Environmental Science & Technology

pubs.acs.org/est

Article

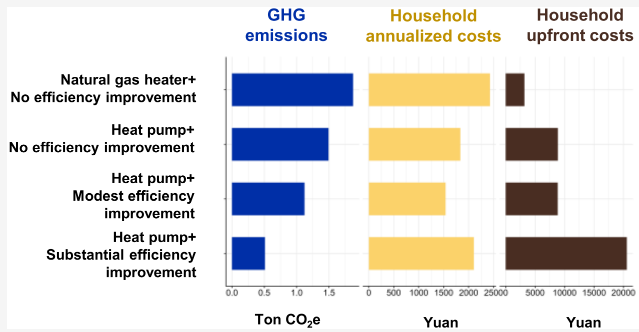
Improving Building Envelope Efficiency Lowers Costs and Emissions from Rural Residential Heating in China

Shangwei Liu, Hongxun Liu, and Denise L. Mauzerall*

Cite This: Environ. Sci. Technol. 2023, 57, 595−605

Read Online

ABSTRACT: In 2017, the Chinese government launched a clean heating campaign that replaced millions of rural coal stoves with various clean heaters. The clean heating program contributed to remarkable improvements in air quality. However, the benefits of reducing heating demand by improving building envelope efficiency were not sufficiently considered. This study provides a needed quantitative assessment of potential energy-savings, costs, greenhouse gas emission reductions, and adoption strategies for improving building envelope efficiency in Chinese rural residential buildings. We find that different strategies must be employed in existing and new buildings to achieve desired outcomes. For existing buildings, to encourage easy and beneficial building retrofits (e.g., air sealing, efficient windows), current fuel subsidies should be replaced with retrofit subsidies. Building retrofits can reduce the size and hence capital costs of new clean heaters. They can also reduce operating costs, hence reducing the likelihood of backsliding to coal. For new construction, whole-home insulation and heat pumps would best avoid carbon lock-in. These efficient technologies have high upfront costs but decrease heating costs and significantly reduce carbon emissions relative to current policies. Hence, subsidies and policies that encourage improvements in building envelopes as well as the uptake of clean and efficient heaters are critical.



KEYWORDS: *Building, Energy Efficiency, Heating, Emissions, China*

■ INTRODUCTION

Ambient and indoor air pollution in China contributed to more than 1 million deaths in 2014, of which more than half were attributed to the residential sector mainly because of the massive and inefficient use of solid fuel, particularly coal.[1,2] Coal remained the predominant heating fuel for rural households without district heating in northern China in 2016. Because small household coal stoves are very inefficient and end-of-pipe controls are infeasible, coal use in rural households contributes disproportionately to air pollution, public health harms, and climate change.[3,4]

In 2017, to address the extensive and polluting use of dispersed coal with traditional stoves (DCTS), the Chinese government launched a clean winter heating campaign (i.e., the Clean Winter Heating Plan in Northern China), focusing on two key regions, the “2 + 26” cities and the Fen-Wei Plain[5] (see Figure S1 in the Supporting Information, SI). A major goal of this campaign was to replace coal stoves in rural households with clean heaters. Natural gas heaters (NGHs), resistance heaters (RHs) with/without thermal storage (RH*w*TS and RH*wo*TS), and air-to-air heat pumps (AAHPs) are the four most widely adopted technologies (see the SI for the description of various heaters).[3,5] Clean coal with improved stoves (CCIS) are also considered a short-term option to replace DCTS.[3,6] Decisions of which clean heaters to adopt are often made at county or village levels. By the end of 2021, >25 million rural and suburban households had switched to clean heaters from solid fuels, resulting in ∼60% of rural households in the “2 + 26” cities and the Fen-Wei Plain region using clean heaters.[7] Most households adopted NGHs and RHs, except in Beijing, where the local government offers generous subsidies for AAHPs.[8]

Previous research has shown that replacing residential coal stoves with clean heaters leads to substantial air quality and health benefits but can both increase and decrease greenhouse gas (GHG) emissions, depending on the choice of clean heaters and the carbon intensity of grid electricity.[9−11] For example, Zhou et al. found that entirely replacing coal stoves with various clean heaters would have led to a 13−15% reduction in ambient $PM_{2.5}$ concentrations and prevented 54−65 thousand premature deaths in northern China in 2015.[3]

Received: September 19, 2022
Revised: November 18, 2022
Accepted: November 21, 2022
Published: December 9, 2022

Although all clean heaters dramatically reduce emissions of air pollutants, their GHG emissions vary significantly. While NGHs offered the largest GHG emission reduction in 2015, natural gas use locks in future GHG emissions. Emissions from electric heaters depend on both their efficiency and the carbon intensity of the power grid. This resulted in increases in GHG emissions from the deployment of inefficient RHs and decreases in GHG emissions from the deployment of efficient AAHPs.

Replacing coal stoves with clean heaters can increase household heating costs substantially. The total annualized costs for clean heating in rural households increase 2−5 times relative to coal stoves due to both capital costs of purchasing clean heaters and operating costs of consuming natural gas and electricity.[12] Therefore, national and local governments provide subsidies to rural households for clean heater purchases and natural gas and electricity consumption. These subsidies vary across cities, depending on governments' budgets. Most cities promise to offer fuel subsidies for at least three years after switching to a clean heater.[13] Nevertheless, even with subsidies, household heating costs still increase by 1.5−3 times relative to coal stoves except for some regions offering generous subsidies.[12] The high operating costs of clean heaters lead some rural households to reignite their coal stoves.[14] For example, ∼15% of households returned to burning coal for heat in the "2 + 26" cities during the 2020 Spring Festival, challenging the sustainability of the clean heating campaign.[15]

One of the major reasons for high heating costs in rural homes is their poor thermal performance.[16] Rural houses in China are usually designed and constructed by rural residents themselves and local homebuilders based on their experience rather than relying on building codes. Rural homes are often poorly insulated and drafty.[17,18] Walls are commonly built of solid clay bricks without any thermal insulation and windows are made with a single layer of glass.[19] Windows and doors are also poorly sealed, resulting in significant heat loss through uncontrolled air infiltration.[19] Due to the poor thermal performance, Chinese rural homes are often warmed only to an indoor temperature of 10−14 °C.[19,20]

Improving building envelope energy efficiency reduces heating demand, hence reducing both the size of the required heater (and associated capital costs) and the fuel needed to operate it (and associated operating costs) as well as resulting air pollutants and GHG emissions. However, these benefits have not been well explored to date. Although the government developed demonstration programs (see Table S1 for a policy review) to subsidize building energy retrofits, less than 1% of rural homes have benefited from those programs. The implementation of voluntary rural residential building energy standards has not been effective because of limited administrative capacity and low income levels.[21]

Few studies investigate rural building envelope energy efficiency. A few case studies calculate the energy-saving potential, costs, and benefits of building energy retrofits in China[22−26] (see Table S2 for a relevant literature review). For example, Cui et al.[27] found that retrofitting a typical rural house in Shandong to meet the current design standard can lead to a ∼70% efficiency improvement, yet they did not estimate the cost of such a retrofit nor did they evaluate the resulting change in GHG emissions. Shan et al.[19] reported a building retrofit program including ∼500 households in suburban areas of Beijing and found that the retrofit program cut energy bills in half with payback periods of 5−6 years. Although these case studies provide useful guidance on implementing building retrofits, their results may not be generalized because regional variations exist with households in different regions using different heaters and experiencing different climates and fuel prices. Additionally, while most previous studies focus on existing buildings, new construction offers a better opportunity to deploy efficient technologies. Chinese rural residential buildings are often short-lived with a lifetime of 15−30 years, indicating that the rural housing stock is likely to be replaced before 2060.[28] Thus, improving the energy efficiency of new buildings will be critical in meeting China's 2060 carbon neutrality commitment.

Here, we provide a comprehensive examination of the energy-saving potential, equivalent CO_2 (CO_2e) emission reductions, costs, and adoption strategies for improving building envelope efficiency in existing and new rural residential buildings with various heaters in the "2 + 26" cities plus the Fen-Wei Plain region of northern China. We find that for existing buildings, implementing some easy and moderate retrofits can reduce CO_2e emissions as well as reducing clean heating costs to avoid backsliding to coal. For new construction, deploying the most efficient technologies—whole-home insulation and heat pumps—reduce CO_2e emissions and annualized costs over the long term compared to current clean heating policy but significantly increase household upfront costs.

■ METHODS

Building Energy Simulations. We simulate household heating loads using an integrated building energy simulation model, EnergyPlus, which has been widely used and validated.[11,29] Building energy simulation in EnergyPlus requires three types of inputs: (1) building prototype and envelopes, (2) thermostat setting, and (3) weather data. We design a baseline building to represent a typical rural house in the "2 + 26" cities and the Fen-Wei Plain region based on Shan et al.[30] The baseline building is a detached single-story house, consisting of one living room and two bedrooms with a total heating floor area of ∼80 m^2 (Tables S3 and S4). The indoor temperature is assumed to be 14 °C in our main analysis. This indoor temperature represents the prevailing practice in northern China in winter.[19,21] In the SI, we also present results for 18 °C (64 °F) to represent rural households requiring a higher level of thermal comfort. The hourly weather data is obtained from the World Meteorological Organization (https://energyplus.net/weather), using the nearest meteorological station for each city.

We first simulate household heating loads on an hourly basis in EnergyPlus to maintain indoor temperatures at 14/18 °C in each city. We use household peak heating loads during the heating season to estimate the required sizes of various heaters and associated capital costs (Table S5). We estimate annual energy consumption by adding up all hourly heating loads during the heating season for each city. The total number of hours (days) in the heating season varies for each city and are obtained from Chinese building energy efficiency design standards.[31] We then convert annual heating loads to annual energy (coal, natural gas, and electricity) consumption based on the heating values of fuels and efficiencies of heating devices, as shown in eq 1:

https://doi.org/10.1021/acs.est.2c06863
Environ. Sci. Technol. 2023, 57, 595−605

Table 1. (a) Building Envelope Scenario Designs and (b) Heater Scenario Designs

(a) building envelope scenarios	envelope efficiency measures	incremental costs for existing buildings (yuan)	incremental costs for new buildings (yuan)	energy savings[b] 14 °C
baseline building envelope[a]		0	0	0
easy envelope improvement	energy efficient windows, air sealing	~2200	~1900	25–35%
moderate envelope improvement	energy efficient windows,air sealing, north wall insulation	~5700	~4600	36–48%
large envelope improvement	energy efficient windows, air sealing,roof insulation, all-wall insulation	~21,000	~16,000	74–85%

(b) heater scenarios	upfront capital costs in the baseline building without subsidies, 14 °C (yuan)	annual operating costs in the baseline building without subsidies, 14 °C (yuan)
dispersed coal with traditional stoves (DCTS)	~300	880–2200
clean coal with improved stoves (CCIS)	~1400	550–2000
natural gas heaters (NGHs)	3000–3500	900–3000
resistance heaters with thermal storage (RH*w*TS)	5400–9200	1000–2600
resistance heaters without thermal storage (RH*wo*TS)	1100–1900	1500–3600
air-to-air heat pumps (AAHPs)	8000–14,000	560–1550

[a]The baseline building represents prevailing envelope efficiency practices in the "2 + 26" cities and the Fen-Wei Plain region. [b]Energy savings are relative changes (%) in simulated operating heating load compared to the baseline building to maintain the indoor temperature at 14 °C during the heating season.

$$AEC_{c,f,h,e} = \frac{AHL_{c,e}}{HV_f \times \eta_h} = \sum_{hr=1}^{nh_c} \frac{HHL_{hr,e}}{HV_f \times \eta_h} \quad (1)$$

where $AEC_{c,f,h,e}$ is household annual energy consumption using fuel f and heater h with various building envelope scenarios (denoted as e; see the scenario design below) in city c during the heating season; $AHL_{c,e}$ is the annual heating loads; HV_f denotes heating values of fuels, and η_h denotes efficiencies of various heaters (Table S6). $HHL_{hr,e}$ is the hourly heating load calculated in EnergyPlus; hr denotes hours, and nh_c is the total number of hours in the heating season for city c. We validate our model by comparing our baseline simulations of annual heating energy intensity (expressed as annual heating loads per unit floor area, GJ/m^2) with survey data (Figure S2). Our results fit within the range of data from previous literature.[3,20,32]

Building Envelope Scenarios and Costs. We collect building energy efficiency measures that can be widely adopted in rural houses from the peer-reviewed literature, government technical guides, and building material suppliers in 2020.[33,34] We include 84 individual energy efficiency measures in our analysis (Table S7). We collected costs (including removal/demolition costs, material costs, accessories costs, and installation costs) of these measures in 2020 from the literature, government documents, conversations with building material suppliers, etc. Costs of increasing building envelope efficiency for existing buildings are 5–20% higher than those for new buildings because of additional demolition costs during the retrofit. We run EnergyPlus to calculate the energy-saving potential of each measure. We do not consider the scenarios of a combination of coal stoves and improved building envelopes because improving airtightness may unintentionally deteriorate indoor air quality and increase the risk of dangerous CO and fine particulate accumulation from coal burning.

We then select the most cost-effective (largest energy-saving per yuan) measures for each envelope and order these measures based on their cost-effectiveness. This order suggests a step-by-step envelope efficiency improvement strategy for common Chinese rural homes: first, the windows (particularly air sealing), then the north wall, roof, and finally, other walls. On this basis, we design three scenarios for improving building envelope efficiency: easy, moderate, and large improvements, as shown in Table 1. Our energy-saving estimates are comparable with the prior literature.[19,27,34]

Household Costs, Burdens, and Payback Period Calculations. Our analysis includes three types of household heating-related costs: heater capital costs, building envelope capital costs, and operating costs. Heater capital costs and building envelope capital costs are described in the previous subsections. We calculate annual operating costs ($AOC_{c,f,d}$) using heater h and fuel f with envelope e in city c as eq 2:

$$AOC_{c,f,h,e} = AEC_{c,f,h,e} \times P_{f,c} \quad (2)$$

where $AEC_{c,f,h,e}$ denotes the household annual energy consumption calculated using eq 1. $P_{f,c}$ denotes the unsubsidized/subsidized price of fuel f in city c (see Tables S8 and S9 and Figure S3). We also estimate operating heating burdens (defined as the percentage of household disposable income in 2020 spent on operating heating costs during the heating season) to examine the affordability of operating heating costs. The use of >10% of household income on energy is usually considered a threshold for energy poverty.[35]

For existing buildings, we calculate payback periods for building envelope retrofits. Payback periods measure how long it takes for cumulative savings to offset the initial investment. We include two types of savings from improving building envelope efficiency: savings from reduced capital costs of clean heaters (one-time savings) and savings from reduced annual operating costs (annual net cash flow). Many rural households plan to move to cities or build new homes in the next 5–15 years, which reduces their inclination to make investments that pay off over the long term.

For new buildings, rural households must purchase clean heaters and decide the efficiency of their building envelopes during the construction process. We calculate the total

https://doi.org/10.1021/acs.est.2c06863
Environ. Sci. Technol. 2023, 57, 595–605

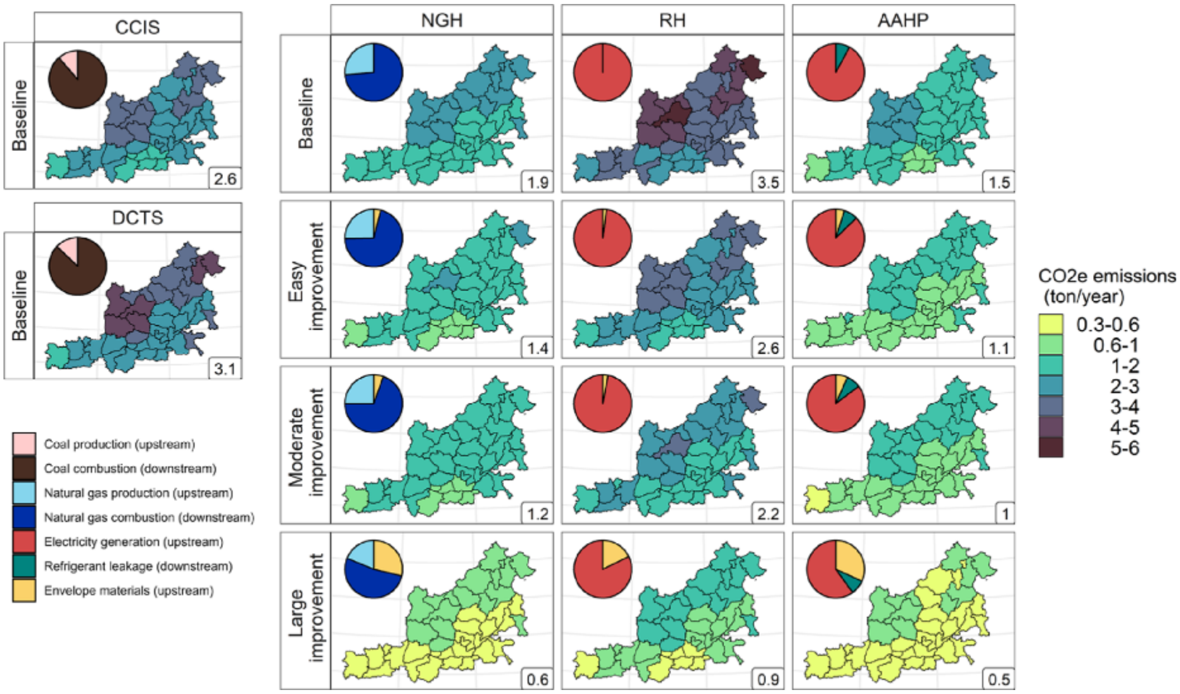


Figure 1. Household heating-related CO_2e emissions under GWP_{100} with various heaters (across top) and building envelopes (down columns) in the "2 + 26" cities plus the Fen-Wei Plain region of northern China. The figure shows the CO_2e emissions related to household space heating necessary to maintain indoor temperatures at 14 °C during the heating season. The pie charts at the upper left of each subfigure show the share of emissions by source types. The numbers at the bottom right of each subfigure denote the population-weighted average household CO_2e emissions for each heater type in the studied region in 2020. Legend at the left shows sources of GHG emissions while legend at the right shows annual CO_2e emissions from each city. Results for CO_2e emissions under GWP_{20} are shown in Figure S15. Results for indoor temperatures at 18 °C are shown in Figure S16. See Table 1 for definitions of the heater acronyms.

annualized costs (TACs, annualized upfront capital costs plus annual operating costs) and upfront capital costs (UCCs) of space heating. TACs reflect what a household must pay annually for heaters, envelopes, and heating fuels when loans are available, while UCCs are the one-time expenses that a household must pay to purchase heaters and envelopes when loans are not available. See "Extended Methods" in the SI for the calculation methods.

Household Air Pollutant and CO_2e Emission Calculations. We calculate household annual air pollutant and CO_2e emissions under the 20/100 year global warming potentials (GWP_{20}/GWP_{100}, including CO_2, CH_4, and fluorinated refrigerants) from space heating with various heaters and building envelopes. We focus on analyzing CO_2e emissions because previous studies showed that replacing coal stoves with clean heaters always significantly reduces air pollutant emissions but does not necessarily decrease CO_2e emissions.[3,11] We also present results for air pollutant emissions in Figures S4−S9. Our emission calculations include both downstream emissions (on-site emissions from fuel burning and the leakage of refrigerant liquids in AAHP) and upstream emissions from fuel production, processing, transmission, and distribution (for gas, coal, and electricity) and the production of efficient building envelopes (i.e., efficient windows and insulation materials). See "Extended Methods" in the SI for the detailed methods.

■ RESULTS

Household Energy Consumption and Heating Loads. Estimated heating energy consumption and peak loads of a typical rural household with various clean heaters and building envelopes are shown in Figure S10. We estimate that a full replacement with NGH in the studied region would require about 20 billion m^3 of natural gas annually (10% of China's domestic natural gas production or 6% of total consumption in 2020), while full electric heating with RHs or AAHPs will require ∼162 or ∼63 TWh of electricity annually (2.1 or 0.6% of China's total electricity consumption), respectively.

Peak heating loads are very important both environmentally ("peaker" power plants are usually inefficient and dirty in China) and economically (peak heat demands affect both required heater size and associated costs for the homeowner as well as power plant and transmission capital costs for power generators and grid operators). The peak heating loads for a typical rural household are estimated to be 5.0−8.7 kW with a NGH, 4.2−7.4 kW with an RH, and 1.6−3.2 kW with an AAHP. For comparison, the household maximum allowable electrical load in Chinese rural areas is, on average, only 2.7 kW.[36] Such a significant increase in household electric peak load will require substantial increases in transmission, distribution, and voltage control infrastructure buildout.

Building envelope efficiency improvements in rural homes can significantly reduce both energy consumption and peak loads from clean heating. Our results show that easy, moderate, and large improvements can reduce energy consumption by 25−35, 36−48, and 74−85% as well as peak heating loads by 23−30, 30−38, and 61−68%, respectively, thus substantially reducing energy infrastructure costs.

Household Capital and Operating Costs. Improving building envelope efficiency reduces required sizes of clean heaters by lowering heating loads, thus reducing associated capital purchase costs (Figures S11 and 12). The capital costs

https://doi.org/10.1021/acs.est.2c06863
Environ. Sci. Technol. 2023, 57, 595−605

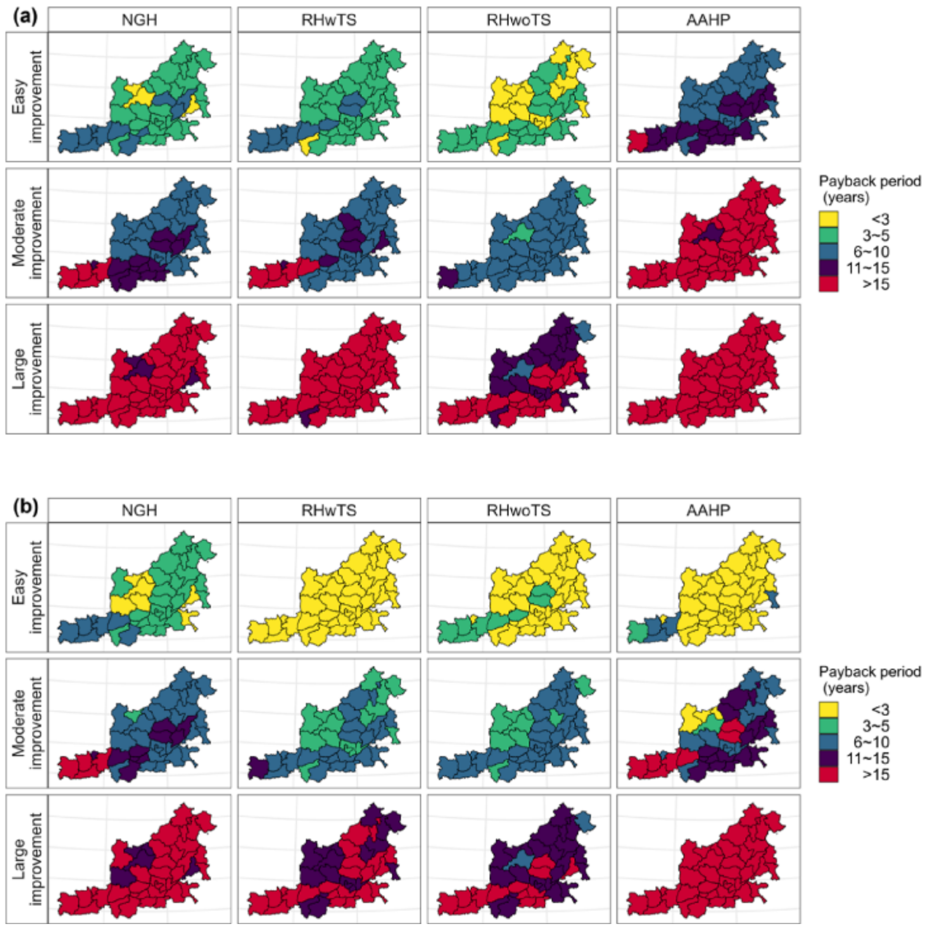


Figure 2. Payback periods for building envelope efficiency improvements to (a) existing buildings already using various clean heaters and (b) existing buildings that will soon install various clean heaters in the "2 + 26" cities plus the Fen-Wei Plain region of northern China. This figure shows payback periods when rural households maintain the indoor temperature at 14 °C during the heating season. The discount rate used is 5%. In subfigure (a), only savings from reduced annual operating costs are considered because capital costs of clean heaters are sunk costs. In contrast, in subfigure (b), both savings from reduced capital costs of clean heaters and savings from reduced annual operating costs are considered. Results for indoor temperatures at 18 °C are shown in Figure S17. See Table 1 for definitions of the heater acronyms.

of NGH are only slightly affected by their heating capacity, so improving building envelope efficiency only leads to marginal capital cost savings when NGH are employed. In contrast, capital costs of electric heaters (RH*w*TS, RH*wo*TS, and AAHPs) strongly depend on their required heating loads. For the most expensive and efficient clean heater, AAHP, the moderate (large) improvements can reduce its needed size and associated capital costs by ~3000 (~6000) yuan on average, equal to ~0.8 (~1.6) months' income of a typical rural household.

Operating heating burdens on rural households with various heaters and building envelopes are shown in Figures S13 and S14. Rural households using CCIS typically spend 5−11% of their income purchasing coal. Switching from CCIS to NGHs, RH*w*TS, and RH*wo*TS will magnify operating heating burdens by a factor of 1.9, 1.9, and 2.5 on average, respectively, making clean heating unaffordable. The operating heating burdens of AAHPs are lower than coal stoves, but few households switched to AAHP because of their high upfront capital costs. With fuel subsidies, household operating clean heating burdens can be reduced to 6−13% of household incomes, generally slightly higher than that of using coal stoves. However, fuel subsidies will encourage clean heating choices with higher CO_2 emissions.

Improving building envelope efficiency can reduce operating fuel consumption, thus reducing operating heating costs and burdens. We find that for rural households using NGHs, RH*w*TS, and RH*wo*TS, easy and moderate building envelope improvements can reduce their operating heating burdens to ~7−14 and ~6−12%, respectively, which are comparable to using CCIS or using clean heaters with fuel subsidies. Moderate (large) improvements in building envelopes, which reduce ~60% (~80%) of energy consumption, can dramatically reduce operating heating burdens to ~4% (~1%) when combined with AAHPs.

Household CO_2e Emissions. Household annual CO_2e emissions under GWP_{100} from space heating with various heaters and building envelopes in the studied region are shown in Figure 1. Household CO_2e emissions from space heating vary significantly and strongly depend on local climate, heater types, the carbon intensity of electricity, and building envelope energy efficiency. Generally, with the 2020 power mix (~64% of electricity is from fossil fuel), switching from CCIS to NGHs and AAHPs reduce household CO_2e emissions by ~27 and ~42% in the baseline building, respectively, while using inefficient RHs increases CO_2e emissions by ~35%. Refrigerant leakage from heat pumps is also an important source of GHG, making up ~10% of total GHG emissions from AAHP

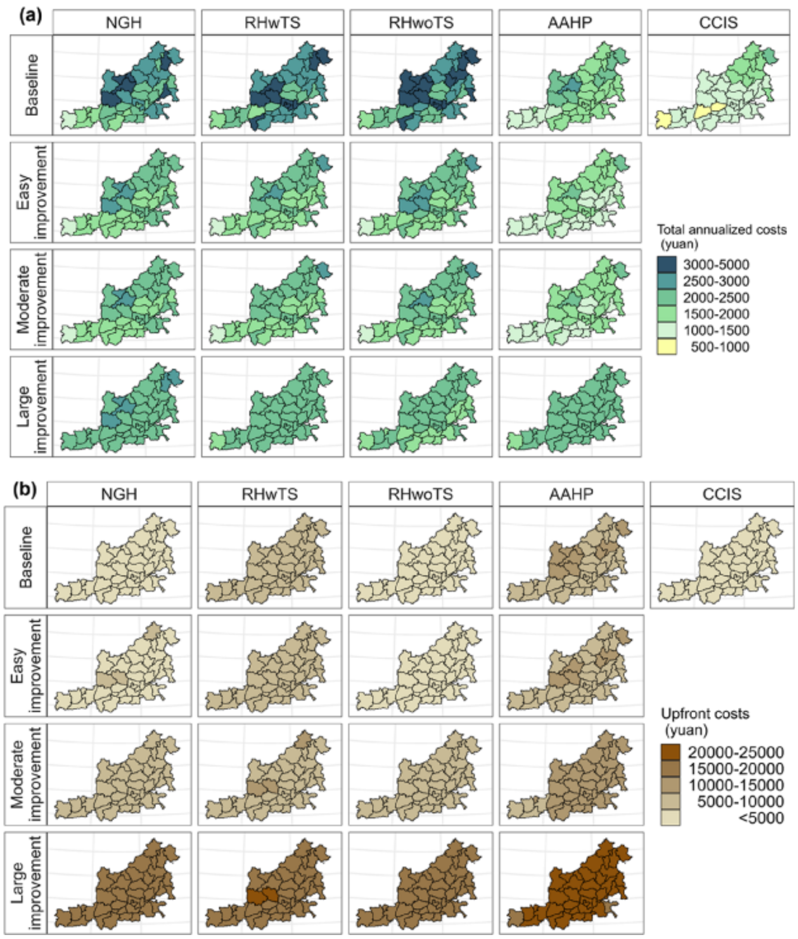


Figure 3. Household (a) total annualized costs (TACs, annualized capital costs plus annual operating costs) and (b) upfront capital costs (UCCs) under various heater and building envelope scenarios in new buildings in the "2 + 26" cities plus the Fen-Wei Plain region of northern China. The figure shows costs when rural households maintain indoor temperatures at 14 °C during the heating season. The discount rate is 5%. The expected lifetime of new building envelopes is assumed to be 15 years. Results for indoor temperatures at 18 °C are shown in Figure S18. See Table 1 for definitions of the heater acronyms.

in the baseline building. Commonly used refrigerants have a strong near-term warming effect because they are hydrofluorocarbons (HFCs) and have high radiative forcing and have short atmospheric lifetimes (see the GWP_{20} results in Figure S15).

Increasing envelope efficiency for rural homes using RHs delivers the largest emission reductions because RHs are less efficient than NGHs and AAHPs. However, with the decarbonization of the power sector, operating RHs and AAHPs will result in less CO_2e emissions, so the CO_2e reduction potentials of building envelope efficiency improvements on rural homes with RHs and AAHPs will decrease as the grid decarbonizes. AAHP combined with large improvements in building envelopes are now the lowest emission heating option (0.6 tons annually per household), cutting ~80% of emissions compared to CCIS with the baseline building. As the grid decarbonizes, AAHP emissions will decrease further.

The CO_2e emission reduction from energy efficiency improvements usually far exceeds the additional emissions required for production of the materials needed to improve building envelopes. However, as rural building envelopes become more efficient, the proportion of life-cycle emissions from the envelope materials increases. For example, as shown in Figure 1, efficient window and insulation material production accounts for 17−27% (2−5%) of total CO_2e emissions in large improvement (easy improvement) building envelope scenarios.

Building Envelope Improvement Strategies for Existing Rural Residential Buildings. For existing buildings with clean heaters, the capital costs of clean heaters are considered sunk costs, so the household benefits of increasing building envelope efficiency only relate to operating cost savings. In contrast, for existing buildings with coal stoves, retrofitting building envelopes before installing clean heaters can reduce the sizes required for the clean heaters and the associated capital costs. Thus, the benefits of increasing building envelope efficiency before installing clean heaters are obtained from savings from both reduced capital costs due to the ability to purchase a smaller heater and operating costs.

Local governments usually decide which clean heaters will be adopted, but rural households can determine whether and when to retrofit their homes. We therefore examine payback periods for various building envelope retrofits. Figure 2a shows payback periods for various building envelope efficiency improvements on existing rural buildings with various clean heaters. We find that easy and moderate envelope improvements to rural houses using NGHs, RH*w*TS, and RH*wo*TS

https://doi.org/10.1021/acs.est.2c06863
Environ. Sci. Technol. 2023, 57, 595−605

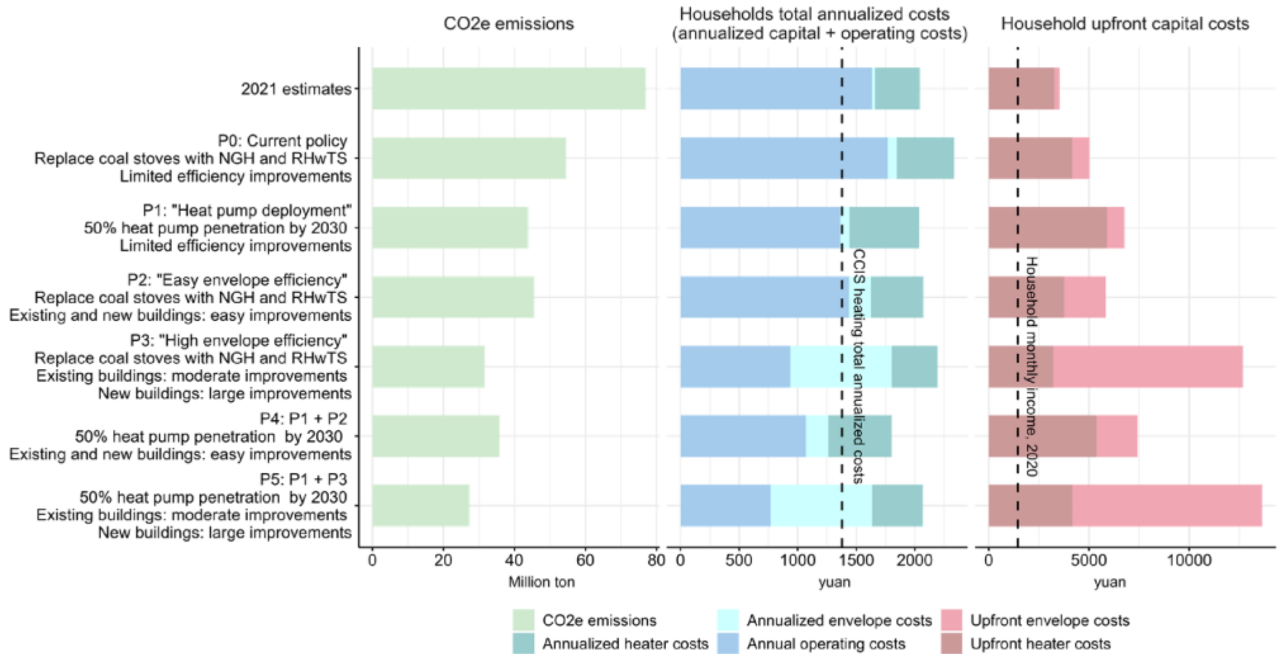


Figure 4. CO_2e emissions, population-weighted household total annualized costs (TACs), and upfront capital costs (UCCs) in 2021 (first row, for comparison) and in 2030 under various policy scenarios in the "2 + 26" cities and the Fen-Wei Plain region of northern China. The vertical dashed lines denote the TAC of CCIS and household monthly income in 2020 for comparison. P_0 represents the current "no-coal zone" policy, while P_1–P_5 are various possible improved clean heating policy scenarios implemented between 2020 and 2030.

have payback periods of 4.1 and 8.8 years on average, respectively, while large improvements are cost-prohibitive due to high capital costs. Retrofitting rural homes with inefficient RH*wo*TS has relatively short capital cost payback periods because so much electricity is saved. However, retrofitting buildings with more efficient AAHPs has much longer payback periods because less electricity is needed to achieve the desired indoor temperature.

Figure 2b shows payback periods for envelope efficiency improvements on existing buildings that current policy requires install clean heaters soon. When savings from reduced capital costs of clean heaters are considered, payback periods for easy and moderate improvements to rural homes that plan to switch to electric heaters (RH*w*TS, RH*wo*TS, and AAHPs) are shortened to 1.1 and 6.8 years on average, respectively. Thus, the order in which the decision to improve building envelope efficiency and choice of clean heater size matters. This is particularly relevant to AAHPs, which have very high capital costs, so building envelope efficiency improvement prior to installation facilitates the purchase of a smaller AAHP with lower capital costs and is critical to enable the penetration of AAHPs. In addition, payback periods are significantly affected by city-level fuel prices and climates. For example, implementing retrofits to rural houses with NGHs in Taiyuan, Jinzhong, and Jinan often has a short payback period of <3 years because of relatively high natural gas prices and cold climates. In contrast, building retrofits are generally less economically attractive in cities in southern Shaanxi because warm climates and relatively low fuel prices result in lower cost savings.

Building Envelope Improvement Strategies for New Rural Residential Buildings. For new buildings, during the construction process, rural households must purchase clean heaters and decide on the efficiency of their building envelopes. New buildings have two additional advantages over existing buildings: first, the construction costs of new efficient envelopes are lower than retrofitting existing buildings; second, new buildings tend to have longer lifetimes than existing buildings, enabling investments that pay off over the long term to be attractive. Here, we compare the TACs and UCCs of space heating scenarios for various building envelopes and heaters in new buildings without subsidies.

Figure 3a shows the TACs for scenarios of various heaters and building envelopes. We find that AAHPs have the lowest TACs among all clean heaters, generally ∼15–22% lower than NGHs, RH*w*TS, and RH*wo*TS. This is consistent with previous studies that showed AAHPs tend to be the most economic clean heater over the long term in the studied region.[3,8,12] Regarding building envelopes, our results show that greater building envelope efficiency is always more economic than current practices (i.e., the baseline buildings). In fact, many new rural residential buildings are now installing efficient windows and some levels of insulation.[18]

The lowest-cost clean heating combination is usually AAHP plus easy improvements in building envelopes in the studied region (Figure S19). AAHP with easy envelope improvements have TACs of ∼1500 yuan (∼6–20% of household income during the heating season), which are on average higher than the TACs of CCIS by ∼20%. However, in some cities where coal prices are high (mostly in the Beijing–Tianjin–Hebei region), the TACs of AAHP plus easy building envelope improvements are close to or already cheaper than the costs of CCIS.

The TACs of the lowest emission combination—AAHP plus large envelope improvements—are higher than the TACs of AAHP plus easy envelope improvements by 30–50%. A carbon price will not make large improvements economically favorable for rural households until the carbon price is very high (e.g., >500 yuan per ton; Figure S19). This is because AAHPs themselves are so efficient that further improvements in building envelopes can only lead to a marginal reduction in

https://doi.org/10.1021/acs.est.2c06863
Environ. Sci. Technol. 2023, 57, 595−605

heating costs and emissions. However, as rural households demand improved thermal comfort and build more durable houses as their incomes increase, AAHP with large envelope improvements become increasingly cost-competitive. In this case with high indoor temperatures (>18 °C) and long lifetimes of building envelopes (~25 years), AAHP plus large improvements in building envelopes will become the lowest-cost option in many cities (Figure S20). Moreover, large improvements are also justified by significantly reducing energy infrastructure costs (e.g., less electricity transmission and gas pipelines) and reducing cooling demand in summer.

Although our results highlight the cost and environmental advantages of combinations of AAHP and efficient building envelopes, rural households may not switch to those combinations because of their high UCCs (Figure 3b). The combination of AAHP plus easy building envelope improvements has a UCC of ~9000 yuan (~10−28% of the annual household income). The combination of AAHP plus large improvements has a high UCC of ~20,000 yuan, roughly equal to half a year's household income or ~20−30% of the construction costs of a typical northern Chinese rural house. The high upfront costs will limit the adoption of efficient building envelopes and AAHP unless financial assistance is offered.

CO_2e Emissions and Cost Implications of Various Clean Heating Policies in 2030. The current clean heating policy focuses on replacing all coal stoves (including CCIS) with clean heaters, particularly NHGs and RH*w*TS, to establish a "no-coal zone" in the studied region by 2030.[5,37] We estimated that the current policy—if fully implemented in the studied region—will reduce rural residential heating-related CO_2e emissions by 29% but increase household TACs by 14% from 2021 levels (P_0 in Figure 4). Such increases in heating costs seem to be acceptable for rural households as rural household incomes are projected to double by 2030 from 2021 levels.[38]

Our analysis indicates that current policies can be strengthened to reduce emissions and household TACs by (1) accelerating heat pump adoption and (2) increasing building envelope efficiency. Therefore, we further explore the emissions and cost implications of various possible strengthened policies between 2020 and 2030. Details of assumptions and policy scenario designs are provided in "Extended Methods" in the SI. We find that, in general, policies that increase heat pump uptake and building envelope efficiency decrease both emissions and household TACs but increase UCCs compared to the current policy. Either deploying heat pumps at scale (P_1) or implementing easy improvements in building envelope efficiency for all rural residential buildings (P_2) can cut emissions by ~40% from 2021 levels in 2030 as well as reduce household TACs by ~12% compared to the current policy. However, either of the two policies will also increase UCCs by 34% (P_1) and 14% (P_2), respectively, compared to the current policy. Implementing those two policies simultaneously ($P_4 = P_1 + P_2$) would further slightly increase household UCCs, but this policy has the lowest household TACs (~1800 yuan) in 2030 across all the scenarios. Requiring large envelope improvements in new construction (P_3) can obtain substantial emission reductions of 60% (or 65% if coupled with heat pump deployment; see $P_5 = P_1 + P_3$) from 2021 levels with a modest decrease in TACs compared to the current policy in 2030. However, the large improvement scenarios have significantly higher UCCs than UCCs in other policy scenarios, indicating that it would be difficult to widely install highly efficient envelopes in rural residential buildings without effective financial assistance.

DISCUSSION

In 2021, the Chinese government released its action plan to peak carbon emissions by 2030, planning to "speed up energy-saving upgrades on rural housing".[37] Our results help inform these efforts on how to improve building envelope efficiency in rural homes.

For existing buildings, replacing current fuel subsidies with retrofit subsidies to encourage the deployment of easy and low-cost efficiency measures is a win-win-win for rural households, local governments, and the environment. An urgent and important issue of the clean heating campaign is the increase in operating costs of clean heaters relative to coal stoves, making many rural households reignite their coal stoves.[16] To address this issue, most local governments now provide fuel subsidies. Fuel subsidies are easy to implement, have relatively low administrative costs, and can be directly perceived by rural households.[13] However, fuel subsidies compromise emission reduction goals and are not a sustainable solution because they place continuous huge burdens on government finances.[15] Therefore, many local governments are now seeking to phase out fuel subsidies. Our results indicate that implementing easy and moderate retrofits can effectively reduce the operating heating costs of clean heating, thus prevent backsliding to coal. Additionally, replacing fuel subsidies with retrofit subsidies to widely and rapidly deploy energy retrofits also reduces required sizes and associated capital costs of clean heaters, thus facilitating the deployment of clean heaters, particularly expensive AAHPs. Building retrofits also lead to reduced GHG emissions and reduced energy infrastructure costs. Most cities now offer 600−800 yuan fuel subsidies to each rural household per year, equal to ~2000 yuan over the three years of the policy (see Figure S3). This money could be better deployed to cover the upfront costs of energy-efficient windows (or north wall insulation) for a typical rural house, which would provide benefits beyond the 3 year window of the existing fuel subsidy policy.

In new construction, promoting and deploying AAHP and efficient building envelopes is critical to reducing both costs and emissions over the long term. AAHPs are clearly the best option among all clean heaters in the studied region and provide both cost and environmental benefits when deployed particularly as the grid decarbonizes.[3] However, the level of energy efficiency recommended for building envelopes is context-specific and determined by local climates and desired indoor temperatures. While AAHP and easy envelope efficiency measures are usually the lowest-cost options for rural households that are satisfied with minimal thermal comfort (~14 °C), whole-home insulation (i.e., large improvement) is the most economic option for many rural households that can afford and prefer higher indoor temperatures (~18 °C). AAHP and well-insulated homes provide multiple co-benefits including improved thermal comfort, reduced carbon emissions, efficient cooling in summer, and reduced energy infrastructure costs.[39] Therefore, our results indicate that deploying the most efficient clean heating technologies in new construction—whole-home insulation combined with heat pumps—is vital to avoid carbon lock-in and reduce heating costs over the long term.

https://doi.org/10.1021/acs.est.2c06863
Environ. Sci. Technol. 2023, 57, 595−605

Unfortunately, the uptake of energy efficiency in rural homes is usually not a speedy and spontaneous process, even when the benefits accumulating over time outweigh initial investment costs.[40] Rural residents are usually conservative and busy with farming.[41] They are either unaware of energy-efficient technologies or skeptical about the technologies despite their energy-saving benefits. When constructing new houses, rural households often hire local homebuilders who lack knowledge and technical skills in building energy efficiency. Qualified contractors are unwilling to serve rural areas because low population density, hard-to-serve customers, and long travel times lead to high costs per rural project.[42] Moreover, energy-efficient technologies such as heat pumps and whole-home insulation have very high upfront costs that rural households with low incomes cannot afford. Financial assistance like loans and on-bill financing is not widely accessible to rural households.

Therefore, policies that are adapted to the rural context are critical to promoting and deploying energy-efficient technologies. First, community-based approaches are central to addressing awareness, access, and geographic barriers. Community-based promotion campaigns have a long history in rural China and have been used to deploy home appliances, electric vehicles, rooftop solar panels, etc. Local authorities can partner with qualified contractors to organize energy efficiency campaigns (e.g., "Weatherization Week") to promote and demonstrate energy-efficient technologies.[42] Rural communities can also leverage the power of collective purchases for group discounts and benefits. Second, providing subsidies and various repayment options for purchases and installations is needed to address high upfront costs. Few cities now offer subsidies for building envelope improvements or AAHPs. One exception is Beijing, where the local government has provided up to 20,000 yuan to a rural household, which builds a safe and energy-efficient house as well as a subsidy of up to 24,000 yuan for purchase and installation of an AAHP.[43] This subsidy program greatly improved the energy efficiency of rural homes in Beijing. Other local governments could introduce similar subsidies and loan programs. Innovative financial and business models are also needed to allow rural households to spread upfront costs over multiple years. For example, energy efficiency contractors can partially pay for home improvements to reduce upfront costs for rural households with rural residents repaying contractors through utility bill savings. Third, training local homebuilders in building energy efficiency technologies is especially urgent. Hiring and training local workers reduce workforce shortages and boost local economies. Moreover, local governments may consider enforcing mandatory building codes in rural homes. Building codes have contributed to significant energy efficiency improvements in urban buildings over the past four decades in China. Adapting the urban implementation system to rural buildings requires significant increases in administrative capacity and increases in availability of low-cost energy-efficient building materials and technologies in rural areas.[21]

Our results are subject to several limitations. First, our analysis is based on a baseline building to represent the average building envelope efficiency in the studied region of northern China because of limited data availability. This approach cannot represent the heterogeneity of the rural residential building stock, such as home sizes, insulation levels, and installed heating systems.[44] Larger energy-saving potential exists in extremely inefficient buildings. Future work that includes field surveys to investigate the current rural residential building stock would be beneficial. Our baseline building is designed based on survey data from 2007−2015, so our results likely overestimate the energy-saving potential of recently constructed buildings.[18] Second, our analysis primarily focuses on costs and benefits, while many other factors can affect the adoption of building envelope efficiency.[45] Understanding those non-economic obstacles to energy efficiency adoption is critical for designing effective policy interventions. Third, our estimates are subject to the rebound effect. Improved building energy efficiency may lead to increased household heating energy use.[46] Fourth, we did not consider future cost reduction of heat pumps and efficient building envelopes. Costs of energy-efficient technologies are expected to decrease over time because of learning effects and economies of scale, which facilitates their deployment.[47] Moreover, the clean heating campaign is now extended to the rest of northern China, where winter is usually colder than our studied regions. AAHPs are less efficient and hence require more electricity to achieve a chosen indoor temperature in cold regions. With higher heating demands, well-insulated homes will be critical to reducing heating emissions and costs across northern China.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c06863.

Literature and policy review, extended methods, and supplementary tables and figures (PDF)

■ AUTHOR INFORMATION

Corresponding Author

Denise L. Mauzerall − *Princeton School of Public and International Affairs and Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey 08544, United States;* orcid.org/0000-0003-3479-1798; Email: mauzerall@princeton.edu

Authors

Shangwei Liu − *Princeton School of Public and International Affairs, Princeton University, Princeton, New Jersey 08544, United States;* orcid.org/0000-0003-4106-3959

Hongxun Liu − *School of Economics and Finance, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.2c06863

Author Contributions

S.L., H.L., and D.L.M. conceived the idea of this project and designed the research. S.L. performed the research. H.L. provided data for heater and building envelope costs. S.L. and D.L.M. wrote the manuscript with feedback from H.L.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank Wei Feng and Nan Zhou for discussions regarding building energy simulations. We thank Minghao Qiu for feedback on the manuscript. We thank the Princeton School of Public and International Affairs at Princeton University for supporting S.L. and the National Natural Science Foundation of China (nos. 72273102 and 72173095), the China

Scholarship Council, and Princeton University for support of H.L.

■ REFERENCES

(1) Yin, P.; Brauer, M.; Cohen, A. J.; Wang, H.; Li, J.; Burnett, R. T.; Stanaway, J. D.; Causey, K.; Larson, S.; Godwin, W.; Frostad, J.; Marks, A.; Wang, L.; Zhou, M.; Murray, C. J. L. The Effect of Air Pollution on Deaths, Disease Burden, and Life Expectancy across China and Its Provinces, 1990−2017: An Analysis for the Global Burden of Disease Study 2017. *Lancet Planet Health* **2020**, *4*, e386−e398.

(2) Yun, X.; Shen, G.; Shen, H.; Meng, W.; Chen, Y.; Xu, H.; Ren, Y.; Zhong, Q.; Du, W.; Ma, J.; Cheng, H.; Wang, X.; Liu, J.; Wang, X.; Li, B.; Hu, J.; Wan, Y.; Tao, S. Residential Solid Fuel Emissions Contribute Significantly to Air Pollution and Associated Health Impacts in China. *Sci. Adv.* **2020**, *6*, 1−8.

(3) Zhou, M.; Liu, H.; Peng, L.; Qin, Y.; Chen, D.; Zhang, L.; Mauzerall, D. L. Environmental Benefits and Household Costs of Clean Heating Options in Northern China. *Nat. Sustain.* **2021**, *5*, 329−338.

(4) Yun, X.; Meng, W.; Xu, H.; Zhang, W.; Yu, X.; Shen, H.; Chen, Y.; Shen, G.; Ma, J.; Li, B.; Cheng, H.; Hu, J.; Tao, S. Coal Is Dirty, but Where It Is Burned Especially Matters. *Environ. Sci. Technol.* **2021**, *55*, 7316−7326.

(5) NDRC (National Development and Reform Commission of China). *Clean winter heating planning for northern areas (2017−2021)*. http://www.gov.cn/xinwen/2017-12/20/content_5248855.htm. (accessed October, 29, 2022)

(6) Liu, Y.; Zhang, Y.; Li, C.; Bai, Y.; Zhang, D.; Xue, C.; Liu, G. Air Pollutant Emissions and Mitigation Potential through the Adoption of Semi-Coke Coals and Improved Heating Stoves: Field Evaluation of a Pilot Intervention Program in Rural China. *Environ. Pollut.* **2018**, *240*, 661−669.

(7) PKU Institue of Energy. *China Dispersed Coal Management Report* **2021**, 2021.

(8) China Coal Consumption Cap Plan and Policy Research Project. *China Dispersed Coal Management Report* **2018**, 2018.

(9) Meng, W.; Shen, H.; Yun, X.; Chen, Y.; Zhong, Q.; Zhang, W.; Yu, X.; Xu, H.; Ren, Y.; Shen, G.; Ma, J.; Liu, J.; Cheng, H.; Wang, X.; Zhu, D.; Tao, S. Differentiated-Rate Clean Heating Strategy with Superior Environmental and Health Benefits in Northern China. *Environ. Sci. Technol.* **2020**, *54*, 13458−13466.

(10) Tao, S.; Meng, W.; Shen, G.; Shen, H.; Chen, Y.; Yun, X.; Li, J.; Ma, J.; Liu, J.; Cheng, H.; Hu, J.; Wan, Y. Synergistic Health Benefits of Household Stove Upgrading and Energy Switching in Rural China. *Environ. Sci. Technol.* **2021**, *55*, 14567−14575.

(11) Wang, J.; Zhong, H.; Yang, Z.; Wang, M.; Kammen, D. M.; Liu, Z.; Ma, Z.; Xia, Q.; Kang, C. Exploring the Trade-Offs between Electric Heating Policy and Carbon Mitigation in China. *Nat. Commun.* **2020**, *11*, 1−11.

(12) Liu, H.; Mauzerall, D. L. Costs of Clean Heating in China: Evidence from Rural Households in the Beijing-Tianjin-Hebei Region. *Energy Econ.* **2020**, 104844.

(13) Gong, Y.; Cai, B.; Sun, Y. Perceived Fiscal Subsidy Predicts Rural Residential Acceptance of Clean Heating: Evidence from an Indoor-Survey in a Pilot City in China. *Energy Policy* **2020**, *144*, 111687.

(14) Li, J.; Song, L.; Zhu, Y. Subsidies, Clean Heating Choices, and Policy Costs: Evidence from Rural Households in Northern China. *Sustainability* **2021**, *13*, 1−18.

(15) China Coal Cap Project *China Dispersed Coal Management Report 2020* 2020.

(16) Liu, C.; Wei, C. The World'S Largest Residential Energy Switching Program Is at Risk. *Environ. Sci. Technol.* **2021**, *55*, 15004−15006.

(17) He, B.; Yang, L.; Ye, M.; Mou, B.; Zhou, Y. Overview of Rural Building Energy Efficiency in China. *Energy Policy* **2014**, *69*, 385−396.

(18) Zhu, L.; Liao, H.; Hou, B.; Cheng, L.; Li, H. The Status of Household Heating in Northern China: A Field Survey in Towns and Villages. *Environ. Sci. Pollut. Res.* **2020**, *27*, 16145−16158.

(19) Shan, M.; Wang, P.; Li, J.; Yue, G.; Yang, X. Energy and Environment in Chinese Rural Buildings: Situations, Challenges, and Intervention Strategies. *Build Environ.* **2015**, *91*, 271−282.

(20) Building Energy Research Center of Tsinghua University. *2012 Annual Report on China Building Energy Efficiency*; China Architecture & Building Press, 2012.

(21) Evans, M.; Yu, S.; Song, B.; Deng, Q.; Liu, J.; Delgado, A. Building Energy Efficiency in Rural China. *Energy Policy* **2014**, *64*, 243−251.

(22) Zhang, Q.; Hao, Y.; Sun, D.; Nie, Q.; Jin, L. Research on the Clean Energy Heating Systems in Rural Beijing. *Energy Procedia* **2017**, *143*, 137−143.

(23) Pan, W.; Mei, H. A Design Strategy for Energy-Efficient Rural Houses in Severe Cold Regions. *Int. J. Environ. Res. Public Health* **2020**, *17*, 1−18.

(24) Liu, J.; Liu, B.; He, L.; Gao, Y. Investigation on the Winter Building Energy Consumption in Rural Areas in Jinan China. *Procedia Eng.* **2015**, *121*, 1819−1826.

(25) Wang, W.; Ge, X.; Xiong, H. Thermal Design Optimization and Analysis on Heating Load of Rural Buildings in Northern China. *E3S Web of Conferences* **2019**, *136*, 1−5.

(26) Zheng, Y. Study on Energy Conservation Reform and Economy of Rural Existing Residential Buildings (in Chinese). *Architecture Technology* **2020**, *51*, 469−471.

(27) Cui, Y.; Sun, N.; Cai, H.; Li, S. Indoor Temperature Improvement and Energy-Saving Renovations in Rural Houses of China's Cold Region—a Case Study of Shandong Province. *Energies* **2020**, 870.

(28) Hong, L.; Zhou, N.; Fridley, D.; Feng, W.; Khanna, N.; Berkeley, L. Modeling China's Building Floor-Area Growth and the Implications for Building Materials and Energy Demand. *ACEEE Summer Study on Energy Efficiency in Buildings* **2014**, 146−157.

(29) Fumo, N. A Review on the Basics of Building Energy Estimation. *Renewable Sustainable Energy Rev.* **2014**, *31*, 53−60.

(30) Shan, M.; Yanqing, L.; Rongjiang, M.; Mengsi, D.; Xingli, D.; Xudong, Y.; Yongjie, Z.; Jiandong, Y. Comparison of Economic and Emission Performances of Different Technologies from Coal to Clean Energy in Northern Rural China (in Chinese). *Environment and Sustainable Developemnt* **2020**, *3*, 43−49.

(31) Ministry of Housing and Urban-Rural Development of China. *Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones (J◐J26−2010)*; 2010.

(32) Peng, L.; Zhang, Q.; Yao, Z.; Mauzerall, D. L.; Kang, S.; Du, Z.; Zheng, Y.; Xue, T.; He, K. Underreported Coal in Statistics: A Survey-Based Solid Fuel Consumption and Emission Inventory for the Rural Residential Sector in China. *Appl Energy* **2019**, *235*, 1169−1182.

(33) Zhu, Y.; Fan, X.; Wang, C.; Sang, G. Analysis of Heat Transfer and Thermal Environment in a Rural Residential Building for Addressing Energy Poverty. *Appl. Sci.* **2018**, *8*, 2077.

(34) Shandong Provincial Department of Housing and Urban-Rural Development (Shandong DHURD). *Technical ◐uidelines for Energy Saving Renovation of Existing Rural Residential Buildings in Shandong Province (Trial, in Chinese)*; 2019.

(35) Drehobl, A.; L., Ross; R., Ayala. *How High are Household Energy Burdens?* 2020, Washington, DC: American Council for an Energy-Efficient Economy.

(36) National Energy Administration. *A press conference on the energy industry's decisive victory in poverty alleviation*. http://www.nea.gov.cn/2020-10/19/c_139451999.htm (accessed September 22, 2022).

(37) State Council. *China's Action Plan for Carbon Dioxide Peaking Before 2030*. 2021.

(38) Institute of Rural Development of Chinese Academy of Social Sciences. *China Rural Development Report* **2022**, 2022.

(39) International Energy Agency (IEA). *Technology Roadmap: Energy Efficent Building Envelopes*; 2013.

(40) Tao, S.; Ru, M. Y.; Du, W.; Zhu, X.; Zhong, Q. R.; Li, B. G.; Shen, G. F.; Pan, X. L.; Meng, W. J.; Chen, Y. L.; Shen, H. Z.; Lin, N.; Su, S.; Zhuo, S. J.; Huang, T. B.; Xu, Y.; Yun, X.; Liu, J. F.; Wang, X. L.; Liu, W. X.; Cheng, H. F.; Zhu, D. Q. Quantifying the Rural Residential Energy Transition in China from 1992 to 2012 through a Representative National Survey. *Nat. Energy* **2018**, *3*, 567−573.
(41) Shoemaker, M.; Gilleo, A.; Ferguson, J. *Reaching Rural Communities with Energy Efficiency Programs*; 2018.
(42) MacDonald, S.; Winner, B.; Smith, L.; Juillerat, J.; Belknap, S. Bridging the Rural Efficiency Gap: Expanding Access to Energy Efficiency Upgrades in Remote and High Energy Cost Communities. *Energy Effic.* **2020**, *13*, 503−521.
(43) Beijing Association of Sustainable Development. *Rural Building Energy Saving and Clean Heating Retrofits in Beijing*; 2021.
(44) Nägeli, C.; Jakob, M.; Catenazzi, G.; Ostermeyer, Y. Towards Agent-Based Building Stock Modeling: Bottom-up Modeling of Long-Term Stock Dynamics Affecting the Energy and Climate Impact of Building Stocks. *Energy Build.* **2020**, *211*, 109763.
(45) Gillingham, K.; Palmery, K. Bridging the Energy Efficiency Gap: Policy Insights from Economic Theory and Empirical Evidence. *Rev. Environ. Econ. Policy* **2014**, *8*, 18−38.
(46) Wu, S.; Zheng, X.; Khanna, N.; Feng, W. Fighting Coal — Effectiveness of Coal-Replacement Programs for Residential Heating in China: Empirical Findings from a Household Survey. *Energy Sustainable Dev.* **2020**, *55*, 170−180.
(47) Malhotra, A.; Schmidt, T. S. Accelerating Low-Carbon Innovation. *Joule* **2020**, *4*, 2259−2267.

https://doi.org/10.1021/acs.est.2c06863
Environ. Sci. Technol. 2023, 57, 595−605