

Region-specific solutions for clean cooking and heating in rural China: a cost-benefit analysis



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Summary

Background Pervasive use of unclean solid fuels is impeding the transition to sustainable household energy by 2030 in many low-income and middle-income countries. The coal to gas or electricity policy in rural north China effectively reduced wintertime air pollution; however, this roadmap was challenged in the nationwide clean heating renovation due to unaffordability and reliable energy supply, rendering it unsustainable.

Methods This study developed a new, multi-pronged framework for clean cooking and heating in rural China, including both long-term and short-term heating regions, relying primarily on affordable electrification with supplemental biofuel pellets. We performed cost-benefit analysis of this cleaning approach following the cause-effect chain from changes in pollutant emissions, indoor and outdoor air quality, and monetised health outcomes.

Findings Under the investment cap for power grid renovation below ¥8000 per household (scenario H3), three-quarters of the population in the long-term heating region (ie, one-third of the national total rural population), could switch to electric heating. For the remaining households, affordable biofuel pellets can be adopted for heating (scenario H9). This transition would deliver notable benefits in reducing national residential primary PM_{2.5} emissions by 65% (IQR 61–70) from the 724 Gg (612–967) in baseline H0 to 256 Gg (205–312) in H9, lowering exposure to PM_{2.5} by 20% (16–25) from 50.2 µg/m³ (40.4–63.5) in H0 to 40.4 µg/m³ (33.1–50.2) in H9, and consequently averting 51 190 (37 480–66 990) premature deaths, with the estimated monetised health benefits being nearly 2.55 (1.43–4.40) times the cost. Meanwhile, clean cooking transition for the whole rural population (scenario C2) would avert 78 740 (56 240–103 390) premature deaths, with the benefit-cost ratio of 7.70 (4.17–14.70). Combining clean cooking and heating would yield more substantial effects across the country. Costs and health benefits exhibit spatial variability and differ across age groups.

Interpretation The proposed pragmatic household clean energy framework would benefit over 1 million rural residents in China who still rely on traditional solid fuels to meet basic energy needs, with the monetised health benefits notably higher than the associated cost.

Funding National Natural Science Foundation of China and Ministry of Education of the People's Republic of China.

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Introduction

Although traditional solid fuels such as raw coals and bio-fuels are unclean, they are important household energy sources for nearly 2.7 billion people globally.¹ Indoor burning of these solid fuels is usually inefficient, producing large amounts of hazardous air pollutants such as PM_{2.5}, black carbon, CO₂, carbon monoxide, and many toxic organic compounds.² Emissions from households contribute to nearly 20% of ambient PM_{2.5} globally, with relatively high contributions in south Asia, and 7% in high-income North America.³ Smoke from incomplete combustion is also released into indoor air directly, causing serious household air pollution.⁴ Exposure to these household air pollutants results in millions of premature deaths every year from adverse respiratory, cardiovascular, and neonatal outcomes.^{5,6}

Transitions to clean modern household energy, such as gaseous fuels and electricity, is crucial in improving air

quality, protecting human health, and mitigating climate change, as burning of traditional solid fuels, such as coals and biomass, produces substantial amounts of air pollutants and various climate forcers. Clean energy transitions can occur as development progresses, or they can be accelerated through policy. Empirical evidence from nationwide surveys in China observed that self-motivated switching to clean cooking has occurred before—from 1992 to 2017, the proportion of the population in rural China using clean cooking fuels and technologies increased from 9% to approximately 69%, which is a substantial spontaneous transition without government intervention, mainly driven by increased income and awareness of air quality protection.^{7–9} However, unclean solid fuels remain major heating energy sources for a large population, especially in high-latitude or high-altitude cold regions with longer heating demands. In 2017, a clean heating campaign was initiated in north China to phase out raw coal

Lancet Planet Health 2026;
10: 101439

Published Online March 19,
2026
<https://doi.org/10.1016/j.lanplh.2026.101439>

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Research in context

Evidence before this study

Household energy consumption for daily cooking and space heating constitutes a relatively small proportion of China's total energy use. However, constrained by the inefficiency of combustion processes, this sector emits substantial quantities of many air pollutants, which subsequently impose pronounced adverse effects on ambient air quality and public health. Clean energy transition interventions, such as the coal to gas or electricity programme in northern China, have been shown to be effective in mitigating wintertime air pollution and reducing the incidence of extreme haze episodes. Despite these demonstrable successes, the initiative remains subject to social controversy, predominantly stemming from concerns regarding household affordability and energy supply reliability, thereby casting doubts on its long-term sustainability in the context of just energy transition.

Added value of this study

A novel, multi-pronged framework for clean household energy in rural China, being adapted to local heating demands, resource endowment, and economic conditions, is proposed. The framework, emphasising affordable electrification supplemental by biofuel pellets, is evaluated for the air pollutant emissions, ambient and indoor air quality, and health outcomes for different clean household energy transition scenarios. Quantitative analysis took costs (including device, grid installation, and maintenance) and benefits in health saving into consideration. Scaling up clean heating and cooking not only materially reduces air pollutant emissions but also drives substantial reductions in PM_{2.5}

exposure, particularly under conditions of reduced indoor pollution. Transitioning to clean heating in the long-term heating region (scenario H9) could avert over 50 000 premature deaths annually in China, and further transitions to clean cooking (scenario C2) could avert approximately 80 000 additional premature deaths. The associated health benefits translate to benefit–cost ratios of 2.55 for clean heating retrofits in H9 and 7.70 for clean cooking initiatives in C2, demonstrating notable cost-effectiveness.

Implications of all the available evidence

In many low-income and middle-income countries, reliance on traditional solid fuels constitutes a major source of indoor air pollution and ranks among the leading environmental risk factors, contributing to millions of premature deaths globally each year. A clean and just energy transition is crucial; as a key indicator of progress towards sustainable development, it effectively reduces air pollutant emissions, thereby generating benefits for air quality improvement, and public health protection. Given substantial challenges associated with modern energy transitions in rural areas, a targeted strategy could be proposed: prioritising electrification for cooking and space heating (rather than transitioning to gas), while leveraging biofuel pellets as a transitional supplementary energy source for households unable to afford electric heating. This strategy demonstrates substantial advantages, including reducing air pollutant emissions, improving indoor and outdoor air quality, lowering exposure to fine particulate matter, and delivering cost-effective human health protection.

use for space heating in urban, peri-urban, and rural areas, being replaced with electricity or gas for heating.¹⁰ The campaign effectively cleaned up household energy and improved regional air quality;^{11,12} however, it also caused highly concerning issues such as cold exposure with reduced or even no heating activities in some homes, reversion to raw coal, gas pipeline explosion accidents, and further inequality in air pollution exposure and well-being.^{13,14} Thus, in promoting gas or electricity for space heating, particularly in rural areas, there are serious concerns about the continued challenges of affordability and sustainability.

With a large population continuing to rely on traditional solid fuels as important household energies, the challenge of universal access and sustained use of clean modern energies, as outlined in Sustainable Development Goal 7, persists.¹⁵ In this study we propose a new framework for clean cooking and heating in rural China, with affordable electrification at the core, supplemented by cleaner biofuel pellets (compared with traditional solid biomass fuels), a standardised high-density solid fuel produced by compressing biomass such as agricultural and forestry waste. We performed cost–benefit analysis of this cleaning approach, following the cause–effect chain from changes in

pollutant emissions, indoor and outdoor air quality, and monetised health outcomes. This pragmatic multi-fuel approach, which is in line with China's natural and socio-economic conditions, is practical and has the potential to achieve substantial environmental and health benefits, providing an affordable path towards cleaner air.

Methods

Heating demand and baseline temperature

China has several climatic zones with different conditions, and not all regions have space heating demands in winter. We analysed heating demands across the country and calculated the heating days under different baseline temperatures (appendix p 3). Spatial patterns indicated that a baseline temperature of 0°C is representational of the actual situation of rural heating demand in China. Most regions in the Qinghai–Tibet Plateau and north of the Qinling–Huaihe line are primary heating areas, whereas some central and eastern regions south of the Qinling–Huaihe line have short-term heating needs, with heating degree days lower than 33. Therefore, a baseline temperature of 0°C was adopted in formulating clean heating plans. The distribution of heating days shows a clear pattern, with more heating days in the north and

See Online for appendix

west of China than in the south and east, mirroring cold climate conditions in high-latitude or high-altitude regions.

Design of clean energy scenarios

Substantial differences exist in cooking and heating behaviours across households, requiring distinct clean energy solutions for each end use. Relative to the 2019 baseline, we proposed two clean cooking scenarios: scenario C1, in which half of the remaining households relying on traditional solid fuels for cooking switch to clean cooking; and scenario C2, in which all such households complete the transition to clean cooking. For clean heating in the long-term heating region, nine scenarios (H1–H9) were tailored to local variations in heating demand, regional economic conditions, and biomass resource endowments. Scenarios H1–H5 were differentiated by per-household investment caps for power grid renovation, set at ¥4000 (H1), ¥6000 (H2), ¥8000 (H3), ¥10 000 (H4), and ¥12 000 (H5); and scenarios H6–H9, based on an ¥8000 per-household grid renovation investment cap (consistent with scenario H3), in which 10% (H6), 20% (H7), 40% (H8), and 40% (H9) of households not covered by the renovated grid adopt processed biomass as an alternative clean heating source (table 1; details in the appendix [p 7]). The difference between H8 and H9 is the 40% biofuel pellet heating transition is distributed evenly or unevenly following the spatial distribution of biomass production.

Residential emissions and contributions to air pollution

Emissions are from the Global Emission Modelling System, which has tracked various air pollutants and greenhouse gases from 1700 to 2021 with a spatial resolution of $0.1^{\circ} \times 0.1^{\circ}$. Residential emissions at baseline and in each scenario were calculated based on the fuel consumption and corresponding emission factors. When replacing solid fuels with electricity, additional emissions from power plants were counted.

Ambient $PM_{2.5}$ was simulated using reduced-form models, which included a series of multivariate regressions using emissions to predict ambient concentrations, and meteorology-related probability functions to separately quantify the variations due to meteorological conditions.¹⁶ The model has been evaluated and validated for robustness by comparing results with the ground-based observations and those from Atmospheric Chemical Transport Modelling.^{16,17} In the present study (appendix p 9), the model performed well in both northern and southern regions over the historical time series, with $R^2=0.987$ for the national mean $PM_{2.5}$, and $R^2=0.993$ in Beijing, a typical city from the long-term heating region (appendix p 10). For the uncertainty induced by meteorological variability, the coefficient of variation was below 10% in the most densely populated eastern regions. Thus, this approach can support $PM_{2.5}$ simulation and prediction of its temporal and spatial characteristics at the national and regional scales. Residential emission contributions were calculated using the normalised marginal attribution method (appendix p 11).^{18,19}

Description

Heating scenarios

- H0 Current baseline situation in 2019
- H1 Clean heating innovation under the investment cap of ¥4000 per household
- H2 Clean heating innovation under the investment cap of ¥6000 per household
- H3 Clean heating innovation under the investment cap of ¥8000 per household
- H4 Clean heating innovation under the investment cap of ¥10 000 per household
- H5 Clean heating innovation under the investment cap of ¥12 000 per household
- H6 Clean heating innovation under the investment cap of ¥8000 per household and 10% of the remaining households, distributed evenly across the area, will adopt biomass pellets with improved stoves for space heating
- H7 Clean heating innovation under the investment cap of ¥8000 per household and 20% of the remaining households, distributed evenly across the area, will adopt biomass pellets with improved stoves for space heating
- H8 Clean heating innovation under the investment cap of ¥8000 per household and 40% of the remaining households, distributed evenly across the area, will adopt biomass pellets with improved stoves for space heating
- H9 Clean heating innovation under the investment cap of ¥8000 per household and 40% of the remaining households, distributed unevenly following the spatial distribution of biomass production, will adopt biomass pellets with improved stoves for space heating

Cooking scenarios

- C0 Current baseline situation in 2019
- C1 Of those households relying on traditional solid fuels for cooking, 50% switch entirely to a clean mixed-energy cooking mode combining electric and liquefied petroleum gas cooking, distributed evenly across the area
- C2 Households that still rely on solid fuels for cooking will all switch to clean cooking solutions

Table 1: Scenarios of clean cooking and heating in rural China

For indoor $PM_{2.5}$, the concentration was calculated using the statistical approach^{20–22} with the updated indoor air quality database detailing measured $PM_{2.5}$ concentrations in heating and non-heating periods across different residential microenvironments, categorised by household energy source, stove type, and stove location (eg, a separate kitchen vs a living or sleeping area, and indoors vs semi-enclosed or outdoor).^{21–23} Household energy information was obtained from nationwide surveys in which stacked energy use had been considered.^{7,9,24} Therefore, for each county, the average indoor $PM_{2.5}$ was calculated by weighting the $PM_{2.5}$ concentration of each energy group by the time-sharing fraction of each respective energy source. The spatial distribution of estimated indoor $PM_{2.5}$ and $PM_{2.5}$ from internal combustion emissions and ambient air, being consistent with several field observations,^{25,26} showed that the indoor model behaved reasonably across regions (appendix p 12).

Exposure, health impact, cost-benefit quantification, and uncertainty

$PM_{2.5}$ exposure was calculated by integrating indoor and outdoor concentrations with time–activity data for different population groups. This approach has been widely applied in exposure estimation, and its results are generally positively correlated with those of personal sampling; the direction and magnitude of relative deviations vary with experimental conditions and pollutant types.^{27,28} The activity data is from the Exposure Factors Handbook of Chinese Population.²⁹ Premature deaths attributed to $PM_{2.5}$ were

For more information on the Global Emission Modelling System see <https://gems.pku.edu.cn>

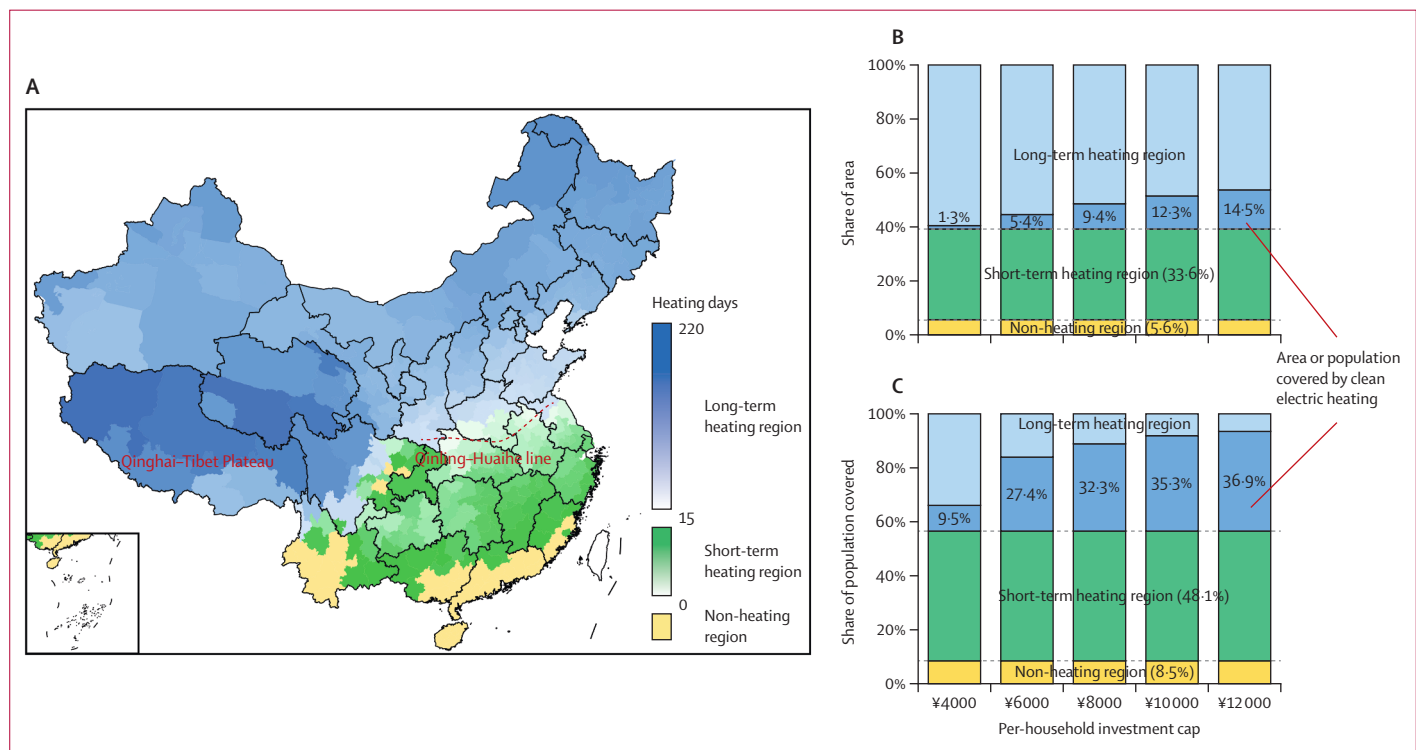


Figure 1: Division of heating regions in China (A) and the share of area (B) and population (C) covered by clean electric heating in different heating scenarios

Based on the heating days, China is divided into three regions in terms of different heating patterns: long-term heating region (≥ 15 heating days), short-term heating region (> 0 to < 15 heating days), and non-heating region (0 heating days). By setting different per-household investment caps, the proportion of the geographical area and population covered by clean electric heating after grid renovation are illustrated by deep blue bars.

estimated using the population-weighted exposure and the latest integrated non-linear Exposure–Response function from The Global Burden of Diseases, Injuries, and Risk Factors Study (GBD; appendix p 15).³⁰

The cost of the clean heating transition included initial capital expenditure for infrastructure construction and installation, costs for the procurement and regular maintenance of heating equipment, expenses for daily electricity consumption, and the avoided costs associated with coal use.^{12,31} For the biomass substitution scenario, costs related to biofuel pellets were also incorporated. Data were collected from the literature and national and provincial statistics. The cost was annualised over 20 years using a 4% discount rate with a sensitivity range of 2–10%.³¹ The costs were further disaggregated to analyse the costs borne by governments and households, such as expenses related to heating renovation, installation, and maintenance and a 20% subsidy on heating equipment purchases from the government to every household (appendix p 17).

The benefits of a clean transition stem from health benefits that are quantified based on premature deaths avoided and regional-specific value of a statistical life (VSL), with a reasonable range of VSL values considered in the sensitivity analysis (appendix p 18).^{31,32}

A 1000-time Monte Carlo simulation is used to assess the uncertainty from emissions to premature mortality. In each simulation, energy consumption was assigned a coefficient

of variation of 20% for biomass fuels and 15% for the other energy types. Pollutant emission factors were randomly sampled from a log-normal distribution of datasets being compiled from literature studies, especially those with local data.^{7,9,11,31,33,34} Indoor $PM_{2.5}$ concentrations were drawn from a statistical approach providing means and standard deviations for different fuel groups. Uncertainties in ambient $PM_{2.5}$ were from reduced-form model simulations that separately quantify changes attributable to emissions and meteorological conditions (appendix p 10). Parameters in the integrated exposure–response function were randomly selected from the parameter distributions reported by GBD.

Role of the funding source

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

Results

At a baseline temperature of $0^{\circ}C$, few areas in China do not have heating demand. Most areas south of the typical Qinling–Huaihe line had heating periods of up to 15 days per year, classifying them as short-term heating regions with heating degree days generally below 33 (figure 1A). As the investment cap per household increased from ¥4000 to ¥12 000 (scenario H1 to H5), the share of national land area

	Primary PM _{2.5} emission (kt)	Ambient PM _{2.5} (µg/m ³)	PM _{2.5} exposure (µg/m ³)	Death avoided (n, thousands)	Annual costs (¥, billions)	Monetised benefits (¥, billions)	Benefit-cost ratio
Baseline (H0 and C0)	H0: 724 (612–967); C0: 1038 (881–1456)	2.00 (1.79–2.30)	50.2 (40.4–63.5)	NA	NA	NA	NA
H1	633 (496–754)	1.91 (1.69–2.25)	48.5 (39.1–61.4)	7 (6–9)	22.8 (18.0–27.5)	31 (16–55)	1.34 (0.68–2.61)
H3	351 (309–470)	1.66 (1.49–1.90)	41.9 (34.2–52.3)	42 (31–55)	88.1 (52.3–72.3)	197 (119–323)	2.24 (1.27–3.88)
H5	266 (236–358)	1.56 (1.40–1.76)	39.3 (32.3–48.6)	60 (44–79)	112.3 (98.1–126.4)	282 (172–462)	2.52 (1.46–4.32)
H9	256 (205–312)	1.57 (1.41–1.77)	40.4 (33.1–50.2)	51 (37–67)	92.6 (79.8–105.4)	236 (140–386)	2.55 (1.43–4.40)
C1	522 (321–779)	1.57 (1.36–1.85)	43.4 (35.4–53.8)	37 (28–48)	24.3 (22.7–26.1)	180 (99.0–334)	7.41 (4.05–13.85)
C2	4 (2–6)	0.99 (0.77–1.21)	37.6 (31.0–45.8)	79 (56–103)	48.6 (45.4–52.3)	374 (204–709)	7.70 (4.17–14.70)

Data shown are median (IQR). NA=not applicable.

Table 2: Primary PM_{2.5} emissions, ambient and indoor PM_{2.5} concentrations, exposure levels, premature deaths averted, costs, and benefit-cost ratios in different scenarios

covered by the renovated power grid increased from 1.3% to 14.5% (figure 1B). Renovation was initially concentrated in densely populated regions where per-capita investment costs are lower; therefore, the share of the population covered increased rapidly from 9.5% in H1 to 32.3% in H3. When investment was expanded to less densely populated areas, the incremental gain in the share of the population covered per unit of investment declined, rising to 36.9% in H5 (figure 1C), indicating diminishing marginal returns. These expenditures on power grid renovation, installation, and maintenance, together with the subsidies for residential heating equipment, account for less than 1% of the government's public expenditure in most provinces (table 2; appendix p 20).

Clean cooking and heating substantially reduce pollutant emissions and carbon emissions (appendix p 22). Primary PM_{2.5} emissions would be reduced from 724 Gg (IQR 612–967) at baseline H0 to 351 Gg (309–470) in H3, or by about 52% (49–56; table 2). After H3, if these other regions adopted biofuel pellets for space heating, primary PM_{2.5} would be further reduced to about 256 Gg (205–312). Consequently, ambient PM_{2.5} due to rural residential cooking emissions would reduce substantially, and the ambient PM_{2.5} does not linearly reduce but shows gradually decreasing marginal benefit (appendix p 23).

Providing cleaner household energy has substantial impacts on indoor air quality, as fugitive emissions contribute substantially to severe indoor air pollution (appendix pp 25–26).^{2,35} As people spend more time indoors, decreases in indoor PM_{2.5} result in notable changes in the overall exposure (figure 2A). For example, in the clean heating scenario H3, the overall PM_{2.5} exposure would be approximately 41.9 µg/m³ (IQR 34.2–52.3), about 17% (15–19) lower than the baseline 50.2 µg/m³ (40.4–63.5; table 2). Indoor exposure reduction contributes to over 95% of the total reduced exposure (appendix p 27). Compared with the baseline scenario, in which only 18.9% of the population had PM_{2.5} exposure below the national standard of 35 µg/m³, scenario H3 represents a notable improvement, achieving compliance for 34.5% of the population. With totally clean cooking, total PM_{2.5} exposure would be further reduced to 32.0 µg/m³ (26.9–37.9) in H3 and C2,

and over half of the population would meet the national air quality standard (appendix p 28).

Lower PM_{2.5} exposure is undoubtedly important to protect human health, especially for older people and children (figure 2B; appendix p 29). Compared with baseline, approximately 42 thousand (IQR 31–55) premature deaths would be avoided in clean heating scenario H3; and in clean heating scenario H5, 60 (44–79) thousand premature deaths would be avoided. The marginal health benefits decreased with the increasing cost of the electric heating intervention, being consistent with changes in PM_{2.5} exposure. In scenario C1, 37 thousand (28–48) premature deaths would be averted; in scenario C2, 79 thousand (56–103) premature deaths would be averted.

The health effects expectedly varied across provinces. Under the clean heating renovation, premature deaths averted were substantial in densely populated areas such as Hebei and Shandong provinces and areas with strong heating demands such as Xinjiang and Heilongjiang provinces (figure 3). For clean cooking, the absolute numbers of premature deaths averted were closely associated with the population still using solid fuels for cooking. There were much greater benefits in southwest China, where many people still rely on traditional solid fuels for daily cooking.⁹

Even under the H3C2 scenario, which assumes substantial clean intervention for both cooking and heating, PM_{2.5} concentrations remained high, posing substantial health burdens, especially for older adults (appendix p 30).

The cost of clean cooking is largely determined by devices and energy; the total annual cost is proportional to the households covered, which was ¥24.3 billion (IQR 22.7–26.1) in scenario C1 and ¥48.6 billion (45.4–52.3) in scenario C2. The clean heating cost difference across scenarios was primarily attributable to grid investment (figure 4A) and, along with the increasing investment cap and coverage households, the total cost expectedly increased faster, but with decreased marginal benefits (appendix p 31). Considering both cooking and heating, the total annual cost reached ¥136 billion (121–153) when adopting H3 and C2 clean solutions, which accounted for 0.14% (0.12–0.15) of national gross domestic product

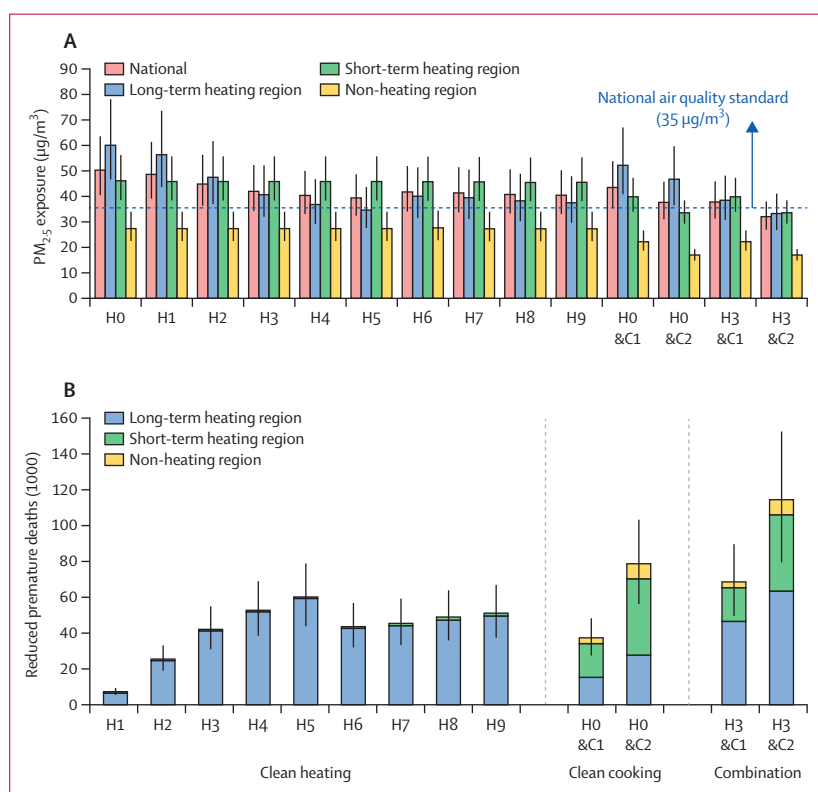


Figure 2: Population-weighted PM_{2.5} exposure (A) and premature deaths avoided due to reduced PM_{2.5} exposure (B) in different scenarios

(¥99 trillion in 2019) and 0.57% (0.50–0.64) of national fiscal expenditure (¥24 trillion in 2019).

The ratio of benefits to costs increased by the scale and type of transitions and the total investment, from 1.34 (IQR 0.68–2.61) in H1 to 2.52 (1.46–4.32) in H5 (figure 4B). Compared with clean heating, the benefit of clean cooking was much more notable, with benefit–cost ratios of 7.41 (4.05–13.85) for C1 and 7.70 (4.17–14.70) for C2. As the per-household investment increased, the benefit–cost ratio showed an upward trend in most provinces (appendix p 33). When clean heating and clean cooking were implemented simultaneously, the benefit–cost ratio for the H3 and C2 scenario was approximately 4.15 (3.21–5.54) at a 2% discount rate and 3.63 (2.80–4.85) at a 10% discount rate (appendix p 17). Although the discount rate exerts a substantial influence on costs, variations within its reasonable range (2–10% in this study) have a relatively small effect on the key cost-effectiveness outcomes of the transition. For different age groups, despite uncertain exposure and VSL values, clean renovation yields substantial net benefits, with the older age group (older than 65 years) showing the highest cost-effectiveness (appendix p 34).

The interprovincial differences in effectiveness are notable since costs vary across different regions, and benefits also differ nationwide due to variations in exposure reductions, population size, and age structure. For clean heating, the benefits were more predominant in the north,

where there are high demands. For clean cooking, the benefits were larger in areas where many people use solid fuels for daily cooking. There is a relatively low benefit–cost ratio in Tibet, where the clean cooking cost is high as biomass fuels are free, but the health saving amount is small due to the small population (appendix pp 34–35).

The Gini coefficient in the exposure level, as an indicator for the inequality, was 0.198 in the baseline scenario and varied from 0.197 to 0.225 in different scenarios (appendix pp 38). This indicates that, although the clean transition strategies are primarily targeted at specific regions, they do not necessarily exacerbate exposure inequality at the national scale. However, disparities in cost burdens and health-saving benefits among different income groups were substantial. The low-income households gained the most, with ¥484 (357–972) per person under scenario H3 and ¥537 (436–1068) per cap under scenario H9 (appendix p 39). The low-income groups had to spend an additional 2% of their annual income on clean renovation, whereas for groups with an annual income over ¥20 000, the burden from clean renovation accounted for only 0.85% of their income.

Discussion

In China, given the fast urbanisation and rapid industrialisation, air pollution is a serious environmental issue. The present study proposed a new framework of clean rural household energy in China. Our framework took into consideration of both affordability and accessibility, and relied primarily on electrification, which is believed to be the main direction of household energy reformation and development in the long term. Given that the total costs represent a small share of provincial public expenditure (generally <1%), they can plausibly be accommodated within existing fiscal space, especially if rolled out in phases. Technology such as the air-source heat pump (ASHP) can adapt to cold winter conditions, with the average coefficient of performance (COP) value of 3.1 in north China, and could potentially reach 4.0 even under -5°C with appropriate technical measures.³⁶ One experiment in Harbin, the coldest provincial capital of China, observed that the ASHP had COPs of 1.04–2.44, and the COPs decreased notably when the difference between indoor and outdoor temperature increased from 35°C to 41°C .³⁷ Field validation studies by the National Renewable Energy Laboratory and Pacific Northwest National Laboratory also showed that some ASHP systems worked well below -20°C , with the COPs being close to 2.0.^{38,39} Although the COPs of ASHPs vary substantially in their performance due to operation parameters and system characteristics, it has been recognised that this technology is feasible for wintertime heating, including in some cold regions. Power plants still emit considerable amounts of pollutants, especially in many parts of China where power plants are coal-fired; however, the use of high-quality coals and effective end-of-pipe control measures, such as ultra-low emissions in power plants, mean that their pollutant emissions in units of effective heat are much lower than those of the

domestic sector—usually 2–3 orders of magnitude lower.⁴⁰ With the development and application of green energy technology, many hazardous air pollutants and carbon emissions from the power sector will be further reduced, potentially achieving greater environmental and climate benefits. According to International Energy Agency projections, electricity prices are expected to fluctuate with an overall upward trend in the medium to long term under global carbon neutrality goals, whereas coal prices might decline at an average annual rate of about 2–3% over the next 5 years.^{41,42} Concurrently, the World Bank anticipates moderate near-term economic growth in China, with a gradual slowdown in the longer term.⁴³ Such trends could influence household energy choices in ways that are difficult to predict precisely. Generally, the burden of clean renovation on rural residents is expected to have a downward trend, primarily driven by increasing household incomes amid economic development (appendix p 40). The reduction in household burden and its maintenance at a low level indicate the long-term sustainability and affordability of clean energy solutions, which can effectively protect residents' health within an affordable range, and the benefit–cost ratios remain substantial, changing from 4·01 (IQR 3·01–5·36) to 3·68 (2·84–4·92) when the electricity price increased from ¥0·51/kWh to ¥0·65/kWh (appendix p 41).

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 of the population concentrated in central mountainous regions (appendix p 43). When comparing the H5 and H9 scenarios, which yield comparable reductions in premature mortality, the cost–benefit analysis confirmed that a hybrid strategy integrating electrification and biofuel pellets for heating, particularly suitable for mountainous regions, exhibited higher cost-effectiveness than a stand-alone electrification approach (appendix p 44). Compressed fuels and improved combustion technologies such as gasification can increase burning and thermal efficiency,³⁰ consequently reducing energy consumption and air pollutant emissions compared with raw biomass burned in traditional stoves. Despite variabilities in pollutant emissions from burning new biomass fuels due to fuel properties, stove types, and combustion conditions; however, emission experiments indicate substantial reductions in most air pollutants (eg, primary PM_{2.5}, carbon monoxide, volatile organic compounds, and black carbon). Although emissions of concern, including nitrogen oxides and ultrafine particles, might not be reduced to the same extent due to the different emission factors,^{44–47} less fuel use with improved thermal efficiency would still substantially lower emissions from the residential sector. There are rich biomass resources in rural China, and the biomass pellet heating model has been adopted in several pilot projects. Its successful empirical practice leads to employment opportunities in rural areas, conducive to promoting farmers' income growth and rural development (appendix pp 45–46).

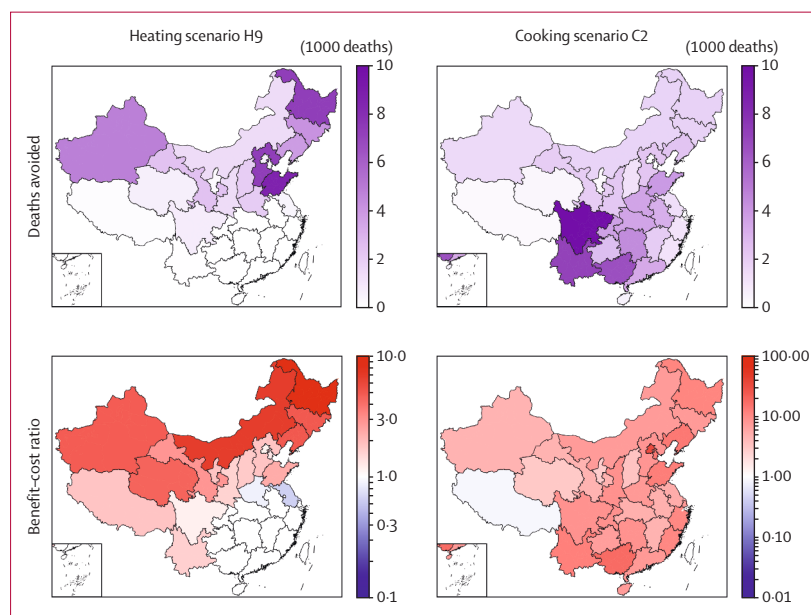


Figure 3: Spatial distributions in the premature deaths averted and quantified benefit-cost ratios in the clean cooking scenario C2 and clean heating scenario H9

The well known clean heating initiative implemented in northern China centres on the switch from coal to gas or electricity. Despite achieving substantial emission reductions, important challenges remained, including cold exposure due to unreliable systems, fuel reversion to raw coal, and safety incidents.^{48,49} These outcomes highlight that a successful transition must integrate crucial lessons from past programmes to avoid unintended consequences, requiring robust policy safeguards that extend beyond purely technical and economic considerations. Our framework addresses these challenges through several key design principles and safeguards: first, our pathway explicitly prioritises electricity as the core energy source, avoiding the instability, infrastructure limitations, and safety risks associated with natural gas.⁵⁰ This approach aligns with China's dual carbon goals, which aim to drive continuous decarbonisation of the power grid while supporting the deployment of high-efficiency technologies such as ASHPs. Second, recognising the barrier of high initial investment, substantial government support and targeted subsidies are essential. We recommend adopting a cost-sharing model combining government subsidies, corporate contributions, and household payments, potentially integrated into national equipment renewal programmes to enhance accessibility and equity. Third, for biomass energy use, although palletisation and stove technologies have become more established and agricultural and forestry residues are widely available, the village-level collection–processing–use model requires active government guidance, standardisation, and promotion. Successful implementation depends not only on technical solutions but also on community governance and organisational innovation.⁵¹ As a national-level framework, practical

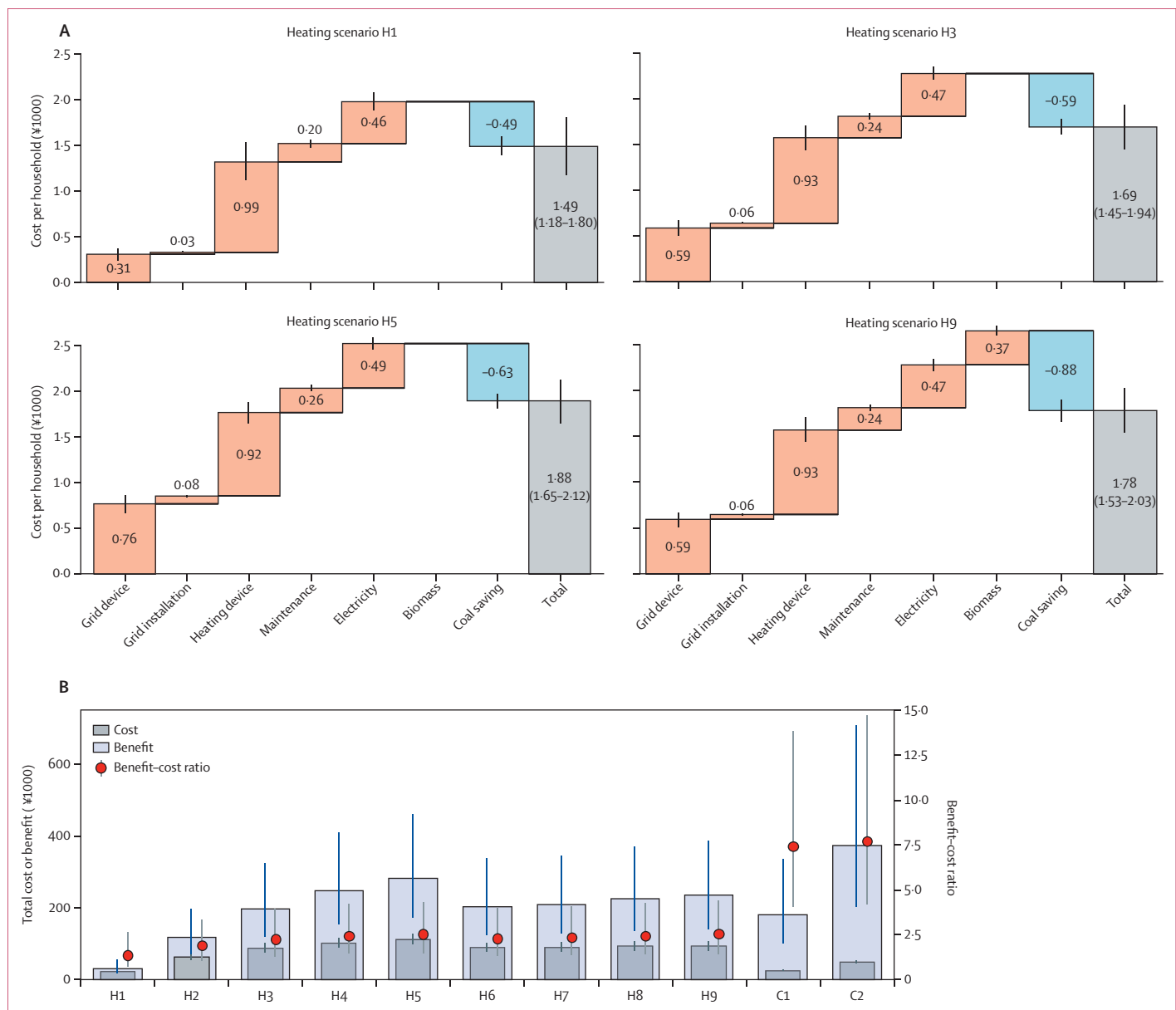


Figure 4: Decomposition of annualised cost per household for clean heating under different scenarios (A) and comparison of total cost-benefit under heating and cooking scenarios (B)

implementation requires context-specific adaptations based on local resources, economic conditions, and user preferences. Furthermore, uncertainties in future energy supply and policy environments necessitate flexible implementation pathways. By combining this differentiated energy pathway with targeted financing mechanisms and community engagement, our framework can avoid previous pitfalls while delivering environmental, health, and social co-benefits.

The present framework primarily addresses the technical and economic dimensions of the energy transition; however, its successful implementation depends on a range of non-technical factors and thoughtful policy design.

Household energy adoption is influenced by socio-economic variables such as income, education, age, and gender. Some surveys suggested that individuals with higher income, more years of education, and younger age show greater willingness to switch to clean fuels,^{8,9} and women, especially those engaged in non-agricultural employment, might show stronger preference for clean energy and electric appliances than men.⁵² Regionally uneven equipment supply and fuel logistics might further constrain large-scale deployment. The incorporation of biofuel pellets in this framework is predicated primarily on regional resource endowments; however, in reality, their promotion is constrained by a multitude of factors. On the

user side, concerns over electricity costs and perceived reliability of biomass systems might hinder adoption or even lead to energy stacking or reversal to solid fuels. Marked disparities in market development across regions stem from variations in economic conditions, policy support, and fiscal subsidies.^{53,54} Even resource-rich regions face barriers to convenient stable fuel access due to problems in the supply chains and inadequate transportation networks.⁵⁵ Thus, the quantitative results here reflect the upper potential limit under idealised supply chain conditions. Prioritising supply chain capacity, including raw material collection, warehousing, logistics, and differentiated market mechanisms, will enhance the practical accessibility of biofuel pellets. At the policy level, the effectiveness of local governance and subsidy distribution mechanisms can strongly influence the pace of transition. These non-technical barriers collectively shape the real-world feasibility and long-term sustainability of transition pathways.^{56,57}

The proposed household clean energy framework offers a nuanced analysis of clean heating solutions, yet its design for clean cooking remains relatively simplistic, as it does not differentiate the distinct effects of socioeconomic heterogeneities, such as income, gender, and occupation, on cooking energy choices. It is believed that household income is a pivotal determinant of energy transition, with over 85% of the variance in clean cooking energy use being explained by the income in rural China,^{7,9} and the probability of clean cooking could increase by approximately 0.2% with a 10% increase in household income.⁵⁸ Besides income, factors such as female responsibility for cooking, higher education attainment, non-agricultural occupations, and more younger family members are also found to be positively correlated with the use of clean cooking energy.^{8,59} In some regions such as the Tibet and Gansu provinces, limited access to clean modern energy has constrained adoption and sustained use of such energy sources for cooking.⁶⁰

Our quantitative analysis shows that the proposed transition can effectively reduce air pollutant emissions, lower PM_{2.5} exposure, and yield cost-benefit advantages. However, when extending the quantitative results to broader scenarios, it is important to acknowledge the uncertainty and the limitations inherent in the calculation process. The real-world emissions vary largely due to fuel quality and stove-use behaviours. This study uses reduced-form models to estimate ambient PM_{2.5} concentrations associated with emission reductions, whereas the variations due to meteorological conditions are a probability function only indicating the direction of potential changes. Following the proposed transition, the absolute ambient concentrations in reality might differ from our simulated values, but the overall reduction trends are expected to remain robust. In the indoor exposure model that adopted a statistical approach building on the reported mean PM_{2.5} in literature studies, the primary fuel is often used for classification, and variations in compiled values are from studies in different

experimental conditions such as burning conditions, room size, and ventilation status. However, such variation could also be from stacked energy use, which is not well counted in the statistical approach relying solely on the primary fuel type. Supplements of other fuels are very common in rural China,^{9,24} but secondary or tertiary fuels are sometimes not reported or not collected as inputs in the statistical model development. The PURE-AIR study, conducted in eight countries, found that in households using wood as a primary cooking fuel, the use of gas as a secondary fuel can lower the average kitchen PM_{2.5} by about 50%.⁶¹ For those using gas as the primary fuel, the use of solid fuels such as animal dung as a secondary fuel might increase the PM_{2.5} concentration by nearly three times.⁶¹ Households using a mix of different solid fuels (eg, crop straws and coal) might have lower pollution concentrations than households only using coal. This energy stacking phenomenon might also change the energy use efficiency and the daily consumption amount;²⁴ this would result in considerable biases in indoor PM_{2.5} exposure and health benefit analysis. Developing more refined indoor air quality models is essential for accurately assessing indoor PM_{2.5} pollution. Finally, the use of VSL to quantify health benefits and perform cost-benefit analyses introduces substantial uncertainty. VSL does not represent actual monetary gains and might not effectively alleviate the financial burden faced by residents in energy transitions.¹³ It is also important to note that the health benefits only include five diseases attributable to PM_{2.5} exposure. There might be greater health benefits if other pollutants (eg, indoor NO₂ exposure) are also considered. As discussed previously, although the burning of gas for cooking or biofuel pellets for heating might not reduce nitrous oxides and ultrafine particle emissions to the same extent as PM_{2.5} mass, the overall reductions in emission amounts and air concentrations of these pollutants can still be expected, owing to the increased thermal efficiency and lower energy consumption amounts. Furthermore, when the effects on morbidity are considered, the health benefits would be more substantial (appendix p 47).⁶² Health outcomes related to air pollution are also modulated by demographic changes, such as population growth, aging, and accessibility to health care. The one-at-a-time variance reduction analysis suggested that values of VSL, the models to estimate indoor exposure and to quantify premature deaths from the exposure, are important influencing factors contributing largely to the quantified cost-effectiveness (appendix p 49). Nevertheless, the projected trends in air pollutant emission reduction, air quality improvement, substantial health benefits, and the cost-effectiveness of the transition are expected to be substantial and robust.

While the present work is at the national scale, future research should disaggregate households into distinct socioeconomic subgroups and incorporate regional differences in clean energy accessibility. This approach would facilitate more precise identification of barriers to energy transition and enhance the targeting of policy

interventions, and it would be valuable to conduct a more detailed dynamic analysis accounting for temporal variations in income and expenditure constraints before the strategy can be effectively implemented.

Ensuring universal access to affordable clean energy is a pivotal target for achieving sustainable development. Against the backdrop of growing global emphasis on a just clean energy transition, the framework proposed herein not only offers actionable insights with profound implications for China, but also provides scientific reference value for other low-income and middle-income countries facing analogous challenges. Grounded in the realities of rural China, which has particularly divergent heating demands across regions and different energy affordability, this study proposes an electrification-centred transition roadmap, supplemented by biofuel pellets, drawing on mature and feasible technologies currently available. The core tenet of this cost-effective framework lies in its contextualised design rooted in local realities, which also underpins its scalability and transferability. Rather than a one-size-fits-all solution, tailored holistic solutions must be devised to align with local contexts encompassing natural conditions, resource endowments, economic conditions, and social characteristics. Environmental and health benefit assessments are essential to validate the technical feasibility and cost-effectiveness of the proposed strategy. Meanwhile, differentiated attainable targets should be set regionally, with detailed action plans incorporating monitoring and oversight throughout the implementation process.

Contributors

ST coordinated and supervised the project, GS, YZ, and KJ designed the experiment and modelling analysis. YZ, KJ, WM, QZ, and HS performed the model analysis and validation. GS, KJ, WM, and ST prepared and interpreted data. YZ and KJ completed the figures. GS, KJ, QZ, HC, and ST analysed the simulation results. ST, AP, and GS drafted and revised the manuscript, and all coauthors contributed to the interpretation of the results and to the text. All authors read the paper and approved the submission. All authors had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

Emissions data in baseline can be openly accessed via the GEMS platform (<https://gems.pku.edu.cn>). The underlying data for emissions, ambient and indoor PM_{2.5} concentrations, exposure, and related premature deaths across all clean-intervention scenarios are presented in part in the tables and figures; complete datasets can be obtained from the corresponding author upon reasonable request.

Acknowledgments

This work was funded by the National Natural Science Foundation of China (grants 42330709, 42371077), the Fundamental and Interdisciplinary Disciplines Breakthrough Plan of the Ministry of Education of China (JYB2025XDXM909), and the Yunnan provincial Science and Technology Project at the Southwest United Graduate School (202302A037001). Part of the analysis was performed on the High-Performance Computing Platform of the Center for Life Science, Peking University. We thank Wenlu Ye and Yana Jin for valuable insights on the methodology and experimental analysis, and the anonymous reviewers for valuable and constructive comments to clarify and improve the paper.

Editorial note: The Lancet Group takes a neutral position with respect to territorial claims in published maps and institutional affiliations.

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