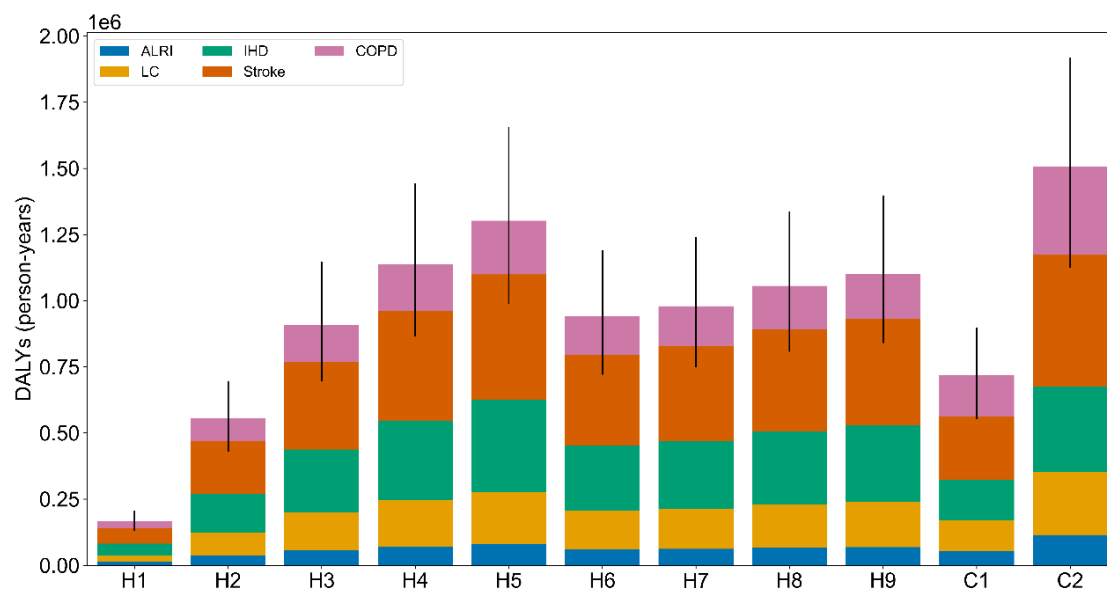


Figure s24: Disability-Adjusted Life Year (DALYs) avoided in different clean cooking and heating energy transition scenarios. Scenario C1, where half of the remaining households relying on traditional solid fuels for cooking switch to clean cooking; and Scenario C2, where all such households complete the transition to clean cooking. For clean heating, scenarios H0 – H5: Differentiated by per-household investment caps for power grid renovation, set at 0 RMB, 4,000 RMB, 6,000 RMB, 8,000 RMB, 10,000 RMB, and 12,000 RMB respectively; Scenarios H6 – H9: Based on an 8,000 RMB per-household grid renovation investment cap (consistent with Scenario H3), where 10%, 20%, 40%, and 40% of households not covered by the renovated grid adopt processed biomass as an alternative clean heating source.

In a quantitative assessment of cost-benefit, our primary economic benefit valuation remains based on VSL values and premature deaths avoided to maintain consistency with the existing valuation framework and also to avoid mixing valuation metrics or potential double counting.

For the concern on monetization of DALYs, there are ongoing discussion and debates on the methodology and the cost-of-illness or willingness-to-pay for YLL and YLD, thus, we did not further quantify monetized benefits in DALYs. Nevertheless, if monetized via approximate approaches, there would obviously increase the total estimated benefits. The current monetized benefits in premature deaths averted should be interpreted as conservative with respect to the full health impacts.

A16. Sources of uncertainty

We quantified the uncertainty in the cost–benefit results using Monte Carlo simulations by sampling key uncertain inputs, grouped into seven sources (VSL, cost, GBD health model, indoor exposure model, outdoor reduced-form model, emission factors, and energy consumption) in the scenario H3C2 as an example. To attribute output uncertainty to these sources in a transparent way, we applied a one-at-a-time variance reduction analysis. For each source i , we re-ran the model while fixing that source at its central value (median) and sampling all other sources as in the baseline Monte Carlo experiment, noted as Y^{all-i} . The contribution of source i was quantified as the reduction in output variance:

$$\Delta i = \text{Var}(Y^{all}) - \text{Var}(Y^{all-i}) \quad (13)$$

and normalized across sources to obtain percentage contributions. This provides an interpretable decomposition of uncertainty, while interactions across sources are reflected in the marginal variance reductions.

As seen from **Figure s25**, the value of VSL contributed the largest to the total variation in the calculated benefit-to-cost ratio. The second source of uncertainty is that in the estimation of premature deaths using the GBD model, values of parameters like the baseline rates and non-linear exposure-response relationship are critical. As indoor concentration comprises largely to the overall exposure, the indoor exposure level is another large factor contributing to about 20% of the variation in the final benefit-to-cost ratio. Compared to these factors, the cost, pollutant emission factors, fuel consumption amount, and ambient air quality modelling process have relatively small impacts on the evaluation of cost-effectiveness.

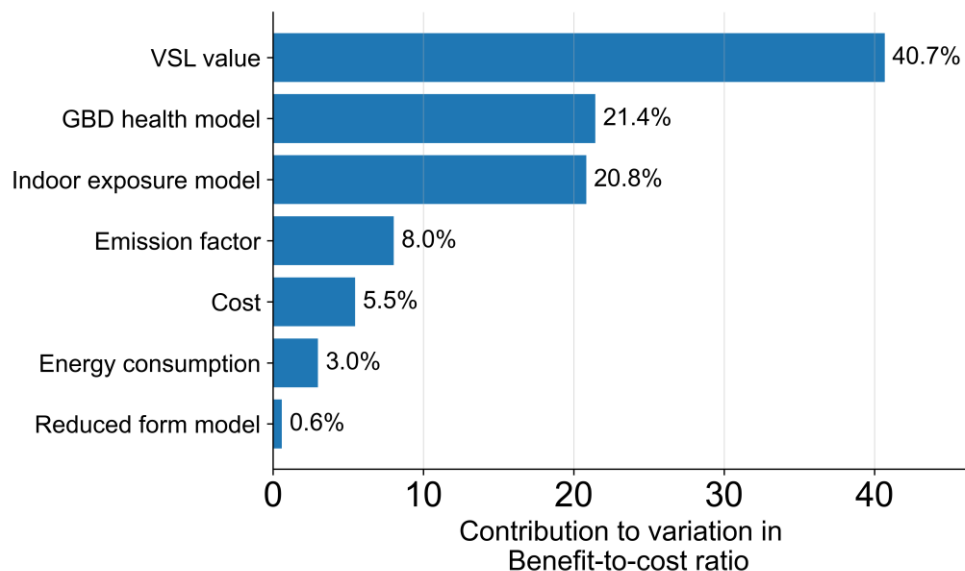


Figure s25: Contributions of main factors to the variation in benefit-to-cost ratio in the H3C2. Scenario C2, where all such households complete the transition to clean cooking. For clean heating, scenario H3 is the per-household investment caps for power grid renovation of 8,000 RMB.