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Environmental benefits and household costs of clean heating options in northern China

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The Chinese government accelerated the clean residential heating transition in northern China as part of a successful effort to improve regional air quality. Meanwhile, China has committed to carbon neutrality by 2060, making strategic choices for long-term decarbonization of the residential sector necessary. However, the synergies and trade-offs for health and carbon of alternative heating options and associated costs have not been systematically considered. Here we investigate air-quality–health–carbon interdependencies as well as household costs of using electricity (heat pumps or resistance heaters), gas or clean coal for residential heating for individual provinces across northern China. We find substantial air-quality and health benefits, varied carbon emissions and increased heating costs across clean heating options. With the 2015 power mix, gas heaters offer the largest health–carbon co-benefits, while resistance heaters lead to health–carbon trade-offs. As the power grid decarbonizes, by 2030 heat pumps achieve the largest health–carbon synergies of the options we analysed. Despite high capital costs, heat pumps generally have the lowest operating costs and thus are competitive for long-term use. With increased subsidies on the purchase of heat pumps, the government can facilitate further air-quality improvements and carbon mitigation in the clean heating transition.

China has among the worst ambient air pollution levels in the world, leading to 2.5 million premature deaths each year[1]. In addition, it is the largest global emitter of greenhouse gases (GHGs)[2]. To restore blue skies, improve public health and meet its commitment to carbon neutrality by 2060, China must accelerate its energy transition from coal to non-fossil energy (NFE)[2].

The residential sector is a major source of health-damaging $PM_{2.5}$ (particulate matter with aerodynamic diameter $\leq 2.5\,\mu m$) air pollution due to the inefficient combustion of solid fuels[3–5]. In 2015, the residential sector contributed ~40% and ~17%, respectively, of China's anthropogenic $PM_{2.5}$ and SO_2 (a gaseous precursor of $PM_{2.5}$) emissions[6]. It thus plays a critical role in regional air quality, particularly during the heating season in northern China[3,7–9]. Around 2015, residential emissions resulted in ~30% of the ambient $PM_{2.5}$-attributable premature deaths in China[1,10]. At the end of 2016, solid fuels still dominated China's residential heating (over 80% in northern China, Supplementary Fig. 1) due to the relatively high cost of clean energy and the lack of policy interventions[11–14].

Recognizing the large impact of the residential sector on air quality and human health, in 2017 the Chinese government promulgated the Clean Winter Heating Plan in northern China (Clean Heating Plan). This required a dramatic increase in the penetration of clean energy (for example, clean coal briquettes, natural gas, electricity and processed biomass) from 34% to 70% in residential heating across northern China from 2016 to 2021[14]. By mid-2020, over 30 million households had converted to clean heaters, but ~50% of these households continued to rely on fossil energy, including natural gas and coal-based electricity[15]. This conversion brought enormous air-quality and health benefits[16,17]. However, more attention on the varying implications for carbon emissions and varying household costs, depending on the alternative heater and fuel, is needed[18–20].

No previous studies have simultaneously evaluated air quality, health, carbon and household cost implications of alternative clean heating options across northern China. In this article, we simultaneously analyse all of these factors for non-district clean heating options (for example, electric, gas and clean coal heating) while also exploring the impact of electricity decarbonization in China on emissions from electric heaters. Going beyond previous studies[17,18], for each heating technology we conduct a detailed cost analysis for both urban and rural households, considering provincial differences in heating demand, fuel prices and subsidies.

We find the transition to clean heating always provides air-quality and health benefits, while changes in GHG emissions and costs vary greatly depending on heater and fuel choices. Heat pumps provide increasingly larger air-quality–health–carbon co-benefits than electric resistance, gas or clean coal heaters as the grid further decarbonizes. Heat pumps generally have low operating costs even without subsidies. However, more financial support for initial heat pump purchase is needed in most regions to encourage uptake.

Clean heating scenarios

Clean coal, gas and electricity provide viable alternative fuel options for non-district residential heating. Clean coal has lower emission factors of major air pollutants than traditional solid fuels[21,22]. Along with higher-efficiency improved stoves, clean coal has been promoted by many local governments since 2013 and was the major clean heating option when the Clean Heating Plan was initiated[14,23]. Natural gas is the cleanest fossil fuel and takes a leading role in coal substitution in the '2+26' cities[23], a key region identified by the plan.

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Table 1 | List of scenarios

Case	Heating option	Configuration
BASE	2015 solid fuel use in residential sector[a]	-
CCIS_high	CCIS	High emission estimate
CCIS_low	CCIS	Low emission estimate
NGH	NGH	Conventional natural gas
AAHP_2015	AAHP	2015 electric power mix
RH_2015	RH[b]	2015 electric power mix
AAHP_2030	AAHP	2030 electric power mix
RH_2030	RH[b]	2030 electric power mix
NFE[c]	AAHP	NFE

[a]In the cost evaluation, we consider two widely used heating options before the clean heating transition for the base case: DCTS and DCIS. We do not consider costs of heating with wood and crop residues as they are free to collect. [b]In the cost evaluation, we consider two types of RH due to their distinct characteristics and costs: RHwTS and RHwoTS. [c]This is an additional scenario investigating the benefits of operating AAHP using electricity entirely from NFE sources. In this scenario, air pollutant emissions from operating heat pumps are assumed to be zero while GHG emissions come only from the refrigerant leakage.

Electric heating removes the emissions from end-use combustion but increases emissions from electricity generation. Among various electric heating devices, air-source heat pumps and resistance heaters (RH) are being widely promoted by the Chinese government[14,24].

In this study, our base case uses a 2015 regional anthropogenic emission inventory that includes residential solid fuel (dispersed coal, firewood and crop residues) use and associated emissions. We then propose seven counterfactual scenarios in which we assume all 2015 residential solid fuel heating in northern China switches to one of the following non-district heating options: clean coal with improved stoves (CCIS), natural gas heaters (NGH), RH or air-to-air heat pumps (AAHP or heat pumps, which are much more efficient than RH) (Table 1 and Supplementary Fig. 2). We construct two scenarios for CCIS as emission factors using clean coal stoves differ by up to an order of magnitude. We further consider two different power grids for electric heating scenarios: the 2015 power grid (68% coal and 3% gas)[25] and a partially decarbonized 2030 power grid (35% coal and 6% gas) developed by the International Energy Agency[26]. For cost analysis, we consider two types of RH as their capital and operating costs are quite different: RH with thermal storage (RHwTS) and RH without thermal storage (RHwoTS), and we include two types of baseline heating options: dispersed coal with improved stoves (DCIS) and dispersed coal with traditional stoves (DCTS).

Changes in air pollutant and CO_2e emissions

Changes in life-cycle emissions of residential $PM_{2.5}$, SO_2, NO_x and CO_2-equivalent (CO_2e) (under the 100-year global warming potentials, GWP_{100}) for upstream (electricity generation and fuel production) and downstream (fuel combustion in households) processes of clean heating options are shown in Fig. 1. We find reductions in downstream emissions in all scenarios except for CO_2e emissions in CCIS_high. These reductions occur because the combustion of clean coal and gas is more efficient, with lower emission factors of pollutants and GHGs, compared with that of solid fuels in the base case while electric heating has no downstream fuel combustion. The refrigerant leakage from the operation of heat pumps is also considered in the downstream process and accounts for ~4 TgCO_2e emissions (~1% of the base case) annually. By contrast, upstream emissions increase in all scenarios due to additional coal, gas or electricity demand. Changes in downstream emissions are generally dominant, leading to a net decrease in total emission. In addition, the spatial pattern of residential heating emissions is altered in electric heating scenarios where emissions in households and neighbourhoods are mostly reallocated to power plants. Although annual total $PM_{2.5}$ emissions decrease (84–99%) in all scenarios, a carbon penalty occurs in CCIS_high and RH_2015, where CO_2e emissions from residential heating increase by 76 Tg (21%) and 170 Tg (47%), respectively, in northern China (Supplementary Table 1). In the RH_2015 scenario, the additional electricity demand accounts for ~10% of national total power generation in 2015. In addition, total NO_x emissions increase dramatically in the AAHP_2015 and RH_2015 scenarios as average removal efficiency of NO_x in China's coal-fired power plants was low (62%) in 2015[27]. Since China's power sector is decarbonizing and the Chinese government released a policy in 2015 to achieve comprehensive ultra-low emissions and energy-saving retrofits of coal-fired power plants by 2020[26,28], emission intensities of both air pollutants and GHGs of electricity generation will be lower after 2015 than occurred with the 2015 power mix. Among the scenarios, NGH emit the least air pollutants when electric heating relies on the 2015 power grid (71% fossil), while AAHP achieve the largest emission reduction of both air pollutants and GHGs when electricity is from a 2030 power grid (41% fossil).

Reductions in ambient $PM_{2.5}$ and associated premature deaths

We apply a regional atmospheric chemistry model to simulate surface $PM_{2.5}$ concentrations in January, March, May, July, September and November for the base case and each scenario. We use simulations in January, March and November to represent the average conditions during the heating season. Modelled baseline $PM_{2.5}$ concentrations are in good agreement with surface observations, with annual mean bias (normalized mean bias) of 0.6 $\mu g\, m^{-3}$ (1%) over mainland China (Supplementary Fig. 3). $PM_{2.5}$ concentrations are notably higher in January and November than other months in northern China due to the intense pollutant emissions associated with residential heating in winter as well as unfavourable and stagnant meteorological conditions[29]. The '2 + 26' cities are hotspots for $PM_{2.5}$ pollution due to the high population density and associated intense anthropogenic emissions (Fig. 2a), which has led to this region being a focus of China's Clean Heating Plan.

We find significant reductions in surface $PM_{2.5}$ concentrations in all clean heating scenarios (Extended Data Fig. 1). The population-weighted (P-W) mean $PM_{2.5}$ concentrations decrease by 13–15 $\mu g\, m^{-3}$ (16–19%) during the heating season in northern China. The largest abatement occurs in the AAHP_2030 scenario (Fig. 2b–d), indicating the benefits of heat pumps combined with electrification using decarbonized electricity. The decreases in $PM_{2.5}$ concentrations have strong seasonality, with largest reductions occur in January. The '2 + 26' cities benefit most from the air-quality improvement, where mean P-W $PM_{2.5}$ concentrations decrease by 18–22 $\mu g\, m^{-3}$ (17–20%) during the heating season across scenarios. In addition, southern China benefits from the clean heating interventions due to decreases in regional transport of air pollutants from northern regions. During the heating season, average P-W $PM_{2.5}$ concentrations in southern China decrease by ~2 $\mu g\, m^{-3}$ (~3%) among the scenarios.

On the basis of the Global Exposure Mortality Model (GEMM), we estimate the ambient $PM_{2.5}$-related premature mortality due to noncommunicable diseases (NCDs) and lower respiratory infections (LRIs)[30] (Supplementary Table 2). Across China, the AAHP_2030 scenario achieves the largest reduction in annual premature mortalities of 81,400 (77,100–85,500), accounting for 3.4% of national ambient $PM_{2.5}$-attributed premature mortality in the base case, followed by NGH and RH_2030. The health benefit of the CCIS_high scenario is smallest of all the scenarios but is still

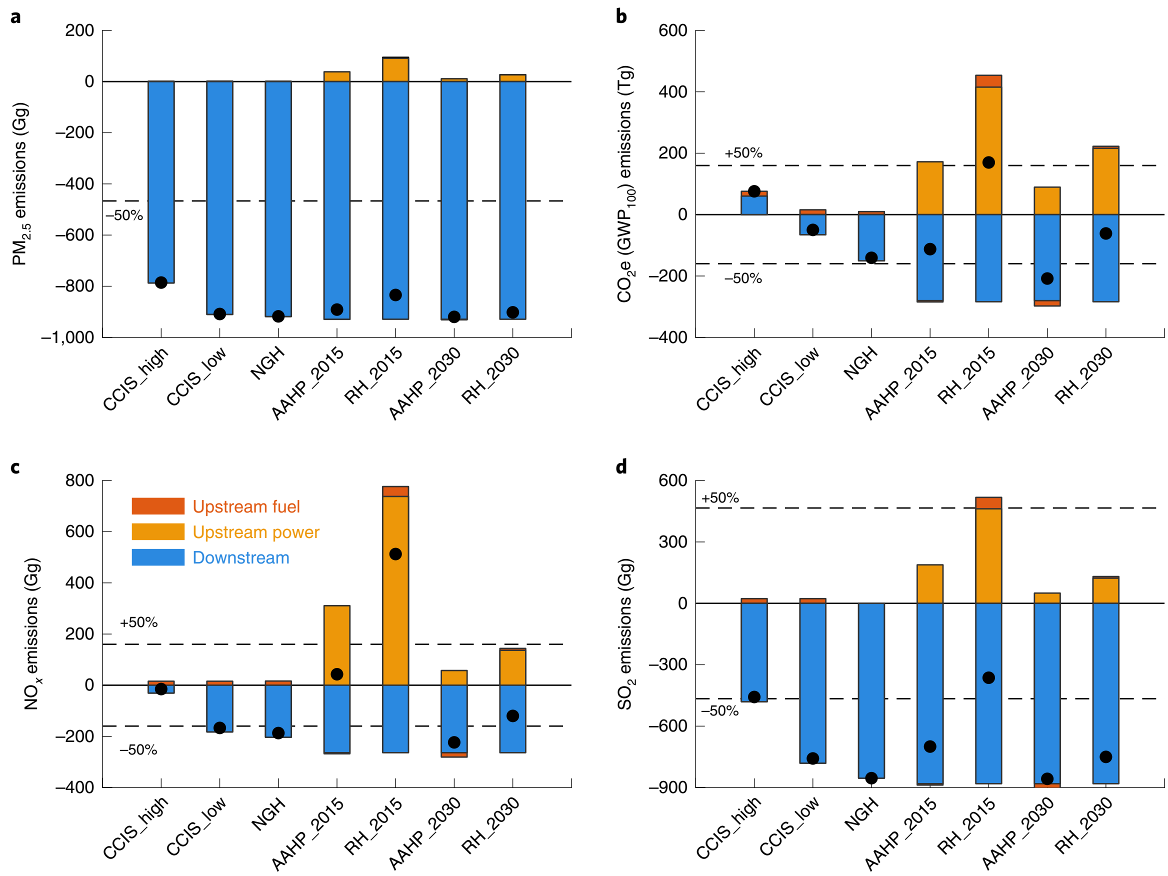

Fig. 1 | Changes in upstream and downstream residential heating emissions in northern China in 2015. **a**, $PM_{2.5}$ emissions. Gg, gigagrams. **b**, CO_2e emissions (GWP_{100}). Tg, teragrams. **c**, NO_x emissions. **d**, SO_2 emissions. Black dots denote net emission changes. Dashed lines denote ±50% of residential heating emissions in the base case. Upstream emissions refer to emissions from coal and gas exploration, processing, transport and distribution (upstream fuel, red bars) and emissions from power plants for additional electricity generation (upstream power, orange bars). Downstream emissions are from fuel combustion for household heating (blue bars). Note that the NFE scenario results in zero air pollutant emissions and ~4 Tg GHG emissions (from the refrigerant leakage) and is not shown in this figure.

larger than reductions achieved by the partial use of clean fuels in the residential sector during 2013–2017 (67,100 versus 49,200) (ref. [31]). Figure 2e,f shows annual avoided premature mortality for each province/municipality/autonomous region (province, hereafter) in AAHP_2030 and CCIS_high. The Beijing–Tianjin–Hebei region gains the largest health benefits, where the reductions account for ~25% of national avoided deaths across scenarios.

Variations in household heating costs

We evaluate upfront capital costs (UCC) and annual operating costs (AOC) of various heating options for urban and rural households in each province across northern China (Fig. 3). UCC are what a household must pay to purchase the heaters and stoves (including installation fees) as few loans are available. AOC are what a household must pay for heating fuels each year.

We find, without subsidies, all clean options increase households' UCC and AOC compared with DCIS. Some clean heating options have lower AOC than DCTS as DCTS is inefficient. Among the clean options we analysed, the UCC are highest for AAHP and RHwTS and are lowest for CCIS and RHwoTS, with NGH falling in the middle. Although the UCC for RHwoTS are low, the AOC for RHwoTS are highest. Therefore, RHwoTS are a good choice only for occasional backup heating. The AOC for AAHP and CCIS_low are lowest (except for Qinghai, where AAHP efficiency and gas price are both low, leading NGH to have the lowest AOC). If we consider the different lifespans of the devices, RHwoTS or RHwTS have the highest total annualized costs (TAC, annualized capital costs plus AOC), while CCIS_low has the lowest TAC (Fig. 4b). For detailed TAC in each province, see Extended Data Fig. 2.

Costs increase from urban (cold) to rural (extremely cold) areas. Compared with urban households, rural households have much higher UCC and AOC due primarily to larger house sizes and lower building energy efficiencies, thus requiring larger heaters and more fuel. We find UCC of AAHP per household are ~6,000–11,000 (~17,000–25,000) renminbi (RMB) in urban (rural) areas without subsidies. By comparison, the average annual per capita consumption expenditures in China were ~28,000 (~13,000) RMB in urban (rural) areas in 2019[32], leading to a far larger fraction of household income required for clean heater uptake in rural than urban areas.

To facilitate the uptake of clean heaters, many provinces in northern China have provided financial support for both fuels and devices (Supplementary Tables 3 and 4). These supports include ceilings in public bidding on clean heating device prices, adjustments on residential electricity and gas pricing (for example, in Beijing and Tianjin, valley-hour electricity rates were reduced from ~0.5 to 0.3 RMB kWh^{-1} during the heating season) and subsidies on both devices and fuels[19]. Subsidies, especially for devices, vary across northern China, depending mainly on local governments' budgets and whether the central government provides support[33–35]. For example, Beijing has been the most successful in widely replacing coal stoves with clean heaters due to generous subsidies from both the central and local governments. The '2+26' cities received

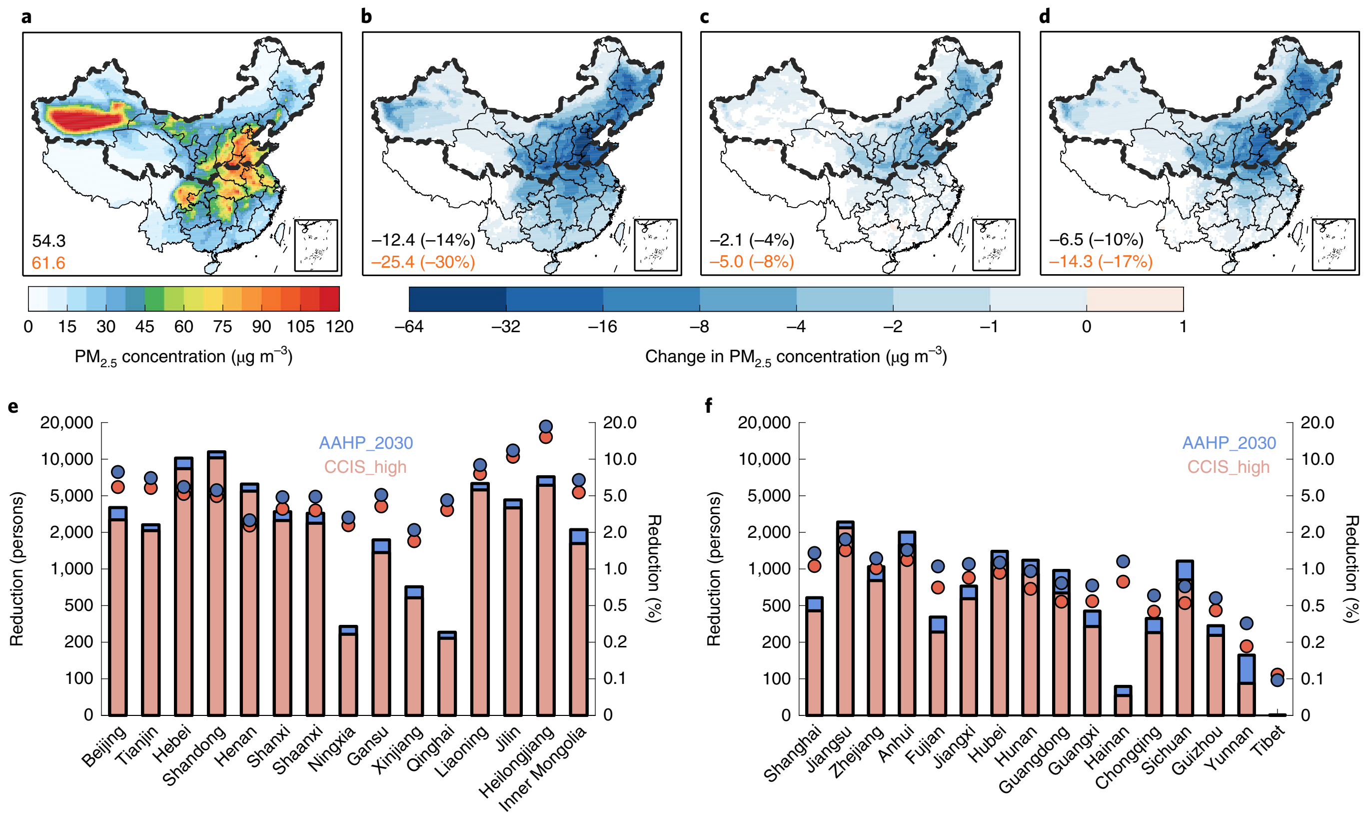

Fig. 2 | Simulated surface $PM_{2.5}$ concentrations and estimated health benefits. **a**, Annual mean surface $PM_{2.5}$ concentrations in the base case. **b**–**d**, Monthly mean $PM_{2.5}$ concentration changes in January (**b**), March (**c**) and November (**d**) in the AAHP_2030 scenario. **e**,**f**, Annual reduction in premature mortality (bars, absolute reduction; circles, percentage reduction) for northern (**e**) and southern (**f**) provinces across mainland China (see Supplementary Fig. 1 for their locations) in the AAHP_2030 (blue) and CCIS_high (pink) scenarios. Note the inset numbers in **a** are P-W mean $PM_{2.5}$ concentrations (μg m^{-3}) for China (black) and northern China (orange) in the base case, while those in **b**–**d** are the corresponding absolute changes (percentage changes in parentheses) in the AAHP_2030 scenario relative to the base case. In **a**–**d**, dashed lines denote the boundaries of northern China identified in the Clean Heating Plan while white areas inside China denote grids where changes are either not statistically significant at 99% confidence level (alpha = 0.01) or smaller than 0.1 μg m^{-3}.

subsidies from the central government, and many of them also received local government subsidies, making them more successful in the clean heating transition than the rest of northern China. By contrast, in Xinjiang, Qinghai, Jilin, and Heilongjiang (where residents' incomes are low but heating costs are high), few clean heating subsidies had been received from either central or local governments by 2020. We find, even when all available 2018–2020 subsidies are applied, rural households in northern China (except for Beijing and Tianjin) are still facing unaffordable clean heating costs (especially UCC). Current subsidies increase rather than decrease cost inequality as households in more developed regions with higher incomes currently receive greater subsidies.

Discussion and policy implications

We analyse the benefits for carbon mitigation, air quality and health as well as household costs of replacing non-district residential heating using solid fuels in northern China with various clean options. We find that air-quality and health benefits are similar across scenarios (except for lower benefits for CCIS_high and RH_2015), but carbon emissions and household heating costs vary greatly (Fig. 4 and Supplementary Table 5).

Heat pumps offer slightly smaller air-quality–health–carbon co-benefits than gas heaters when powered with the 2015 grid (68% coal). As air pollutant emission intensities of remaining coal-fired power plants decrease and the power grid decarbonizes[26,28], both $PM_{2.5}$ and CO_2e emissions from operating heat pumps will decrease relative to gas heaters (Fig. 5). By 2020, carbon reductions that could be obtained by using heat pumps had become comparable to reductions possible with gas heaters. Among the scenarios analysed, heat pumps using a partially decarbonized 2030 power grid (35% coal) offer the largest synergies between health and carbon reductions of the clean heating options considered. Additional reductions of ~106 TgCO_2e emissions and ~1,000 premature deaths would occur if all electricity comes from NFE sources (the NFE scenario, Fig. 4a). In addition, controls on the leakage of refrigerant liquids provide another opportunity to mitigate GHG emissions (up to ~4 Tg) from heat pump operation. Compared with RH, heat pumps are 60–200% more efficient (depending on ambient temperature) and thus result in ~60% less electricity demand and greater health and carbon co-benefits. Currently, without subsidies, operating costs of heat pumps are ~10% to ~70% (~10% to ~50%) lower than RH (gas heaters) in northern China (except for Qinghai and Inner Mongolia, where heat pumps are inefficient and gas prices are low). The efficiency of heat pumps is expected to increase[36], which will further reduce both air pollutant and GHG emissions (Fig. 5), as well as their operating costs. However, capital costs of heat pumps are 2–7 times (5–18 times) higher than gas (clean coal) heaters at present, making them unaffordable for many households. Only a few local governments (for example, in Beijing, Tianjin) provided sufficient subsidies to cover the capital costs of heat pumps.

Due to their inefficiency, RH provide smaller health and carbon benefits than heat pumps and gas heaters while having the highest

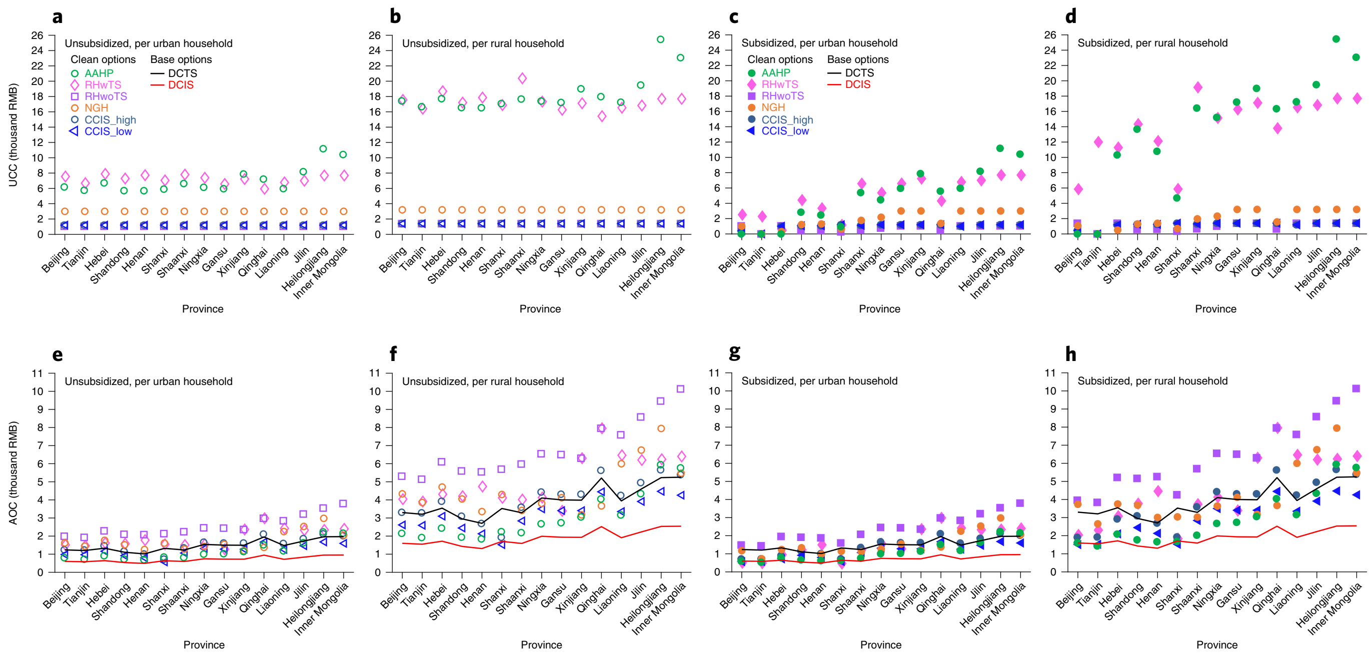

Fig. 3 | Unsubsidized and subsidized UCC and AOC of various heating options for typical urban and rural households in each province across northern China. a,b, Unsubsidized UCC for urban (**a**) and rural (**b**) households. **c,d**, Subsidized UCC for urban (**c**) and rural (**d**) households. **e,f**, Unsubsidized AOC for urban (**e**) and rural (**f**) households. **g,h**, Subsidized AOC for urban (**g**) and rural (**h**) households. The subsidies we use were in effect during 2018–2020. For provinces having different subsidies across their subordinate cities/counties, we use the P-W average subsidies to calculate the subsidized UCC and AOC at the provincial level. Subsidies for UCC and AOC in each province are listed in Supplementary Tables 3 and 4. See location of each province in Supplementary Fig. 1. Note that RHwTS can store thermal energy during off-peak hours when electricity prices are low and release the heat later as needed. By contrast, RHwoTS release all heat immediately. In addition, we do not show UCC for the base case (200–300 RMB for DCTS and 1,200–1,400 RMB for DCIS) as they are sunk costs, and DCTS and DCIS are not subsidized in our calculation.

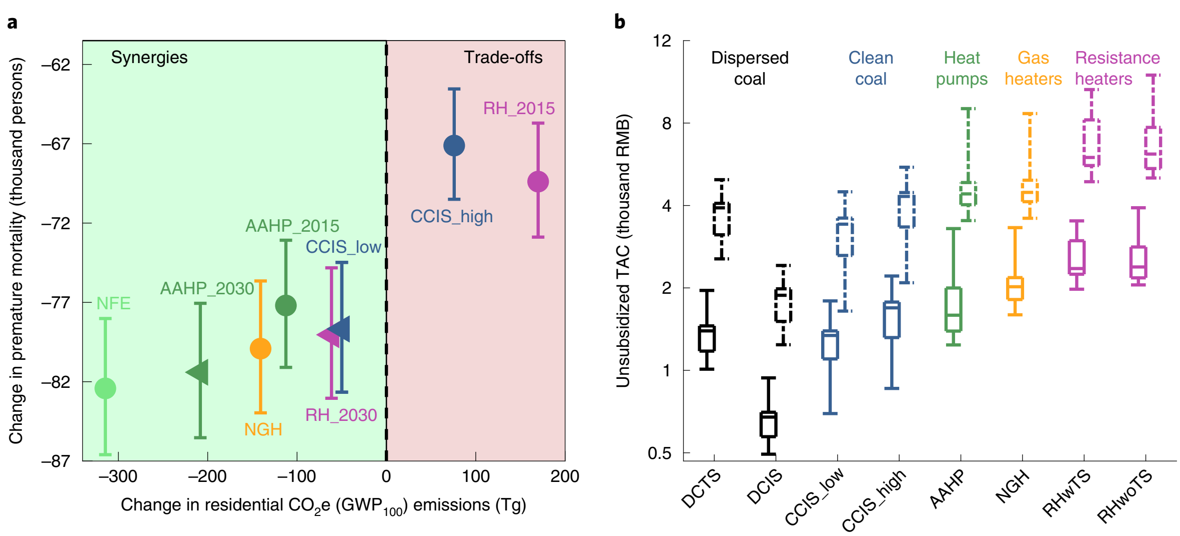

Fig. 4 | Benefits and costs of each clean heating option. a, Comparison of changes in premature mortality and CO_2e (GWP_{100}) emissions in each scenario relative to the 2015 base case. Error bars denote 95% confidence intervals for the mortality calculation, while green and red shaded areas denote synergies and trade-offs between health and carbon, respectively. Apart from seven counterfactual scenarios, we also show the result from NFE, an additional scenario where heat pumps are operated with electricity entirely from NFE sources. **b**, Comparison of unsubsidized provincial-level TAC per household across northern China for various heating options. The solid (dashed) lines represent costs for urban (rural) households. The boxes denote 25th, 50th and 75th percentiles and the whiskers denote minimum and maximum provincial-level TAC for each heating option. We do not consider the impact of electricity source on heating costs. See Extended Data Fig. 2 for TAC details by province.

TAC. For these reasons, some local governments no longer subsidize RHwoTS[37] as they will greatly increase power loads and heating operating costs. As RHwTS can be used for load shifting and charged with off-peak electricity and renewable energy at any time, governments continue to subsidize and promote them. Similar to our results, a previous study found that replacing coal with RH

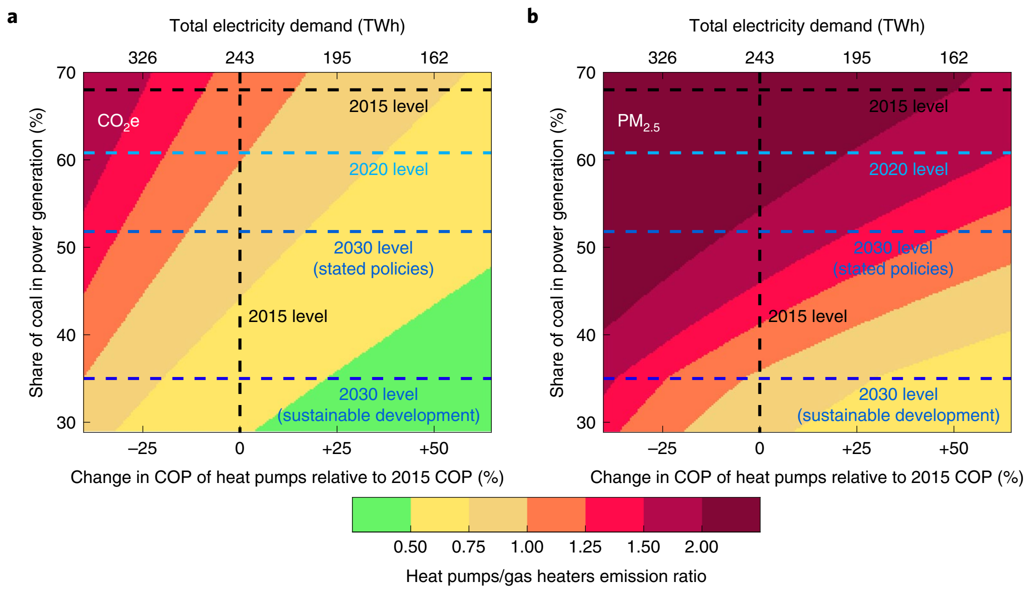

Fig. 5 | Emission ratio of operating AAHP and NGH under various conditions. a, CO_2e emissions. **b**, $PM_{2.5}$ emissions. We assume no changes in emissions from gas heating under conditions discussed in this figure. The vertical dashed line indicates the coefficients of performance (COP) of heat pumps and the additional electricity required for heat pump operations in 2015. Horizontal dashed lines denote the coal share in the 2015[25], 2020[63] and two projected 2030[26] power grids, respectively. In this study, COP are assumed to be a function of temperature and vary from place to place. Provincial average COP during the 2015–2016 heating season are listed in Supplementary Table 9. Other research indicates that COP are likely to increase in the future[36], which will decrease CO_2e and $PM_{2.5}$ emissions as well as total electricity demand from operating heat pumps. The 2030 power grid used in air-quality–health–carbon co-benefit evaluation is based on the sustainable development scenario from *World Energy Outlook 2020*[26]. Here we also show another projection from the stated policies scenario. Note that the grid projections were made before China committed to carbon neutrality.

using fossil-intense electricity increases GHG emissions[18]. Adoption of high-efficiency electric heaters (for example, heat pumps) avoids the carbon penalty resulting from a transition from coal to electric heating. Labelling heating devices with annual energy demand and associated cost estimates, in a similar fashion to the US Energy Star programme, would be a valuable tool to encourage household uptake of high-efficiency devices[38].

In 2015, gas heating brought the largest reductions in GHG emissions and premature mortality, slightly larger than heat pumps. However, gas heating will result in continued GHG emissions during the lifetime of the gas infrastructure. In addition, gas heating faces a stringent supply constraint. Our results indicate that in 2015 ~60% (~81 billion m^3) more domestic natural gas production would have been required in China to meet the additional gas demand in the gas heating scenario. However, the growth rate of China's domestic gas production (for example, 8.6% annually from 2006 to 2018[39]) is insufficient to fill this gap. Long-term committed GHG emissions from gas use as well as the potential risks of gas shortages and associated adverse environmental impacts[39,40] make gas heating a less attractive clean heating policy option. In addition, household operating costs of gas heaters will be higher than those of heat pumps and clean coal stoves after fuel subsidies are phased out. In most provinces, without subsidies, the total heating costs (UCC plus the total operating costs over time) of a gas heater over its lifetime (~8 years) will exceed the total costs of heat pumps (Extended Data Fig. 3). However, in extremely cold provinces, gas heating remains more economical than electric heating.

Clean coal heating generally has the lowest TAC among the clean options we analysed. A notification from the National Energy Administration indicates that CCIS can be a clean heating option in remote areas where the coal-to-gas/electricity conversion is temporarily unavailable due to the lack of suitable infrastructure[41]. However, we find annual differences of 11,600 premature deaths and 126 $TgCO_2e$ emissions between the two clean coal scenarios, CCIS_low and CCIS_high. This indicates that regulations requiring the use of clean coal and improved stoves is necessary in remote areas where coal will continue to be used for heating.

Our results are subject to several limitations and uncertainties. First, we chose 2015 as the base year for this study because 2015 is the most recent year for which we have access to modelling data. Considering China's decreasing residential emissions in recent years[6], combined with the higher $PM_{2.5}$ concentrations resulting from relatively stagnant meteorology in 2015 (Supplementary Fig. 4), the environmental and health benefits we calculated in each scenario are probably larger than what might typically result in the future. Second, our counterfactual scenarios, where clean coal, gas or electric heaters are uniformly applied over northern China, are sensitivity analyses designed to investigate the implications of viable clean heating strategies. These scenarios are not intended to be interpreted as real-world results. Third, our analysis examines only ambient air quality and does not include the impacts of indoor air pollution on health. The absolute reductions in premature deaths and the differences between scenarios would be far larger if we included the health impacts of indoor air pollution as well[5,11]. Furthermore, we consider only the capital and operating costs for a household of a typical size and constant indoor temperature 24 hours per day. In reality, costs vary depending on households' actual situations (for example, home size, building energy efficiency and indoor temperature choices).

Our findings can help guide further implementation of the Clean Heating Plan. First, heat pumps, rather than gas heaters, are clearly the best long-term option for clean heating. Policies that decrease the capital costs of heat pumps are needed, including increasing heat pump subsidies and providing zero-/low-interest loans. Energy efficiency labelling including operating costs for all heaters would also facilitate the uptake of heat pumps. Second, clean coal is a viable and economical interim option for remote areas before a full coal-to-electricity conversion is possible. However, stringent uniform emission standards for clean coal heating are critical. Third, for extremely cold regions where heat pumps are less efficient, heat pumps with backup (resistance or gas) heaters would be a reasonable choice. Last, our study reveals the inequalities, as a fraction of household income, associated with variations in incremental clean heating costs, given existing subsidies. Greater financial support for households in rural areas and in extremely cold regions (for example, Heilongjiang, Jilin and Inner Mongolia) is needed to facilitate the conversion to clean heating throughout northern China. In addition, improving building envelope efficiency is a possible way to reduce heating costs, which will also bring air-quality–health–carbon co-benefits.

Methods

We develop an integrated assessment approach to estimate changes in major air pollutant and CO_2e emissions for upstream and downstream processes, surface $PM_{2.5}$ concentrations and associated premature deaths, and household costs resulting from each clean heating option. On the basis of a regional anthropogenic emission inventory, we estimate emissions of CO, NO_x, SO_2, $PM_{2.5}$, black carbon, primary organic carbon, volatile organic compounds (VOC), CO_2 and CH_4 in each scenario. Upstream emissions include emissions from extraction, processing, transport and distribution of coal and gas as well as those from power plants for additional electricity generation. Downstream emissions refer to emissions from coal and gas combustion for household heating. We apply a meteorology–chemistry coupled model to simulate changes in surface $PM_{2.5}$ concentrations and use concentration–risk relationships to calculate associated premature mortality. We evaluate capital and operating costs of various heating options for urban and rural households in each province, taking account of heating demands that vary with provincial temperature, building energy efficiency and heating area.

Air pollutant and CO_2e emissions. We use the Multi-resolution Emission Inventory of China (MEIC) in 2015 for our baseline scenario[6,42]. MEIC provides monthly anthropogenic emissions of major gaseous and particulate pollutants from power plants, industries, residential cooking and heating, transportation and agriculture in mainland China with a horizontal resolution of 0.25°. We apply the residential emissions in July as non-heating emissions for each month, which is justified by the fact that these emissions (cooking and water heating) are generally constant throughout the year and no heating occurs in July in most regions[10]. We then calculate annual residential heating emissions by subtracting annual non-heating emissions in northern China from annual residential emissions. We also use this method to differentiate residential heating and non-heating solid fuel use in MEIC (Supplementary Fig. 4). We estimate annual heating demand associated with residential heating solid fuel use in the base case for each province in northern China using equation (1). Then we keep the estimated heating demand unchanged between the base case and each scenario and further calculate annual coal, gas and electricity demand at the end-use side in northern China using equation (2) and gas and electricity demand at the production side via equation (3).

$$\mathrm{HD}_p = \sum_{f=1}^{5}\sum_{d=1}^{4} M_{p,f} \times \mathrm{TD}_{p,f,d} \times \mathrm{HV}_f \times \mathrm{TE}_{d,f} \quad (1)$$

$$D_{p,f} = \frac{\mathrm{HD}_p}{\mathrm{TE}_{d,f} \times \mathrm{HV}_f} \quad (2)$$

$$P_{p,f} = \frac{D_{p,f}}{\gamma} \quad (3)$$

where HD_p is annual total heating demand in province p; $M_{p,f}$ is the mass of solid fuel f used in province p; $\mathrm{TD}_{p,f,d}$ is the technology distribution of stove d used for solid fuel f in province p[43]; HV_f is the heating value for fuel f; $\mathrm{TE}_{d,f}$ is the thermal efficiency for stove d using fuel f; $D_{p,f}$ and $P_{p,f}$ are the demand for clean fuel f for residential heating in province p at end-use and production side, respectively; $P_{p,f}$ considers the loss of electricity during transmission and the leakage of natural gas during transport. For electricity, γ considers transmission loss and electricity consumed by the power plants and equals 0.89[25]. For gas, γ considers gas leakage during transport and equals 0.95[44]. We do not consider the loss of coal during transport. Solid fuels considered in equation (1) include raw coal, washed coal, coal briquettes, wood and crop residues, consistent with MEIC. Stoves considered in equation (1) include traditional coal stove, traditional biomass stove, improved coal stove and improved biomass stove. Clean fuels considered in equation (2) include clean coal briquettes, gas and electricity. Clean heaters considered in equation (2) include improved coal stoves, gas heaters, RH and AAHP. The values of HV and TE are shown in Supplementary Tables 6 and 7. Note the COP of AAHP are assumed to be a function of the ambient air temperature[45].

We then estimate annual total emissions (ATE) for residential heating in northern China using equations (4)–(9). We estimate annual downstream emissions (DE) in clean coal and gas heating scenarios using equation (4). We estimate annual upstream emissions from electricity generation (UE1, equations (5) and (6)) for electric heating scenarios. We calculate annual upstream emissions from production, processing, transport and distribution of coal and gas (UE2, equations (7) and (8)) for the base case and all the clean heating scenarios. In equation (5), we assume electricity for residential heating is supplied by regional power grids (no inter-grid transmissions). In addition, we assume zero emissions for renewable, nuclear and hydro generation. We also include the impact of higher penetration of end-of-pipe emission control measures for both coal-fired and gas-fired power plants on the 2030 power grid[46]. Note that equation (7) is for the base case and the non-electric heating scenarios while equation (8) is for the electric heating scenarios.

$$\mathrm{DE}_{\mathrm{nc},i} = \sum_{p=1}^{15} D_{p,f} \times \mathrm{DEF}_i \quad (4)$$

$$\mathrm{UE1}_{\mathrm{nc},i} = \sum_{r=1}^{4} \frac{\sum_{p=1}^{\mathrm{np}_r} P_{p,\mathrm{ele}}}{\sum_{p=1}^{\mathrm{np}_r} G_{p,\mathrm{ele}}} \times E_{\mathrm{meic},r,i} \times \mathrm{SF}_i \quad (5)$$

$$\mathrm{SF}_i = \frac{\mathrm{PEF}_{\mathrm{coal},2030,i} \times S_{\mathrm{coal},2030} + \mathrm{PEF}_{\mathrm{gas},2030,i} \times S_{\mathrm{gas},2030}}{\mathrm{PEF}_{\mathrm{coal},2015,i} \times S_{\mathrm{coal},2015} + \mathrm{PEF}_{\mathrm{gas},2015,i} \times S_{\mathrm{gas},2015}} \quad (6)$$

$$\mathrm{UE2}_{\mathrm{nc},i} = \sum_{p=1}^{15} \left(D_{p,\mathrm{coal}} \times \mathrm{UEF}_{\mathrm{coal},i} + D_{p,\mathrm{gas}} \times \mathrm{UEF}_{\mathrm{gas},i}\right) \quad (7)$$

$$\mathrm{UE2}_{\mathrm{nc},i} = \sum_{p=1}^{15} P_{p,\mathrm{ele}} \times S_{\mathrm{coal}} \times \mathrm{CR}_{\mathrm{coal}} \times \mathrm{HV}_{\mathrm{scoal}} \times \mathrm{UEF}_{\mathrm{coal},i} + \sum_{p=1}^{15} P_{p,\mathrm{ele}} \times \frac{S_{\mathrm{gas}}}{\mathrm{TE}_{\mathrm{gas}}} \times \mathrm{UEF}_{\mathrm{gas},i} \quad (8)$$

$$\mathrm{ATE}_{\mathrm{nc},i} = \mathrm{DE}_{\mathrm{nc},i} + \mathrm{UE1}_{\mathrm{nc},i} + \mathrm{UE2}_{\mathrm{nc},i} \quad (9)$$

where $\mathrm{DE}_{\mathrm{nc},i}$ is annual downstream emissions for residential heating in northern China for species i (CO, NO_x, SO_2, $PM_{2.5}$, black carbon, primary organic carbon, VOC, CO_2 and CH_4); $D_{p,f}$ is the clean coal or gas demand for residential heating in province p estimated in equation (2); DEF_i is the downstream emission factors of clean coal or gas combustion for species i (Supplementary Table 7); $\mathrm{UE1}_{\mathrm{nc},i}$ is annual upstream emissions from electricity generation in northern China for species i; $P_{p,\mathrm{ele}}$ is total electricity generation for residential heating in province p derived from equation (3); np_r is the number of provinces in region grid r (northeast/north/northwest/central grids); $G_{p,\mathrm{ele}}$ refers to actual total electricity generation in province p in 2015[25]; $E_{\mathrm{meic},r,i}$ is the total emissions from power sector in region r for species i in MEIC 2015; SF_i is a scale factor for species i. For 2015 electric heating scenarios, $\mathrm{SF}_i = 1$; for 2030 electric heating scenarios, SF_i is calculated by equation (6). $\mathrm{PEF}_{\mathrm{coal/gas},2015/2030,i}$ is the national average emission factors for coal-fired or gas-fired power plants in 2015 or 2030 for species i and is adopted from the Eclipse_V5a_CLE (evaluating the climate and air-quality impacts of short-lived pollutants) scenario developed by the Greenhouse Gas and Air Pollution Interactions and Synergies[46]; $S_{\mathrm{coal/gas}}$ is the national share of coal or gas generation in the 2015 or 2030 power mix (Supplementary Table 8); $\mathrm{UE2}_{\mathrm{nc},i}$ is annual upstream emissions from coal or gas production, processing, transport and distribution in northern China for species i; $D_{p,\mathrm{coal/gas}}$ is annual total coal or gas demand (derived from MEIC or equation (2)) for residential heating in province p; $\mathrm{UEF}_{\mathrm{coal/gas},i}$ is the upstream emission factors (consumption side) of coal or conventional natural gas for species i[20]; $P_{p,\mathrm{ele}}$ is annual total electricity generation for residential heating in province p derived from equation (3); $\mathrm{CR}_{\mathrm{coal}}$ is the coal consumption rate of coal-fired power plants in 2015 or 2030 (via extrapolation)[27]; $\mathrm{HV}_{\mathrm{scoal}}$ is the heating value for standard coal (29 MJ kg^{-1}); $\mathrm{TE}_{\mathrm{gas}}$ is the thermal efficiency for gas-fired power plant (49%)[47].

We estimate CO_2e under the GWP_{100} via equations 10 and 11.

$$CO_2e = CO_2 + 24 \times CH_4 + \mathrm{LR} \quad (10)$$

$$\mathrm{LR} = \sum_{p=1}^{\mathrm{np}} \frac{D_p}{24 \times \mathrm{HDY}_p} \times \frac{\mathrm{EC}}{15} \quad (11)$$

where LR is the GHG emissions due to the leakage of refrigerants and is considered only for heat pump scenarios; HDY_p is the average heating days per year in province p (Supplementary Table 9); EC is the GHG emission intensity (750 kgCO_2e per kW of installed capacity) for the leakage of refrigerants over the entire life cycle[36]. In this study, we assume that the lifespan of heat pumps is 15 years and all heat pumps operate 24 h per day during the heating period.

All the emissions estimated in the preceding are considered residential heating emissions. We present total residential heating emissions of air pollutants and GHG in northern China in the base case and the corresponding changes in each scenario in Supplementary Table 1. We allocate total residential emissions to the modelling domain as follows. For downstream emissions from fuel combustion ($DE_{p,i}$ from equation (4)), we first allocate annual provincial-level emissions to each city or county on the basis of population data[48] and then follow the spatial distribution of residential emissions in MEIC 2015 inside each city or county. For upstream emissions from electricity generation ($UE1_{r,i}$ from equation (5)), we directly allocate annual emissions in each region using the spatial information of emissions from the power sector in MEIC 2015. For upstream emissions from fuel production, processing, transport and distribution ($UE2_{nc,i}$ from equations 7 and 8), we first allocate annual emissions to each province on the basis of the production capacity in 2015[49] and apply the distribution of annual total emissions in MEIC 2015 inside each province, similar to a previous study[20].

Evaluating air-quality impacts. We use the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem)[50] (version 3.6.1) to simulate surface concentrations of ambient air pollutants for the base case and for each counterfactual scenario. The model domain covers China and its peripheral regions with a horizontal resolution of 27 km and 37 vertical layers extending from a 40-m-thick surface layer to 50 millibars (mb) (Supplementary Fig. 1). We drive the model with meteorological and chemical initial and boundary conditions in 2015. The initial and lateral boundary conditions of meteorology are provided by National Centers for Environmental Prediction Final Operational Global Analysis data[51] at 1° × 1° resolution. Chemical initial and boundary conditions are archived from the Community Atmosphere Model with Chemistry (CAM-Chem)[52]. The biogenic non-methane VOC emissions are calculated online by the Model of Emissions of Gases and Aerosols from Nature coupled with WRF-Chem[53]. For anthropogenic emissions in the base case, we use MEIC 2015 over mainland China and the 2010 MIX Asia emission inventory over the rest of the WRF-Chem domain[6,54]. For anthropogenic emissions in each clean heating scenario, we replace residential heating emissions in MEIC with those constructed in this study and keep other sectors' emissions unchanged. To improve the $PM_{2.5}$ simulations, we adopt a recently developed agricultural ammonia emission inventory over mainland China[55] and apply a scheme that better resolves the formation of secondary inorganic aerosols in China[56].

We perform the simulations for January, March, May, July, September and November for the year 2015 and assume the annual average concentration is the mean of these six months. We reinitiate WRF-Chem every 48 h to prevent the drifting effects of simulated meteorological fields. However, this leads to an underestimation of the emission–aerosol–meteorology interactions, resulting in slightly smaller $PM_{2.5}$ changes associated with emission reductions in each scenario[57]. To evaluate the model performance, we compare modelled meteorological parameters (2 m air temperature, dewpoint temperature, 10 m wind speed and sea-level pressure) and $PM_{2.5}$ dry mass concentrations in the base case with observations from the National Climate Data Center and Ministry of Ecological Environment of the People's Republic of China (Supplementary Information, Model evaluation). Improvements of air quality can be estimated from the differences of surface $PM_{2.5}$ concentrations between the base case and each scenario.

Evaluating health impacts. We use the recently developed GEMM to estimate avoided premature deaths of NCDs and LRIs[30] that are related to ambient $PM_{2.5}$ pollution. The GEMM framework constructs a $PM_{2.5}$-mortality relative risk function on the basis of cohort studies of outdoor air pollution that covers the global exposure range, including high concentrations in China[30], and has been widely applied in recent studies[3,31]. The relative risks (RR) from GEMM are used to estimate the contribution of $PM_{2.5}$ pollution to the baseline mortality rate of a disease (NCDs and LRIs in our study) for a chosen age group. We therefore use it to estimate the change in the number of $PM_{2.5}$-related premature deaths for each clean heating scenario. The RR are calculated for adults (≥25 yr) with age groups in 5 yr intervals from 25 to greater than 85 via equation (12).

$$\mathrm{RR}\,(c) = e^{\frac{\theta \times \log\left(\frac{z}{\alpha+1}\right)}{1+e^{-\frac{z-\mu}{\nu}}}}, z = \max\,(0, c - 2.4) \tag{12}$$

where c is long-term ambient $PM_{2.5}$ concentration; e is natural logarithm; θ, σ, μ and ν are parameters that determine the shape of RR in GEMM and are specified for each age group; 2.4 μg m^{-3} is the $PM_{2.5}$ threshold below which no effect occurs. The reduction in premature deaths in each scenario can be estimated using equation (13).

$$\delta \mathrm{Mort}_{s,i,j} = \mathrm{Pop}_{i,j} \times \mathrm{Base}_i \times \left(\frac{1}{\mathrm{RR}_{s,i,j}} - \frac{1}{\mathrm{RR}_{b,i,j}}\right) \tag{13}$$

where $\delta\mathrm{Mort}_{s,i,j}$ is the abated premature mortality in scenario s for age group i in WRF-Chem grid j; $\mathrm{Pop}_{i,j}$ is the population within age group i in grid j; Base_i is national average mortality rate of NCDs and LRIs in 2015 for age group i; $\mathrm{RR}_{s,i,j}$ and $\mathrm{RR}_{b,i,j}$ are the RR of NCDs (or LRIs) for age group i, in grid j, at $PM_{2.5}$ exposure level in counterfactual scenario s and base case b, respectively. Gridded population data for 2015 are derived from the Global Population for the World dataset[58] and further scaled to reported total population within each province from the National Bureau of Statistics of China[48]. National mortality rate and age distribution data are both retrieved from the Global Burden of Diseases study 2017 (https://gbd2017.healthdata.org/gbd-search/). In our study, we perturb the value of θ on the basis of its mean and standard error described by Burnett et al.[30], generate 100,000 shapes of RR and further calculate the mean and 95% confidence intervals of avoided premature deaths in each clean heating scenario. We present the results rounded to the nearest hundred for all of China, northern China, the '2 + 26' cities and the Fen-Wei Plain in Supplementary Table 2. We estimate 2.39 million premature deaths in the base case across China in 2015; a similar result of 2.47 million was reported by Burnett et al.[30].

Evaluating heating costs for households. We evaluate capital and operating costs of various heating options for urban and rural households in each province, taking account of heating demands that vary with provincial temperature, building energy efficiency and home size. Capital costs depend on the required power capacity (kW) of each device per household and associated purchasing and installation charges (RMB). We use parameters including annual heat demand in residential buildings (GJ m^{-2} yr^{-1}), heating areas per household (m^2), heating days per year in each province, as well as thermal efficiency and running hours per day of various devices to estimate the required power capacities of various devices. Operating costs are determined by fuel demand and prices. To determine fuel demand, we use parameters including annual heat demand in residential buildings (GJ m^{-2} yr^{-1}) in each province, heating areas per household (m^2) for a typical urban/rural household, heating values of various fuels, as well as energy conversion coefficients from gigajoule to kilowatt-hour (for electricity), cubic metre (for gas) or ton (for coal). We do not consider infrastructure costs of constructing (upgrading) the gas transport (electricity transmission) and dispatch systems as these costs are covered by governments and utility companies rather than households.

Specifically, we evaluate UCC ($UCC_{i,p}$) and AOC ($AOC_{i,p}$) of each heating option i for urban and rural households in each province p of northern China. UCC are what a household must pay to purchase the heaters/stoves (including installation fees) as few loans are available to finance purchases. AOC are what a household must pay for heating fuels (including electricity, natural gas, clean coal briquettes and dispersed coal) each year. Dispersed coal includes raw coal, washed coal and coal briquettes (both bituminous and anthracite briquettes), on the basis of the MEIC inventory. $UCC_{i,p}$ of RHwoTS, NGH and coal stoves are directly priced by the heating areas in each household (Supplementary Table 10), while $UCC_{i,p}$ of AAHP and RHwTS are priced by the needed power capacities ($PC_{i,p}$) of the devices. Unlike previous studies, which assumed electric heating capacity to be the same[18], here we calculate $PC_{i,p}$ in equations 14 and 15.

$$\mathrm{PC}_{i,p} = \frac{Q_{i,p}}{\mathrm{HDY}_p \times \mathrm{OH}_i} \tag{14}$$

$$Q_{i,p} = \frac{1,000 \times \mathrm{HDM}_p \times \mathrm{HA}}{\mathrm{HV}_f \times \mathrm{TE}_i} \tag{15}$$

where $Q_{i,p}$ is the annual electricity consumption of heater i for a household in province p; HDY_p and OH_i are the average heating days per year in province p and the operating hours per day of the heating devices i in a household, respectively (Supplementary Table 9). For AAHP, we convert their power capacities from kilowatt to horsepower (1 horsepower = 0.735 kW) as horsepower is the unit commonly used for heat pumps in the marketplace. HDM_p is the average heat demand per square metre per year for residential buildings (GJ m^{-2} yr^{-1}) in province p from the survey data[59]. As the survey data provide only HDM_p in urban areas, we assume that rural HDM_p are twice urban HDM_p on the basis of the estimation of our previous work[19]. HA is the heating area (rather than building area) for a typical household (m^2), which we assume to be 60 m^2 and 80 m^2 for urban and rural homes, respectively, according to the survey data[59,60]. HV_f and TE_i are the heating values of fuel f and the thermal efficiency of heater i, respectively (Supplementary Table 6). For dispersed coal, we take the quantity-weighted average heating values (~22 MJ kg^{-1}) of raw coal, washed coal and coal briquettes in accordance with the MEIC inventory in each province.

$AOC_{i,p}$ are determined by the product of annual fuel demand of each heating device i ($Q_{i,p}$) and the prices of the fuels (Supplementary Table 11) in province p. Data on prices of heating devices and fuels were collected from the Chinese market in 2019. Subsidies from governments were in effect during 2018–2020. Considering that the heating devices have different lifespans, we further evaluate the TAC ($TAC_{i,p}$) of a heating device i in province p for a representative household by adding $AOC_{i,p}$ to $ACC_{i,p}$, as shown in equations 16 and 17.

$$\mathrm{TAC}_{i,p} = \mathrm{AOC}_{i,p} + \mathrm{ACC}_{i,p} \tag{16}$$

$$\mathrm{ACC}_{i,p} = \frac{\mathrm{UCC}_{i,p}}{\left(1 + \frac{1}{1+\mathrm{dr}} + \ldots + \frac{1}{(1+\mathrm{dr})^{n_i - 1}}\right)} \tag{17}$$

where dr in equation (17) is the discount rate (8%) for the residential sector[61] and n_i is the lifespan of a heating device *i* (Supplementary Table 9). Salvage values of the heaters are not considered in our calculation as they rarely influence the residents' decisions due to their low present values[62].

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The Multi-Resolution Emission Inventory of China (MEIC) and the MIX Asia emission inventory are available from the MEIC website (http://meicmodel.org, registration required). WRF-Chem outputs and data generated in this study are publicly available on the Princeton archive at https://doi.org/10.34770/wz62-f790. Data for cost analyses are collected from governmental documents, newspapers, reports, previous literature and conversations with local residents and heating device suppliers, and are listed in the Supplementary Information. Hourly surface $PM_{2.5}$ measurements across mainland China are available at http://106.37.208.233:20035, and processed monthly mean $PM_{2.5}$ concentrations are provided as additional supplementary file. Surface meteorological observations are available at https://www.ncei.noaa.gov/products/land-based-station/integrated-surface-database. Source codes of the WRF-Chem model utilized in this study are available at https://github.com/wrf-model/WRF/releases/tag/V3.6.1. Source data are provided with this paper.

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Author contributions

D.L.M. designed the research. M.Z. and H.L. performed the research. H.L., L.Z., L.P. and Y.Q. contributed data for scenario setups. M.Z., L.Z. and D.C. contributed air-quality model improvements. M.Z., H.L. and D.L.M. analysed data. M.Z., H.L., and D.L.M. wrote the paper with feedback from all other authors. M.Z. and H.L. contributed equally to this work.

Competing interests

The authors declare no competing interests.

Additional information

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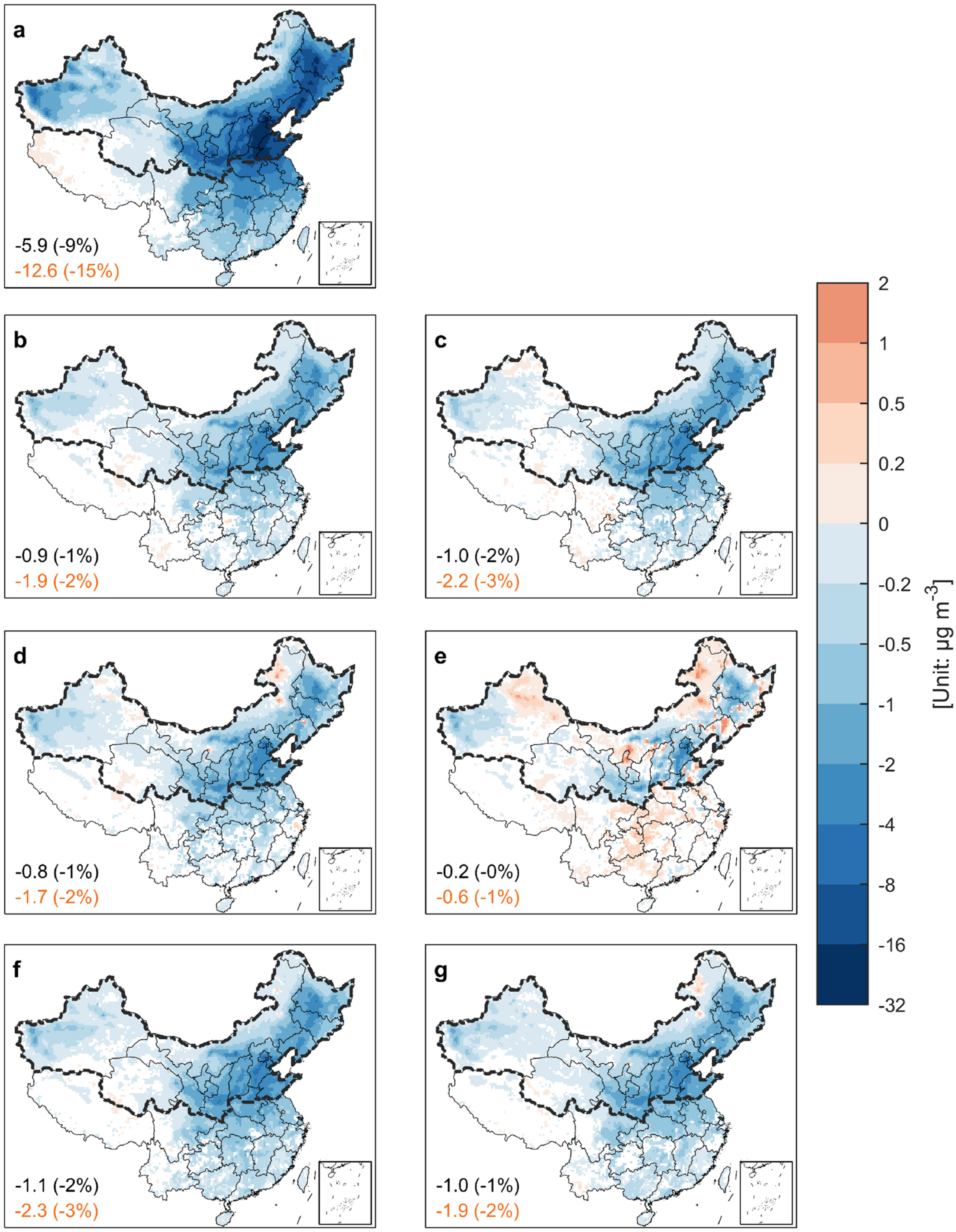
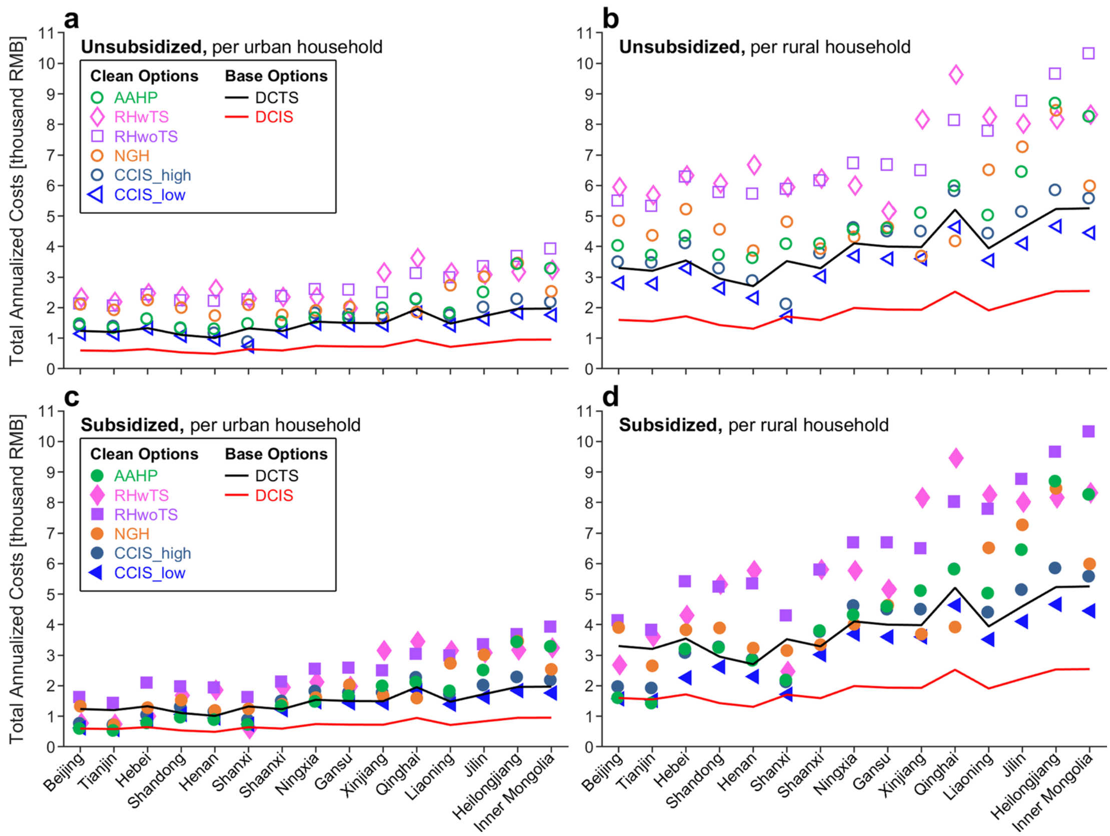
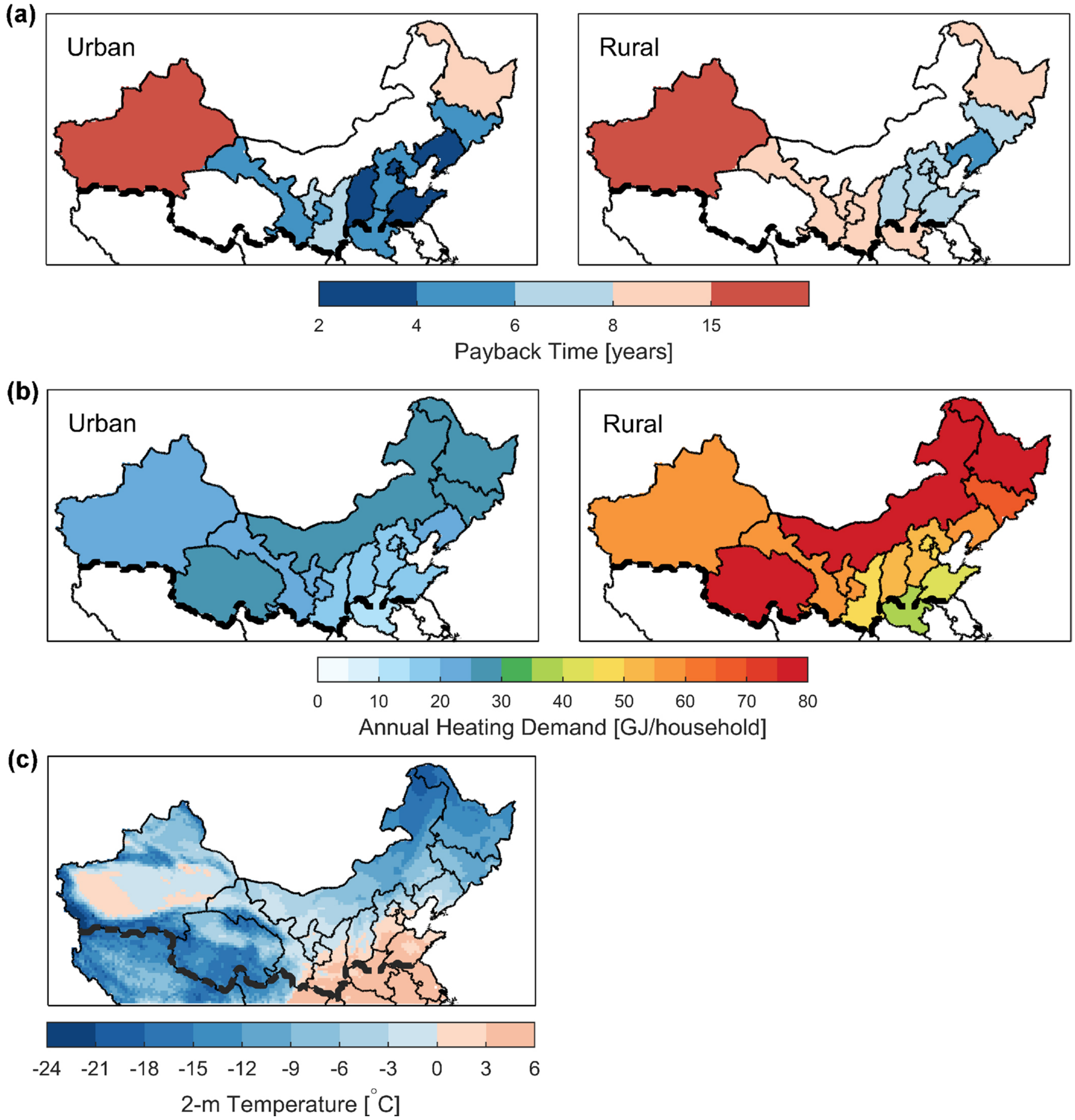


Extended Data Fig. 1 | Mean surface $PM_{2.5}$ concentration changes during the heating season. Surface $PM_{2.5}$ concentration changes averaged over three months (January, March, and November) in 2015. $PM_{2.5}$ concentration changes in the CCIS_high scenario (CCIS_high minus BASE, **a**), and the further changes in CCIS_low (CCIS_low minus CCIS_high, **b**), NGH (NGH minus CCIS_high, **c**), AAHP_2015 (AAHP_2015 minus CCIS_high, **d**), RH_2015 (RH_2015 minus CCIS_high, **e**), AAHP_2030 (AAHP_2030 minus CCIS_high, **f**), and RH_2030 (RH_2030 minus CCIS_high, **g**). Note the inset numbers are the absolute changes (percentage changes in parentheses) of population-weighted mean $PM_{2.5}$ concentrations for China (Black) and northern China (Orange). Dashed lines denote the boundaries of northern China identified in the Clean Heating Plan. White areas inside China denote grids where changes are either not statistically significant at 99% confidence level (alpha = 0.01) or smaller than 0.1 μg/m^3.



Extended Data Fig. 2 | Unsubsidized and subsidized total annual costs (TAC) for typical urban and rural households in each province across northern China. Unsubsidized and subsidized total annualized costs (TAC) for typical urban and rural households in each province across northern China. TAC equals annual operating costs (AOC) plus annualized capital costs (ACC). ACC was determined by upfront capital costs (UCC) and lifespan of each heating device, as well as discount rate, which is 8% in this paper. See Table 1 for definition of heating option acronyms. The subsidies we use were in effect during 2018-2020. For provinces having different subsidies across their subordinate cities/counties, we use the population-weighted average subsidies to calculate the subsidized UCC and AOC at provincial level. Subsidies for UCC and AOC in each province are listed in Supplementary Tables 3 and 4. See location of each province in Supplementary Figure 1. DCTS and DCIS were not subsidized in our calculation.



Extended Data Fig. 3 | Payback time for households if coal stoves are replaced with AAHP rather than NGH. Payback time if households switch to heat pumps rather than gas heaters, household heating demand, and averaged temperature during heating season across northern China. a, Required time (payback time, in years) for the total heating costs of gas heaters to exceed those of heat pumps for households in each province. Total heating costs are UCC plus the total operating costs over time. Life span for gas heaters is 8 years while that for heat pumps is 15 years. Note that in Qinghai and Inner Mongolia, AOC of NGH are lower than AOC of AAHP because AAHP are inefficient in these cold regions and gas price there are low. Therefore, the total heating costs of gas heaters are always lower than those of heat pumps in Qinghai and Inner Mongolia. For each color interval, the lower bound is included while the upper bound is excluded. b, Annual heating demand for households in each province. c, The spatial pattern of 2-m temperature averaged for the winter heating season from 2010 to 2019. Here, we use monthly mean temperature in January, February, March, November, and December to represent the average conditions during the heating season in each year. The reanalysis data is from the European Centre for Medium-Range Weather Forecasts (https://www.ecmwf.int/). Dashed lines denote the boundaries of northern China identified in the Clean Heating Plan.

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☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	(1) We utilized the official version of the WRF-Chem air quality model v.3.6.1 which is publicly available. (2) Emission inventory for the base case was adopted from the Multi-Resolution Emission Inventory of China (MEIC) and the MIX Asia emission inventory , which are available from the MEIC website (meicmodel.org, registration required). (3) Data for the cost analysis was collected from previous literature, market, government documents, as well as conversations with local residents and heating device suppliers. (4) Other data, including emission factors for air pollutants, energy share in China's power grids, and surface pollutant observations are all provided in the manuscript and Supplemental Information with sources clearly specified.
Data analysis	For the evaluations of air quality, health, carbon emissions, and household costs, all the plotting scripts, as well as scripts for data process and analysis are written in MATLAB.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

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- A description of any restrictions on data availability

Surface PM2.5 measurements across mainland China are available at http://106.37.208.233:20035. Surface meteorological observations are available at ftp://

ftp.ncdc.noaa.gov/pub/data/noaa/isd-lite/. The Multi-Resolution Emission Inventory of China (MEIC) and the MIX Asia emission inventory are available from the MEIC website (meicmodel.org, registration required). Monthly mean PM2.5 concentrations from the WRF-Chem model will be made available upon publication of the manuscript. Data for cost analyses are collected from governmental documents, newspapers, reports, previous literature, and conversations with local residents and heating device suppliers, and are listed in the Supplementary Information. Source codes of the WRF-Chem model utilized in this study are available at https://github.com/wrf-model/WRF/releases/tag/V3.6.1.

Field-specific reporting

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Integrated assessment on air quality, health, carbon emission, and household costs of various clean heating options in northern China
Research sample	15 provinces in northern China as covered in the Clean Winter Heating Plan 2017-2021
Sampling strategy	N/A
Data collection	Data required for constructing scenarios and estimating heating emissions were collected from literature and reports. Data needed for cost evaluations were obtained via market and governmental documents.
Timing and spatial scale	All the information collected are specifically for China. Data required for scenario configurations and emission estimations were collected for 2000-2020. Data needed for cost evaluations were collected for 2018-2020.
Data exclusions	No data was excluded
Reproducibility	Others will be able to reproduce our results
Randomization	N/A
Blinding	N/A

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

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