

China's Clean Heating Policy and Effects on Blood Pressure in Rural Beijing Adults

Talia Sternbach, Sam Harper, Xiaoying Li, Collin Brehmer, Yuanxun Zhang,* Wenlu Yuan, Shu Tao, Kaibing Xue, Kennedy Hirst, Guofeng Shen, Christopher Barrington-Leigh, Xiang Zhang, Brian Robinson, Ellison Carter, and Jill Baumgartner*



Cite This: <https://doi.org/10.1021/EHP.6c00053>



Read Online

ACCESS |



Metrics & More

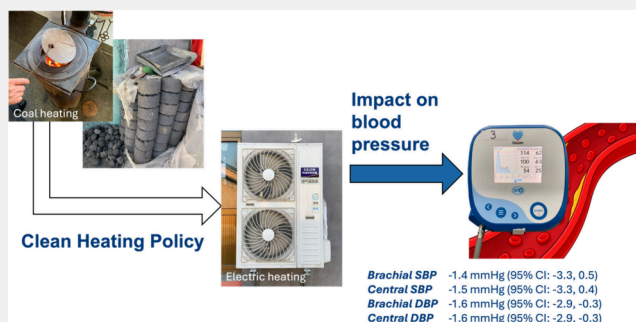


Article Recommendations



Supporting Information

ABSTRACT: Large-scale residential energy transitions from solid fuel to clean energy are promising strategies to mitigate climate change and improve population health, but rigorous evaluation of their impacts is rare. China's Clean Heating Policy (CHP) aimed to transition tens of millions of households from coal to electric and gas-based space heating. Following evidence of policy-driven improvements in indoor air pollution and indoor temperature, we evaluated the CHP's impact on blood pressure (BP). In winter 2018–2019, we enrolled 1,003 adults aged >40 years from 50 Beijing villages not yet treated by the CHP; 20 villages were treated during follow-up (winters 2019–2020 and 2021–2022). Brachial and central BP and covariates were measured during household visits by trained staff. Policy impacts were estimated using an extended two-way fixed-effects difference-in-differences approach with village-clustered standard errors and adjustment for key BP predictors to improve precision. We found evidence of reductions (in mmHg) in brachial systolic BP (−1.4, 95% confidence interval [CI]: −3.3, 0.5), central systolic BP (−1.5, 95% CI: −3.3, 0.4), brachial diastolic BP (−1.6, 95% CI: −2.9, −0.3), and central diastolic BP (−1.6, 95% CI: −2.9, −0.3) among villages treated by the CHP compared with those untreated. Treatment effects varied by the year villages were treated by the CHP (p for homogeneity = 0.00 to 0.14) with greater BP reductions among participants in earlier-treated villages. Household energy policies like the CHP may serve as effective population-level interventions to reduce BP in China and complement high-risk cardiovascular prevention strategies.



INTRODUCTION

Approximately one-third of the global population relies on solid fuels for household energy, contributing to an estimated 3.1 million premature deaths annually from household air pollution.¹ The inefficient combustion of coal and biomass (i.e., solid fuels) emits high concentrations of air pollutants that harm human health and contribute substantially to outdoor air pollution.^{1,2} Expanding access to modern and reliable household energy is therefore a global priority to reduce poverty, mitigate climate change, and protect human health, as articulated by the World Health Organization, United Nations, World Bank, and International Energy Agency.³

Transitioning households from solid fuels to gas or electricity is expected to improve health through reductions in air pollution exposure and other improvements to the indoor environment. Observational studies have linked fine particulate matter (PM_{2.5}) exposure to many health outcomes, including higher blood pressure (BP), while trials and other intervention studies show that replacing solid fuel cookstoves with gas or electric alternatives can reduce indoor PM_{2.5} to

levels below the WHO interim air quality guideline of 25 $\mu\text{g}/\text{m}^3$.^{4–6} By providing more consistent heating and reducing fuel-loading demands on residents, cleaner heating systems may offer the additional benefit of improved indoor temperature, which is an important determinant of BP and cardiovascular health.^{7,8} Despite these established exposure-response relationships linking PM_{2.5} and indoor temperature to cardiovascular health, evidence that large-scale household energy transitions, most of which have focused on cookstoves, produce measurable health benefits remains limited. This reflects the challenges of achieving sustained adoption of clean fuels while minimizing exposure from other pollution sources and accounting for behavioral changes that may also affect health.^{9,10}

Received: March 27, 2026

Revised: July 18, 2026

Accepted: July 30, 2026

In 2015, China launched the Clean Heating Policy (CHP) to reduce coal use and air pollution emissions while promoting rural development (Text S1).¹¹ The policy targeted 70% of rural households in northern China for transition from coal-based heating to gas- or electric-powered systems through subsidies for equipment and fuel, combined with restrictions on coal use. Implementation was staggered across villages, and by 2021, approximately 36 million households had been treated, creating an unprecedented opportunity to assess the policy's health impacts.¹² Although previous risk assessments and ecological studies at township or city scales suggest health benefits of the CHP, no study has evaluated its effects on health outcomes using individual-level data while accounting for secular trends through an appropriate control group.^{13,14} Following evidence of CHP-driven improvements in indoor air pollution and indoor temperature, this study capitalizes on the staggered rollout of the policy across rural Beijing villages to estimate its impact on adult BP, the leading modifiable risk factor for the disease burden in China and globally.^{15–17}

METHODS

Study Location

The study was conducted in the Beijing Municipality Region, which consists of a densely populated urban core surrounded by thousands of peri-urban and rural villages that extend from flat plains areas to mountainous terrain. Beijing winters are cold and dry with an average temperature of -1.1°C from 1990–2020, and the minimum reaching an average of -7.1°C in January, thus necessitating space heating.¹⁸ While urban households have access to centralized heating, most rural households use coal- and biomass-fueled heaters and kang (combined cooking/heating stove and bed) and electric-powered heaters for space heating (Figure S1).

Study Design

Data were collected over four winter campaigns: 2018–19 (wave 1, W1), 2019–20 (W2), 2020–21 (W3), and 2021–22 (W4) (Figure 1). In each wave, trained staff conducted household visits from

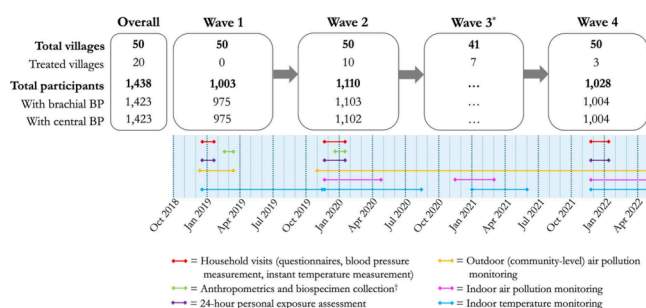


Figure 1. Overall and wave-specific study participation and data collection timeline. *Household visits and health measurements were not conducted in Wave 3 due to restrictions during COVID-19. Limited environmental monitoring was possible. In Wave 4, anthropometric measures were conducted during household visits to avoid group contact during COVID-19. Biospecimens were not collected.

November to January where they administered household and individual questionnaires, measured BP, and deployed temperature and air pollution monitors in homes. In W1 and W2, participants were invited to centrally located clinics in each district where anthropometrics were measured and biospecimens were collected several weeks later. Anthropometrics were measured during household visits in W4 to avoid group contact during the COVID-19 pandemic, and biospecimens were not collected. Environmental monitoring equipment and BP monitors were stored in climate-

controlled facilities between study waves and tested before the start of each study wave. Malfunctioning devices were removed from use and not redeployed until repaired by the manufacturer or according to manufacturer instructions. Detailed quality assurance and quality control procedures are published elsewhere.¹⁹

Village and Participant Recruitment and Enrollment

Villages eligible for but not treated by the CHP were recruited between December 2018 and January 2019. Initial households (4–5 per village) were selected with help from village guides, and subsequent homes were recruited via participant referrals and public encounters. We recruited 10–23 households (median = 20) per village and randomly selected one eligible participant per household using a tablet-based tool. Eligible participants were >40 years old, maintained a primary residence in the village, were not planning to move within a year, and were not receiving immunotherapy or corticosteroids. Participants were followed prospectively, as an open cohort, where some individuals exited the study population and additional village residents meeting eligibility criteria entered in later waves. All participants provided written informed consent.

If participants were unavailable or unwilling to continue participation, staff recruited another eligible household member; if unsuccessful, we enrolled a new participant from a new household using the original sampling procedures. Study protocols were approved by ethics boards at Peking University (IRB00001052-18090), Peking Union Medical College Hospital (HS-3184), and McGill University (A08-E53-18B).

Data Collection

Staff administered questionnaires to collect information on household demographics, assets and income, home insulation and structure (e.g., number of rooms), stove and fuel use, and participant education, health behaviors (e.g., exercise frequency, smoking, alcohol consumption), medication use, and clinician-diagnosed health conditions (Text S2). Assets and income data were used to construct a household wealth index via principal component analysis.²⁰ Height, weight, and waist circumference were measured at clinic visits in W1 and W2 and during household visits in W4. Blood serum samples collected in W1 and W2 during clinic visits were analyzed for total cholesterol, high- and low-density lipoproteins, and triglycerides. Personal air pollution exposures were measured over the 24 h following household visits in a 50% random subsample in W1, W2, and W4. We additionally measured indoor PM_{2.5} throughout the winter heating season in approximately 300 homes per wave in W2, W3, and W4, and community-level outdoor air pollution was measured continuously in all study villages (Text S3).¹⁷ We aimed to collect personal and indoor samples in the same households.

Blood Pressure Measurement

Following 5 min of quiet rest, participants' brachial systolic and diastolic BP were measured at 1 min intervals in participant homes using an automated oscillometric device (BP+; Uscom Ltd., New Zealand). This device also estimates central BP from brachial cuff pressure fluctuations, a method previously validated against invasive central BP measurements.²¹ Monitors were calibrated by the manufacturer before W1 and W4. BP measurement and quality-control procedures are described elsewhere.¹⁷ Briefly, if the difference between the last two readings exceeded 5 mmHg or the device failed to generate a BP reading, up to five measurements were taken. The average of the final two measures was used for analysis, unless only one was obtained ($n = 13$). Time of day, day of week, and indoor temperature in the 5 min preceding BP measurement were recorded. Hypertension was considered present if the participant was clinically diagnosed with high BP, reported use of antihypertensive medication, or had a measured SBP > 140 mmHg and/or DBP > 90 mmHg.

Difference-in-Differences

We estimated the impact of the CHP on BP using a difference-in-differences (DiD) design. Simple comparisons of treated and untreated (i.e., control) villages after policy implementation could be biased by unmeasured village-level characteristics (e.g., average

Table 1. Characteristics of Participants Enrolled in Wave 1 (Baseline) in Villages That Remained Untreated by the Clean Heating Policy (CHP) during the Study Period Compared with Participants from Villages That Were Treated by Waves 2, 3, or 4 in the Imputed Data

	Summary measure	Overall ^a	Untreated	Treated	Mean difference (SE) ^b
Number of villages	N	50	30	20	
Number of participants	N	1003	603	400	
Age (years)	Mean (SD)	60.0 (9.3)	59.9 (9.4)	60.3 (9.1)	0.5 (0.6)
Sex (% female)	N (%)	598 (59.6)	358 (59.3)	240 (60.0)	0.7 (3.2)
Marital Status					
Married	N (%)	892 (88.9)	543 (90.0)	349 (87.3)	−2.7 (2.1)
Separated or divorced		24 (2.3)	9 (1.6)	14 (3.5)	2.0 (1.1)
Widowed		79 (7.9)	47 (7.7)	33 (8.2)	0.4 (1.8)
Never married		8 (0.8)	4 (0.7)	4 (1.0)	0.3 (0.6)
Tobacco smoking					
Current smoker	N (%)	260 (25.9)	158 (26.3)	101 (25.3)	−1.0 (2.8)
Former smoker		132 (13.2)	72 (11.9)	60 (15.0)	3.1 (2.2)
Never smoker who lived with smoker		404 (40.2)	241 (40.0)	162 (40.6)	0.6 (3.2)
No exposure to tobacco smoking		208 (20.7)	131 (21.8)	77 (19.1)	−2.6 (2.6)
Frequency of alcohol consumption					
Never	N (%)	548 (54.6)	337 (55.9)	211 (52.6)	−3.2 (3.2)
Occasionally		194 (19.4)	112 (18.6)	82 (20.6)	1.9 (2.6)
Regularly		67 (6.6)	47 (7.7)	20 (5.0)	−2.7 (1.6)
Every day		194 (19.4)	107 (17.8)	87 (21.8)	4.0 (2.6)
Exercise frequency					
Never	N (%)	181 (18.0)	103 (17.1)	77 (19.4)	2.2 (2.5)
Occasionally		69 (6.9)	42 (6.9)	27 (6.8)	−0.1 (1.6)
Regularly		192 (19.2)	129 (21.4)	63 (15.8)	−5.6 (2.5)
Every day		561 (56.0)	329 (54.6)	232 (58.1)	3.5 (3.2)
Farming frequency					
Never	N (%)	360 (35.9)	223 (36.9)	137 (34.3)	−2.7 (3.1)
Occasionally		127 (12.7)	85 (14.1)	42 (10.6)	−3.5 (2.1)
Regularly		372 (37.1)	222 (36.7)	150 (37.6)	0.8 (3.1)
Every day		144 (14.4)	74 (12.3)	70 (17.6)	5.3 (2.3)
Asset based wealth index					
Lowest quintile (<20%)	N (%)	201 (20.0)	126 (21.0)	75 (18.6)	−2.3 (2.6)
Second quintile (20 to <40%)		200 (20.0)	129 (21.4)	71 (17.8)	−3.6 (2.6)
Third quintile (40 to <60%)		201 (20.0)	112 (18.6)	89 (22.2)	3.6 (2.6)
Fourth quintile (60 to <80%)		200 (19.9)	114 (19.0)	86 (21.4)	2.4 (2.7)
Highest quintile (80 to 100%)		201 (20.0)	121 (20.1)	80 (19.9)	−0.2 (2.6)
Education					
No school	N (%)	118 (11.8)	69 (11.4)	49 (12.3)	0.9 (2.1)
Primary school		766 (76.4)	456 (75.6)	310 (77.6)	2.0 (2.8)
High school or greater		119 (11.8)	78 (13.0)	40 (10.1)	−2.9 (2.1)
Current occupation					
Agriculture	N (%)	642 (64.0)	373 (61.9)	269 (67.2)	5.3 (3.1)
Work outside the home		54 (5.4)	35 (5.8)	19 (4.8)	−1.0 (1.5)
Work inside the home, retired, or unemployed		255 (25.4)	154 (25.6)	101 (25.1)	−0.5 (2.8)
Other or not stated		52 (5.2)	41 (6.7)	11 (2.8)	−3.9 (1.3)
Environmental measures					
Indoor temperature (°C) ^c	Mean (SD)	13.7 (3.5)	13.8 (3.6)	13.5 (3.4)	−0.3 (0.2)
Outdoor temperature (°C) ^d		−1.4 (1.4)	−1.0 (1.6)	−1.8 (0.8)	−0.8 (0.1)
Mean winter indoor PM _{2.5} (μg/m ³) ^e	Geometric mean (SD)	58.5 (1.4)	56.0 (1.4)	62.6 (1.4)	6.6 (8.9)
Mean winter outdoor PM _{2.5} (μg/m ³) ^{e,f}		44.8 (1.4)	44.9 (1.5)	44.6 (1.3)	−0.3 (0.1)
Health measures					
Waist circumference (cm)	Mean (SD)	86.9 (10.8)	87.8 (11.0)	85.6 (11.1)	−2.2 (0.8)
BMI (kg/m ²)		26.1 (3.7)	26.3 (3.8)	25.8 (3.8)	−0.5 (0.3)
Blood pressure					
Systolic brachial (mmHg)	Mean (SD)	130.3 (15.9)	131.4 (16.8)	128.7 (14.3)	−2.7 (1.0)
Systolic central (mmHg)		124.6 (15.5)	125.6 (16.2)	123.0 (14.1)	−2.6 (1.0)
Diastolic brachial (mmHg)		82.4 (11.5)	82.7 (11.6)	82.1 (11.3)	−0.6 (0.8)
Diastolic central (mmHg)		83.5 (11.6)	83.7 (11.6)	83.1 (11.5)	−0.6 (0.8)
Brachial PP (mmHg)		47.9 (11.3)	48.7 (11.8)	46.6 (10.4)	−2.1 (0.7)
Central PP (mmHg)		41.1 (10.6)	41.9 (10.9)	39.9 (10.1)	−2.0 (0.7)

Table 1. continued

	Summary measure	Overall ^a	Untreated	Treated	Mean difference (SE) ^b
Antihypertensive medication use	N (%)	466 (46.5)	302 (50.0)	165 (41.2)	−8.8 (3.8)
High BP ^c	N (%)	674 (67.2)	417 (69.1)	257 (64.3)	−4.8 (3.6) ^d

^aThe ‘Overall’ column value may differ from the sum of ‘Untreated’ and ‘Treated’ values due to rounding when summarizing the sample size across imputed data sets. ^bCalculated as the difference in means/proportions between ‘Treated’ and ‘Untreated’ villages for each of the 30 imputed data sets. Differences and standard errors were pooled across data sets according to Rubin’s Rules. ²⁶ ^cMeasured in participant homes in the 5 min before blood pressure measurement. ^dData are from the National Oceanic and Atmospheric Administration (NOAA). ^eAverage of real-time PM_{2.5} measurements, taken every minute, from January 15 to March 15. ^fBecause this was a village-level measurement, summary statistics were calculated at the village level. The corresponding village sample sizes are reported in the first row. ^gHigh BP was defined as SBP > 140 mmHg, DBP > 90 mmHg, self-reported physician diagnosis of hypertension, and/or use of antihypertensive medication.

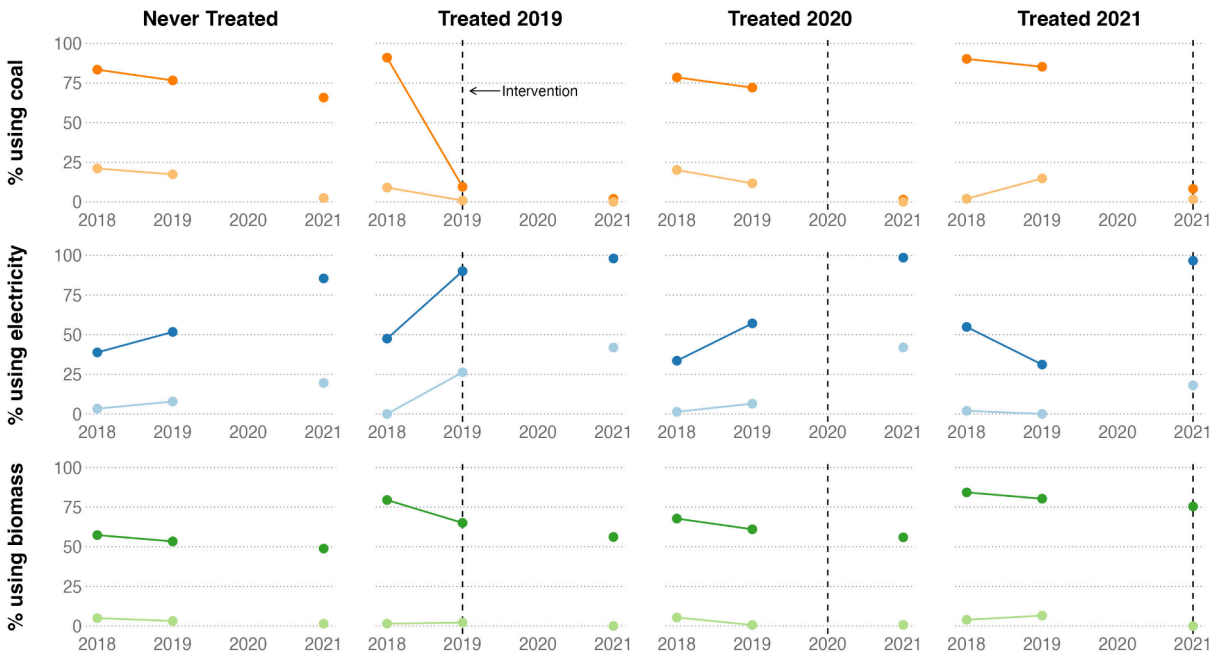


Figure 2. Any use (darker line) and exclusive use (lighter line) of coal, electricity, and biomass for household heating by treatment cohort (column names) and time (horizontal axis). Heating fuel type is indicated by the vertical axis title. Note: Trend lines from 2019 to 2021 were omitted to avoid inferring a continuous trend across 2020, when data were not collected due to the COVID-19 pandemic.

winter temperature, altitude, wealth, pre-existing health conditions) that affect BP. Likewise, comparing only treated villages before and after the policy could introduce bias if factors unrelated to the CHP affect BP trends across all villages over time (i.e., secular trends). The DiD design addresses these issues by comparing changes in BP in treated villages before and after policy implementation with the corresponding changes in control villages over the same time period. This approach controls for unmeasured, time-invariant differences between villages as well as broader secular trends in BP unrelated to the policy.

Covariates

DiD assumes parallel outcome trends across groups of villages treated at the same time (i.e., ‘cohorts’ of villages) in the absence of the CHP.²² To improve both the credibility of this assumption and precision, we adjusted models for strong time-varying predictors of BP unlikely affected by the CHP.^{23,24} Models for all BP outcomes were adjusted for sex, age, waist circumference, residential exposure to tobacco smoke, and alcohol consumption frequency. Covariate selection was guided by directed acyclic graphs (DAGs) developed from prior literature and expert knowledge (Figure S2).

Participants who did not attend the clinic visit in W1 and W2 (17%) were missing waist circumference measurements. Thus, we used multiple imputation with chained equations to impute missing values and retain observations in covariate-adjusted models (mice package in RStudio, m = 30 data sets, with 30 iterations).²⁵ Analysis was performed on each imputed data set. Estimates and standard

errors were combined using Rubin’s rules to account for within- and between-imputation variance (Tables S1–S2, Figure S3).²⁶

Statistical Analysis

A two-way fixed effects model is commonly used in DiD analysis, but can yield biased estimates when treatment effects vary across groups treated at different times.^{22,27} Thus, we used an ‘extended’ two-way fixed effects (ETWFE) model that accommodates the policy’s staggered implementation and estimates the average treatment effect on the treated (ATT) for each cohort *r* at each post-treatment time *s*—i.e., ATT(*r*,*s*).²⁸ These effects were estimated using pooled linear regression:

$$Y_{ivt} = \alpha + \sum_{r=q}^T \beta_r d_r + \sum_{s=r}^T \gamma_s f_s + \sum_{r=q}^T \sum_{s=r}^T \tau_{rs} (d_r \times f_s) + Z_{ivt} + \epsilon_{ivt}$$

where *Y_{ivt}* is the BP outcome for individual *i* in village *v* at time *t*; α is the intercept; *d_r* and *f_s* are fixed effects for cohorts *r* and survey waves *s*, respectively; *q* is the first year of policy enrollment; τ_{rs} are cohort-time ATTs; *Z_{ivt}* is a vector of covariates; ϵ_{ivt} is the idiosyncratic error; and *T* indicates the final study year, 2021. We report cohort-time-specific ATTs and the overall ATT, calculated as a weighted average of cohort-time estimates with weights proportional to the cohort size treated at time *t*.²⁹ Separate regressions were estimated for each BP outcome in RStudio using the ‘fixest’ package, and the overall ATT was obtained using marginal effects with the ‘marginal effects’ package.^{30–32} Standard errors were clustered at the village level. We

used joint F-tests to test for differences across cohort-time ATTs, and we also tested for effect heterogeneity by age (≥ 65 y/ <65 y), hypertension status (yes/no), antihypertensive medication use (yes/no), and sex (male/female). Each variable was added to separate regression models with interactions between the modifier, cohort and time fixed effects, and the cohort-time ATT term.

Sensitivity analyses restricted the sample to participants enrolled in W1; restricted the sample to participants with BP measurements in W1, W2, and W4; used only measured (nonimputed) data; and additionally adjusted for blood lipids and antihypertensive medication use in separate models.

RESULTS

Village Enrollment and Participant Characteristics

Fifty villages were recruited at baseline, of which 20 were subsequently treated by the CHP across three cohorts: 10 in W2, 7 in W3, and 3 in W4 (Figure S4). Individual measurements were not collected in W3 due to COVID-19 disruptions, so analyses included data from W1, W2, and W4. All villages were retained throughout the study with no cluster-level attrition. In total, 1,438 participants from 1,236 households were recruited, and participant sample sizes ranged from 1,003 to 1,028 across study waves (Figure 1). Of these, 1,423 (99%) participants contributed a BP measurement and were included in the analysis, with 601 (42%) participating in all three waves, 457 (32%) in two waves, and 365 (26%) in one wave. There were no systematic differences between participants who contributed to a different number of waves (Table S3).

At baseline, mean participant age was 60 years and 60% were female (Table 1). Most participants (66%) either smoked or lived with a smoker, and 64% worked in agriculture. Approximately two-thirds had hypertension, and 46% of those diagnosed reported taking antihypertensive medication. Baseline socio-demographic and health characteristics were similar between participants in CHP-treated villages versus untreated villages.

Mean BP trends over the first two waves were visually similar and statistically indistinguishable between untreated villages and those treated in the latter two waves (p for homogeneity = 0.6 to 0.9) (Figure S5), supporting the assumption of parallel trends in the absence of the CHP.

Policy Uptake, Indoor Air Quality, and Indoor Temperature

The CHP reduced household coal use and increased the adoption of electric heating in treated villages. In villages first treated by the policy in 2019, coal heating declined from 91.0% of households in W1 to 9.5% in W2 and 1.9% in W4 (Figure 2, Table S4). Correspondingly, electric heating increased from 47.5% (0.0% exclusive) in W1 to 90.1% (26.0% exclusive) in W2 and 98.1% (42.0% exclusive) in W4. We observed similar energy trends in villages first treated by the CHP in 2020. Uptake of exclusive electric heating was lower in the three villages first treated in 2021 (18.0% in W4). In villages that remained untreated by the policy, exclusive electric heating increased from 3.3% to 19.5% during the study period and coal heating remained common (66.0% of households in W4).

Biomass use, though not explicitly targeted by the CHP, decreased slightly across treatment cohorts but remained most prevalent in villages first treated in 2021 (75.0% in 2021-treated villages versus 56.0% in villages treated in 2019 or 2020 in W4). At follow-up, exclusive biomass use was uncommon, comprising 0.0–0.7% of households in treated villages and

1.5% of households in untreated villages. The quantity of self-reported biomass used for heating also declined over the study period in all villages except for those first treated in 2021, where it increased from approximately 1.6 tons in W1 to 2.2 tons in W4 (Figure S6).¹⁷

Average winter outdoor PM_{2.5} concentrations declined throughout the study, but changes were not attributable to the CHP.¹⁷ Average winter indoor PM_{2.5} decreased from W2 to W4 (Figure S7, Table S5), with CHP-driven reductions of 20.3 $\mu\text{g}/\text{m}^3$ (95% CI: -37.5 , -3.0). No corresponding reductions were observed in 24-h personal PM_{2.5} exposure among villages treated by the CHP.¹⁵

The CHP increased indoor temperature measured before BP by approximately 1.9°C (95% CI: 0.9, 2.9), with average temperatures in treated homes reaching 18°C at follow-up (Figure S7, Table S5).¹⁷ Over the same period, untreated villages also experienced a secular increase in indoor temperature, from 13.8°C to 16.1°C.

Further details on policy uptake and impacts on coal use, indoor temperature, and air quality are reported elsewhere.¹⁷

Policy Impacts on BP

Treatment by the CHP reduced systolic (brachial: -1.4 mmHg, 95% CI: -3.3 , 0.5 ; central: -1.5 mmHg, 95% CI: -3.3 , 0.4) and diastolic BP (brachial/central: -1.6 mmHg, 95% CI: -2.9 , -0.3). Estimates of diastolic BP reductions were more precise than systolic, where changes in systolic BP were compatible with modest reductions and little to no change. No changes were observed for pulse pressure (Figure 3, Table S6).

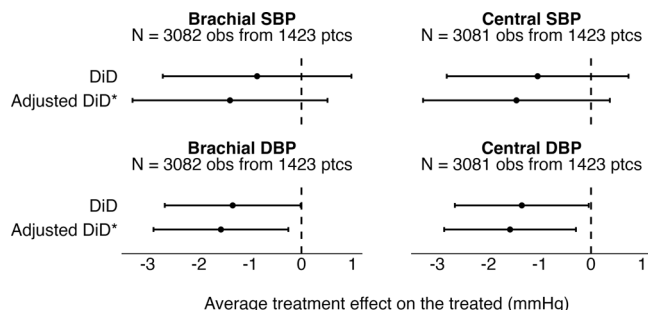


Figure 3. Overall average treatment effects on the treated and 95% confidence intervals for the effect of the Clean Heating Policy on blood pressure in the imputed data. Note: DBP, diastolic blood pressure; DiD, difference-in-differences; mmHg, millimeters of mercury; obs, observations; ptes, participants; SBP, systolic blood pressure. *Adjusted for age (continuous), sex (binary), waist circumference (continuous), smoking (categorical), and alcohol consumption (categorical).

The CHP's effect on BP varied by treatment cohort (Figure 4, Table S7). BP reductions were larger in villages first treated in 2019 and 2020 compared with those treated later in 2021. For example, in the year of treatment, the CHP reduced central DBP by 2.5 mmHg (95% CI: -4.4 , -0.7) in villages first treated in 2019 but increased central DBP by 1.1 mmHg (95% CI: 0.0, 2.2) in villages first treated in 2021 (p -value for test of homogeneity <0.0001). We observed similar cohort-specific trends in treatment effects for all measures of SBP and DBP, but there was less evidence of differential effects by cohort for pulse pressure (p -values for homogeneity = 0.18–0.31).

We did not observe effect heterogeneity for SBP or DBP by sex, age (≥ 65 y), hypertension status, or use of antihypertensive

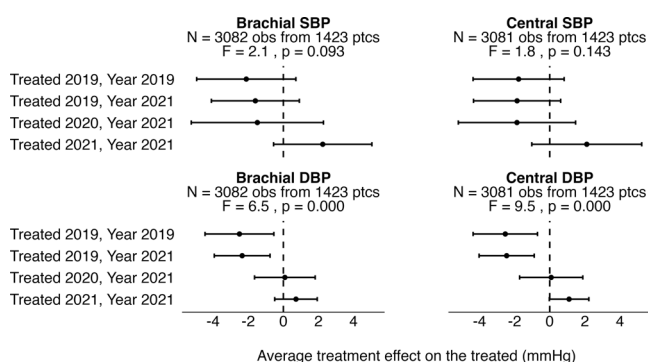


Figure 4. Covariate-adjusted cohort-time average treatment effects on the treated (ATTs) and 95% confidence intervals for the effect of the Clean Heating Policy on blood pressure in the imputed data. F-statistics (F) and p-values are provided for joint tests of equality across cohort-time ATTs. Note: DBP, diastolic blood pressure; mmHg, millimeters of mercury; obs, observations; ptcs, participants; SBP, systolic blood pressure. All results were adjusted for age (continuous), sex (binary), waist circumference (continuous), smoking (categorical), and alcohol consumption (categorical).

medication (p -values = 0.4 to 0.9) (Figure S8). Results were consistent after restricting the analysis to participants enrolled at baseline (Table S8) and to participants with BP measurements in all study waves (Table S9). They also did not meaningfully change when using observed rather than imputed covariate data (Table S10) and were robust to additional covariate adjustment for blood lipids and use of antihypertensive medication (Tables S11 and S12).

DISCUSSION

Our study provides evidence that household energy policies can yield cardiovascular benefits. Adults in CHP-treated villages experienced modest but consistent reductions in systolic and diastolic BP that persisted over at least two years of follow-up, with evidence of heterogeneity by treatment cohort. Although household energy transitions are central to global clean energy and public health agendas, population-level evidence of their health benefits remains limited. The CHP is one of the largest, most comprehensive, and most rapidly implemented household energy policies to date, and our findings suggest it was associated with measurable improvements in a key cardiovascular risk factor in rural Beijing.

The observed BP reductions (1.4 mmHg systolic, 1.6 mmHg diastolic) in our study align with randomized and controlled observational studies in Guatemala, Nigeria, and Ghana, which reported similar BP reductions (−3.7 to −0.1 mmHg) following biomass chimney or ethanol cookstove interventions.³³ In contrast, LPG stove trials in older adults in Peru and in pregnant women in a multicountry trial (Guatemala, India, Peru, and Rwanda) found no improvements in BP despite substantial reductions in $PM_{2.5}$ exposures (46–75 $\mu\text{g}/\text{m}^3$), although observational analyses within these studies reported 1.6–2.0 mmHg higher systolic BP among participants in the highest versus lowest quartiles of $PM_{2.5}$ and black carbon exposure.^{34–36} Differences in participant demographics and pollutant profiles (e.g., unmeasured NO_2 from LPG stoves), as well as their shorter follow-up periods of ≤ 1 year, may explain the discrepancy between these findings and our results.

To our knowledge, no other studies have examined the CHP's health impacts using individual-level data. Our results align with a recent township-level analysis reporting a 6.6%

(95% CI: −12.3, −0.8) reduction in acute myocardial infarction incidence in Beijing townships where >50% of villages were treated by the CHP for 3–4 years, compared with townships where a smaller proportion of villages were treated.¹³ In contrast, a city-scale study observed small reductions in physician-diagnosed respiratory disease but no CVD change in CHP pilot cities, though follow-up was limited to one year and changes in clinical CVD events may require a longer response time.¹⁴ Although the 1.4–1.6 mmHg reductions in BP observed in our study may have limited clinical significance for individuals, the population health implications are large given the tens of millions of households treated by the CHP and the relationship of BP with CVD, chronic kidney disease, and diabetes.³⁷

We observed heterogeneity in BP effects by treatment year, with larger reductions among earlier-treated cohorts than among villages first treated in 2021. A possible explanation is variation in post-implementation heating practices across cohorts. Although heat pump uptake and coal suspension were very high overall, villages in the 2021 cohort were more likely to continue using biomass.¹⁷ Continued indoor biomass burning, which was not targeted by the policy, may have attenuated reductions in air pollution and associated BP benefits. We also observed smaller increases in indoor temperature in the 2021 cohort compared with earlier cohorts, which may have further reduced BP benefits.¹⁷ Interpreting these cohort-specific effects is further complicated by the COVID-19 pandemic, which coincided with CHP enrollment of the 2020 and 2021 cohorts. Although we found no evidence that the pandemic disrupted CHP implementation, differential effects of the pandemic across treated cohorts could have contributed to the observed heterogeneity.

We did not observe differences in policy impacts by age, sex, hypertension status, or antihypertensive medication use, though subgroup-specific uncertainty intervals were wide, reflecting limited power to detect heterogeneity. In contrast, several cookstove intervention studies observed greater BP benefits among older individuals (>50 years) and those with higher baseline BP and chronic conditions.³⁸ Older adults and individuals with preexisting cardiovascular disease may be more susceptible to air pollution and thus benefit most from air pollution interventions, though potential health benefits may also depend on pollutant characteristics, including their source, toxicity, and chemical composition.³⁹

Heating stove interventions could benefit BP by reducing levels of household air pollution and improving indoor temperature. Inhaled $PM_{2.5}$ triggers pulmonary inflammation that can extend systemically, causing endothelial dysfunction and impaired vasodilation.⁴⁰ Cold exposure and $PM_{2.5}$ also increase sympathetic activity and release catecholamines, promoting vasoconstriction and increased BP.^{40,41} Cold-related physiological changes in skin vasomotor tone, blood viscosity, erythrocyte deformability, and sodium retention may further increase BP.⁴¹ The combined policy-driven changes in indoor temperature and air quality may thus explain BP reductions in our study that were unobserved in other solid fuel cooking interventions.¹⁷ Since heating is continuous throughout the winter, heating interventions may provide more consistent emissions reductions than cooking interventions which typically target shorter exposure periods.⁴²

The effects of the CHP on air pollution and indoor temperature are described in detail elsewhere.¹⁵ Briefly, although we observed reductions in indoor $PM_{2.5}$ in CHP-

treated villages, estimates for personal $\text{PM}_{2.5}$ exposure were compatible with both increases and decreases of approximately $20 \mu\text{g}/\text{m}^3$, a finding that may reflect the limitations of a single 24-h measurement for capturing longer-term changes in heating-related exposure across the winter season.¹⁵ In contrast, the CHP increased average indoor temperatures by nearly 2°C , suggesting more consistent improvements in household thermal environments.

The validity of our estimation approach rests on crucial assumptions of no differential treatment anticipation between cohorts, parallel outcome trends across cohorts in the absence of the CHP, and no cointerventions differentially affecting BP.²² These assumptions cannot be empirically verified but are plausible in this study. Villages could be assigned to or apply for the CHP but were generally unaware of whether or when they would be treated. We observed similar pretreatment BP trajectories in untreated villages and those first treated in 2020 and 2021, supporting the use of untreated villages as a counterfactual. Finally, annual interviews with village leaders identified no other policies during the study period that would have differentially affected BP across treatment cohorts.

A primary strength of this study is the use of a DiD design to evaluate a policy as implemented, which would be cost-prohibitive and logistically challenging in an experimental design of similar scale. The double-differencing approach accounts for fixed differences between treatment cohorts (e.g., genetics, medical history) and secular time trends affecting BP, which were not often captured in previous observational studies.⁴³ BP was measured objectively, minimizing potential measurement error regardless of knowledge of treatment status, and all 50 villages were retained over four years despite COVID-19-related disruptions. Except for two recent studies, our sample of over 1,400 participants was larger than previous work, and sensitivity analyses restricted to participants enrolled at baseline and those with measurements across all waves indicated that compositional changes in the study sample had minimal impact on results.^{34,44} Moreover, because our primary interest was in the effect of village-level CHP treatment on the resident population's BP over time, individual entry into and exit from the analytic cohort reflected the dynamic population of interest rather than study attrition.⁴⁵

Several limitations warrant consideration. We controlled for strong predictors of BP but cannot rule out confounding by unmeasured time-varying factors that differed by treatment status. For example, dietary intake was not measured, although it is unlikely to have changed differentially between treated and untreated villages unless it was affected by the policy itself.²³ Similar baseline characteristics and preintervention BP trends reduce the likelihood of substantial time-varying confounding, and additional adjustment for cholesterol and blood lipids did not materially change results. Other short-term behavioral predictors of BP, like sleep and exercise, did not change differentially by cohort or over time, and thus, were not regarded as confounders. Similarly, outdoor temperature was not expected to systematically differ by CHP treatment cohort, and we did not adjust for indoor temperature since it was likely to be affected by the CHP. Our sampling approach relied, in part, on participant recruitment from public spaces, which may limit generalizability to less socially active or less healthy adults in rural Beijing. Village guides also directed staff to winter-occupied homes, and in many villages, recruitment approached a census of households, suggesting that the study population remained broadly representative of the participating villages.

Although a recent validation study found systematic differences between Uscom BP+ cuff-estimated central BP and invasively measured central BP, any bias is likely consistent over time and nondifferential between treatment groups, making bias in ATT estimates for central BP unlikely.⁴⁶ Finally, while BP was measured in nearly all (99%) participants, we used multiple imputation to avoid dropping $\sim 17\%$ of observations with missing covariates. Analyses of nonimputed data did not change the results.

COVID-19 also warrants consideration because it began at the end of W2 data collection and coincided with the treatment periods of the 2020 and 2021 cohorts. Throughout this period, China maintained a nationally standardized Zero-COVID policy that remained in effect until December 2022.⁴⁷ Measures including intensive contact tracing, mass testing, travel restrictions, centralized quarantines, and localized lockdowns were intended to contain outbreaks while maintaining social and economic activity.⁴⁸ Consistent with this, CHP implementation does not appear to have been substantially disrupted by the pandemic, as villages continued to be treated by the policy in 2020 and 2021. Because pandemic control measures were implemented according to national directives, villages across Beijing were likely affected in broadly similar ways.⁴⁹ However, we cannot exclude the possibility that the pandemic influenced heating behaviors or other factors differently across treatment cohorts. Such differences, if related to BP, could contribute to cohort-specific effects observed during 2020–2022 and complicate attribution of these effects solely to CHP implementation.

China's investments in rural electrification, heating technology, and rural development facilitated the CHP's success in substituting coal-based heating with electricity. Substantial rural electrification began after 1950, with centralized grid expansion and modernization since the late 1990s.⁵⁰ Full electrification of rural areas was achieved by 2015, laying a strong infrastructure base for shifting to electric-powered household energy.³ Clean heating devices including direct electric heaters, thermal storage units, and heat pumps were piloted in Beijing for their efficiency and residential acceptability prior to deploying heat pumps.⁵¹ The policy's dual approach of coal restriction and subsidized electricity and heating technologies responded to widespread calls for more nuanced household energy interventions that went beyond single-stove solutions and considered contextual factors.¹⁰ By integrating multiple strategies, this 'package approach' addressed solid fuel suspension, a persistent barrier to attaining the environmental and health benefits of clean household energy.⁵² However, continued biomass use, which was not targeted by the CHP, could attenuate long-term health gains.

The CHP specifically applied to rural areas surrounding the "2 + 26" cities with historically high wintertime outdoor $\text{PM}_{2.5}$.⁵³ The extent to which our findings generalize beyond rural Beijing depends, at a minimum, on the comparability of CHP implementation across regions. Although the policy was guided by national objectives, local governments had discretion over key implementation decisions, including stove subsidy levels and technologies, infrastructure investments, and electricity pricing.⁵⁴ Subsidies in Beijing may have covered a greater proportion of clean heating transition costs than other northern provinces, and thus, the impacts in our Beijing study villages may not directly generalize to all regions with the policy.^{55,56} Differences in subsidies, supporting infrastructure, population characteristics, and sustained adoption of clean

heating technologies may influence PM_{2.5} and indoor temperature exposures and, consequently, associated BP benefits.⁵⁶ These factors should be considered when interpreting the broader applicability of our findings.

Our findings may also be relevant for populations in Mongolia, South America, eastern Europe, and other parts of Asia where solid fuel heating remains common.^{2,57} However, similar policies may achieve environmental and health benefits more effectively when adapted to local conditions, including through a combination of interventions, device performance testing, and supporting infrastructure improvements. Although previous work suggests that villages across socioeconomic strata benefited from the CHP, wealthier villages may have been better positioned to afford the transition to electricity.¹⁶ Since our study villages were farther from Beijing's urban core and generally of lower socioeconomic status than villages treated earlier, our findings may not generalize to more urbanized and wealthier villages treated between 2015 and 2018. Finally, our findings suggest that the BP benefits under the CHP were achieved within the existing policy package and may depend on sustained implementation of its core components. However, because our analysis does not identify the specific mechanisms underlying the weaker effects observed in the later treated cohort, the results do not support specific recommendations regarding subsidy design or other policy modifications.

CONCLUSIONS

The CHP produced small but measurable reductions in BP among adults in rural Beijing. Large-scale clean household energy policies like the CHP may yield population-level cardiovascular benefits that complement high-risk prevention strategies. In comparison with smaller-scale trials conducted under relatively controlled conditions, this evaluation of a large-scale, policy-driven transition provides important evidence for operationalizing sustainable development and improving population health.

ASSOCIATED CONTENT

Data Availability Statement

Data and code to reproduce all results in this paper are available from the Open Science Foundation (<https://osf.io/7nxac/overview>).

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/EHP.6c00053>.

Additional study details, materials, methods, and results from sensitivity analyses (PDF)

AUTHOR INFORMATION

Corresponding Authors

Yuanxun Zhang — National Field Observation and Research Station (Beijing Yanshan) for Earth Critical Zone and College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China; Phone: +86-10-6967-2956; Email: yxzhang@ucas.ac.cn

Jill Baumgartner — Department of Epidemiology, Biostatistics, and Occupational Health and Department of Equity, Ethics, and Policy, McGill University, Montréal, Quebec H3A 0G4, Canada; orcid.org/0000-0001-8397-6380; Phone: +1-514-398-6688; Email: jill.baumgartner@mcgill.ca

Authors

Talia Sternbach — Department of Epidemiology, Biostatistics, and Occupational Health, McGill University, Montréal, Quebec H3A 0G4, Canada; orcid.org/0009-0007-9898-4982

Sam Harper — Department of Epidemiology, Biostatistics, and Occupational Health, McGill University, Montréal, Quebec H3A 0G4, Canada

Xiaoying Li — Department of Mechanical Engineering, Colorado State University, Fort Collins, Colorado 80523-1019, United States; orcid.org/0000-0002-9932-6654

Collin Brehmer — Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado 80523-1019, United States

Wenlu Yuan — Department of Epidemiology, Biostatistics, and Occupational Health, McGill University, Montréal, Quebec H3A 0G4, Canada

Shu Tao — College of Urban and Environmental Sciences, Peking University, Beijing 100871, China; orcid.org/0000-0002-7374-7063

Kaibing Xue — College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

Kennedy Hirst — Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado 80523-1019, United States

Guofeng Shen — College of Urban and Environmental Sciences, Peking University, Beijing 100871, China; orcid.org/0000-0002-7731-5399

Christopher Barrington-Leigh — Bieler School of Environment and Department of Equity, Ethics, and Policy, McGill University, Montréal, Quebec H3A 0G4, Canada

Xiang Zhang — Department of Geography, McGill University, Montréal, Quebec H3A 0G4, Canada

Brian Robinson — Department of Geography, McGill University, Montréal, Quebec H3A 0G4, Canada

Ellison Carter — Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, Colorado 80523-1019, United States

Complete contact information is available at: <https://pubs.acs.org/10.1021/EHP.6c00053>

Author Contributions

Talia Sternbach: Analysis, Data Curation, Investigation, Software, Writing - Original Draft, Writing - Review & Editing. **Sam Harper:** Analysis, Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing - Original Draft, Writing - Review & Editing. **Xiaoying Li:** Data Curation, Investigation, Project administration, Writing - Review & Editing. **Collin Brehmer:** Data Curation, Investigation, Writing - Review & Editing. **Yuanxun Zhang:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources. **Wenlu Yuan:** Investigation. **Shu Tao:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources. **Kaibing Xue:** Investigation, Writing - Review & Editing. **Kennedy Hirst:** Data Curation, Investigation. **Guofeng Shen:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Writing - Review & Editing. **Christopher Barrington-Leigh:** Conceptualization, Funding acquisition, Data Curation, Investigation, Project administration, Resources, Writing - Review &

Editing. **Xiang Zhang:** Data Curation, Investigation, Software, Writing - Review & Editing. **Brian Robinson:** Conceptualization, Funding acquisition, Data Curation, Investigation, Project administration, Resources, Writing - Review & Editing. **Ellison Carter:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Writing - Review & Editing. **Jill Baumgartner:** Analysis, Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing - Original Draft, Writing - Review & Editing

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank our study participants and field staff for their contributions to this work, as well as the Health Effects Institute (HEI) review and research committees for their valuable feedback. This work was funded by the Canadian Institutes of Health Research (CIHR; 148697, 159477) and the Health Effects Institute (HEI; R-82811201). HEI is jointly funded by the United States Environmental Protection Agency (EPA) and certain motor vehicle and engine manufacturers. The contents of this article do not necessarily reflect the views of HEI, or its sponsors, nor do they necessarily reflect the views and policies of the EPA or motor vehicle and engine manufacturers. The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

REFERENCES

- (1) Bennitt, F. B.; Wozniak, S.; Causey, K.; Spearman, S.; Okereke, C.; Garcia, V.; et al. Global, regional, and national burden of household air pollution, 1990–2021: a systematic analysis for the Global Burden of Disease Study 2021. *Lancet*. **2025**, *405* (10485), 1167–81.
- (2) Chowdhury, S.; Pillarisetti, A.; Oberholzer, A.; Jetter, J.; Mitchell, J.; Cappuccilli, E.; et al. A global review of the state of the evidence of household air pollution's contribution to ambient fine particulate matter and their related health impacts. *Environment International*. **2023**, *173*, No. 107835.
- (3) IEA, IRENA, UNSD, World Bank, WHO. Tracking SDG 7: The Energy Progress Report [Internet]. World Bank, Washington DC, 2024 [cited 2025 May 31]. Available from: <https://trackingsdg7.esmap.org/>.
- (4) Fedak, K. M.; Good, N.; Walker, E. S.; Balmes, J.; Brook, R. D.; Clark, M. L. Acute Effects on Blood Pressure Following Controlled Exposure to Cookstove Air Pollution in the STOVES Study. *JAMA*. **2019**, *8* (14), e012246.
- (5) Johnson, M.; Pillarisetti, A.; Piedrahita, R.; Balakrishnan, K.; Peel, J. L.; Steenland, K. Exposure contrasts of pregnant women during the Household Air Pollution Intervention Network randomized controlled trial. *Environmental Health Perspectives*. **2022**, *130*, 097005 DOI: 10.1101/2021.11.04.21265938.
- (6) Kanagasabai, T.; Xie, W.; Yan, L.; Zhao, L.; Carter, E.; Guo, D.; et al. Household Air Pollution and Blood Pressure, Vascular Damage, and Subclinical Indicators of Cardiovascular Disease in Older Chinese Adults. *American Journal of Hypertension*. **2022**, *35* (2), 121–31.
- (7) Sternbach, T. J.; Harper, S.; Li, X.; Zhang, X.; Carter, E.; Zhang, Y.; et al. Effects of indoor and outdoor temperatures on blood pressure and central hemodynamics in a wintertime longitudinal study of Chinese adults. *Journal of Hypertension*. **2022**, *40* (10), 1950–9.
- (8) Zhang, J.; Smith, K. R. Indoor air pollution: a global health concern. *British Medical Bulletin*. **2003**, *68* (1), 209–25.
- (9) Lai, P. S.; Lam, N. L.; Gallery, B.; Lee, A. G.; Adair-Rohani, H.; Alexander, D.; et al. Household Air Pollution Interventions to Improve Health in Low- and Middle-Income Countries: An Official American Thoracic Society Research Statement. *Am. J. Respir Crit Care Med*. **2024**, *209* (8), 909–27.
- (10) Ezzati, M.; Baumgartner, J. C. Household energy and health: where next for research and practice? *Lancet*. **2017**, *389* (10065), 130–2.
- (11) National Development and Reform Commission of China. Winter Clean Heating Plan for Northern China (2017–2021) [Government Report] [Internet] (in Chinese); Available from: <http://www.gov.cn/xinwen/2017-12/20/S248855/files/7ed7d7cda8984ae39a4e9620a4660c7f.pdf>. [cited 2026 Aug 20].
- (12) Dispersed Coal Management Research Group. China Dispersed Coal Management Report 2023; Peking University Energy Research Institute, 2023 Sep.
- (13) Lee, M.; Chang, J.; Deng, Q.; Hu, P.; Bixby, H.; Harper, S.; et al. Effects of a coal to clean heating policy on acute myocardial infarction in Beijing: a difference-in-differences analysis. *Lancet Planetary Health*. **2024**, *8* (11), e924–32.
- (14) Wen, H.-x.; Nie, P.-y.; Liu, M.; Peng, R.; Guo, T.; Wang, C.; et al. Multi-health effects of clean residential heating: Evidences from rural China's coal-to-gas/electricity project. *Energy for Sustainable Development*. **2023**, *73*, 66–75.
- (15) Li, X.; Brehmer, C.; Hirst, K.; Sternbach, T.; Yuan, W.; Zhang, X.; et al. Multi-year Evaluation of a Clean Heating Policy on Residents' Air Pollution Exposures in Beijing, China. *Environ. Sci. Technol*. **2025**, *59*, 24347.
- (16) Barrington-Leigh, C.; Baumgartner, J.; Carter, E.; Robinson, B. E.; Tao, S.; Zhang, Y. An evaluation of air quality, home heating and well-being under Beijing's programme to eliminate household coal use. *Nat. Energy*. **2019**, *4* (5), 416–23.
- (17) Baumgartner, J.; Harper, S.; Barrington-Leigh, C.; Brehmer, C.; Carter, E. M.; Li, X. et al. How Do Household Energy Transitions Work? [Research Report] [Internet]. Health Effects Institute: Boston, MA; Res. Rep. Health Eff. Inst. **2025 Dec**. Research Report no.: 235. Available from: <https://www.healtheffects.org/publication/how-do-household-energy-interventions-work>.
- (18) Lawrimore, J. H.; Gleason, B. E.; Williams, C. N.; Wuertz, D. B.; Vose, R. S.; Rennie, J. Global Historical Climatology Network - Monthly (GHCN-M), Version 3 [Internet]. NOAA National Centers for Environmental Information; National Centers of Environmental Information **1997** [cited 2025 May 14]. Available from: <https://www.ncdc.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00839> DOI: 10.7289/V5X34VDR.
- (19) Sternbach, T.; Harper, S.; Robinson, B.; Barrington-Leigh, C.; Carter, E.; Baumgartner, J.; et al. Protocols [Internet]. **2020 Apr 23** [cited 2026 May 31]. Available from: <https://osf.io/9hkpq/overview>.
- (20) Li, X.; Baumgartner, J.; Barrington-Leigh, C.; Harper, S.; Robinson, B.; Shen, G.; et al. Socioeconomic and Demographic Associations with Wintertime Air Pollution Exposures at Household, Community, and District Scales in Rural Beijing, China. *Environ. Sci. Technol*. **2022**, *56* (12), 8308–18.
- (21) Lowe, A.; Harrison, W.; El-Aklouk, E.; Ruygrok, P.; Al-Jumaily, A. M. Non-invasive model-based estimation of aortic pulse pressure using suprasystolic brachial pressure waveforms. *J. Biomech*. **2009**, *42* (13), 2111–5.
- (22) Angrist, J. D.; Pischke, J. S. *Mostly Harmless Econometrics: An Empiricist's Companion*; Princeton University Press: Princeton, New Jersey, 2009; p 1.
- (23) Schisterman, E. F.; Cole, S. R.; Platt, R. W. Overadjustment bias and unnecessary adjustment in epidemiologic studies. *Epidemiology*. **2009**, *20* (4), 488–95.
- (24) Zeldow, B.; Hatfield, L. A. Confounding and regression adjustment in difference-in-differences studies. *Health Services Research*. **2021**, *56* (5), 932–41.
- (25) Buuren, S. V.; Groothuis-Oudshoorn, K. *mice*: Multivariate Imputation by Chained Equations in R. *J. Stat Soft.* **2011**; *45*, 1–67 DOI: 10.18637/jss.v045.i03.
- (26) Rubin, D. B. *Multiple Imputation for Nonresponse in Surveys*, 1st ed; Wiley, **1987** [cited 2024 Jun 7]. (Wiley Series in Probability and

Statistics). Available from: <https://onlinelibrary.wiley.com/doi/book/10.1002/9780470316696> DOI: 10.1002/9780470316696.

(27) Goodman-Bacon, A. Difference-in-differences with variation in treatment timing. *Journal of Econometrics*. **2021**, 225 (2), 254–77.

(28) Wooldridge, J. M. Two-Way Fixed Effects, the Two-Way Mundlak Regression, and Difference-in-Differences Estimators. *Empirical Economics* **2025**, 69, 2545–258, DOI: 10.2139/ssrn.3906345.

(29) Goin, D. E.; Riddell, C. A. Comparing Two-way Fixed Effects and New Estimators for Difference-in-Differences: A Simulation Study and Empirical Example. *Epidemiology*. **2023**, 34 (4), 535–43.

(30) Arel-Bundock, V.; Greifer, N.; Heiss, A. How to Interpret Statistical Models Using `marginalEffects` for R and Python. *J. Stat Soft.* **2024**, 111 (9), 1 DOI: 10.18637/jss.v111.i09.

(31) Posit team. RStudio: Integrated Development Environment for R [Internet]; Posit Software, PBC: Boston, MA, 2025; <http://www.posit.co/>.

(32) Bergé, L. R.; Butts, K.; McDermott, G. fixest: A fast and feature-rich framework for econometric estimations in R [Internet]. *arXiv*; 2026 [cited 2026 Jun 1]. Available from: <https://arxiv.org/abs/2601.21749> DOI: 10.48550/ARXIV.2601.21749.

(33) Onakomaiya, D.; Gyamfi, J.; Iwelunmor, J.; Opeyemi, J.; Oluwasanmi, M.; Obiezu-Umeh, C.; et al. Implementation of clean cookstove interventions and its effects on blood pressure in low-income and middle-income countries: systematic review. *BMJ. Open*. **2019**, 9 (5), No. e026517.

(34) Ye, W.; Steenland, K.; Quinn, A.; Liao, J.; Balakrishnan, K.; Rosa, G.; et al. Effects of a Liquefied Petroleum Gas Stove Intervention on Gestational Blood Pressure: Intention-to-Treat and Exposure-Response Findings From the HAPIN Trial. *Hypertension*. **2022**, 79 (8), 1887–98.

(35) Checkley, W.; Williams, K. N.; Kephart, J. L.; Fandiño-Del-Rio, M.; Steenland, N. K.; Gonzales, G. F.; et al. Effects of a Household Air Pollution Intervention with Liquefied Petroleum Gas on Cardiopulmonary Outcomes in Peru. A Randomized Controlled Trial. *Am. J. Respir. Crit. Care Med.* **2021**, 203 (11), 1386–97.

(36) Pillarisetti, A.; Ye, W.; Peel, J. L.; Chang, H.; Underhill, L. J.; Balakrishnan, K.; et al. Household air pollution and blood pressure among adult women participants of the Household Air Pollution Intervention Network Trial: An exposure-response analysis. *Environmental Research*. **2025**, 285, No. 122570.

(37) Zhou, M.; Wang, H.; Zeng, X.; Yin, P.; Zhu, J.; Chen, W.; et al. Mortality, morbidity, and risk factors in China and its provinces, 1990–2017: a systematic analysis for the Global Burden of Disease Study 2017. *Lancet*. **2019**, 394 (10204), 1145–58.

(38) Clark, M. L.; Bachand, A. M.; Heiderscheidt, J. M.; Yoder, S. A.; Luna, B.; Volckens, J.; et al. Impact of a cleaner-burning cookstove intervention on blood pressure in Nicaraguan women. *Indoor Air*. **2013**, 23 (2), 105–14.

(39) Kelly, F. J.; Fussell, J. C. Air pollution and public health: emerging hazards and improved understanding of risk. *Environ. Geochem Health*. **2015**, 37 (4), 631–49.

(40) Hamanaka, R. B.; Mutlu, G. M. Particulate Matter Air Pollution: Effects on the Cardiovascular System. *Front Endocrinol (Lausanne)*. **2018**, 9, 680.

(41) Cuspidi, C.; Ochoa, J. E.; Parati, G. Seasonal variations in blood pressure: a complex phenomenon. *Journal of Hypertension*. **2012**, 30 (7), 1315–20.

(42) Baumgartner, J.; Carter, E.; Schauer, J. J.; Ezzati, M.; Daskalopoulou, S. S.; Valois, M. F.; et al. Household air pollution and measures of blood pressure, arterial stiffness and central haemodynamics. *Heart*. **2018**, 104 (18), 1515–21.

(43) Callaway, B.; Sant'Anna, P. H. C. Difference-in-Differences with multiple time periods. *Journal of Econometrics*. **2021**, 225 (2), 200–30.

(44) Berkouwer, S.; Dean, J. Private Actions in the Presence of Externalities: The Health Impacts of Reducing Air Pollution Peaks but not Ambient Exposure [Internet]; National Bureau of Economic Research, Cambridge, MA. <http://www.nber.org/papers/w31614.pdf>

2023 Sep [cited 2024 Mar 9]. p. w31614. Report no.: w31614. DOI: 10.3386/w31614.

(45) Copas, A. J.; Lewis, J. J.; Thompson, J. A.; Davey, C.; Baio, G.; Hargreaves, J. R. Designing a stepped wedge trial: three main designs, carry-over effects and randomisation approaches. *Trials*. **2015**, 16 (1), 352.

(46) Bui, T. V.; Picone, D. S.; Kosmala, W. P.; Kosowski, M. J.; Zachwyc, J.; Pucci, G.; et al. Validation assessment of a cuff-based central blood pressure device according to Artery Society recommendations. *Blood Pressure Monitoring*. **2025**, 30 (4), 181–6.

(47) Wei, X.; Han, G.; Wang, Q. China's policies: post-COVID-19 challenges for the older population. *Global Health Action*. **2024**, 17 (1), No. 2345968.

(48) Lu, G.; Razum, O.; Jahn, A.; Zhang, Y.; Sutton, B.; Sridhar, D.; et al. COVID-19 in Germany and China: mitigation versus elimination strategy. *Global Health Action*. **2021**, 14 (1), No. 1875601.

(49) Mark, J.; Schuman, M. China's faltering "zero COVID" policy: Politics in command, economy in reverse; **2022**, (cited 2026 May 29) <https://www.atlanticcouncil.org/in-depth-research-reports/report/chinas-faltering-zero-covid-policy-politics-in-command-economy-in-reverse/>. Atlantic Council.

(50) Luo, G.; Guo, Y. Rural electrification in China: A policy and institutional analysis. *Renewable and Sustainable Energy Reviews*. **2013**, 23, 320–329.

(51) Xu, S.; Wang, Y.; Niu, J.; Ma, G. Coal-to-electricity' project is ongoing in north China. *Energy* **2020**, 191, No. 116525.

(52) Carter, E.; Yan, L.; Fu, Y.; Robinson, B.; Kelly, F.; Elliott, P.; et al. Household transitions to clean energy in a multiprovincial cohort study in China. *Nature Sustainability* **2020**, 3 (1), 42–50.

(53) Zhou, M.; Liu, H.; Peng, L.; Qin, Y.; Chen, D.; Zhang, L.; et al. Environmental benefits and household costs of clean heating options in northern China. *Nature Sustainability* **2022**, 5 (4), 329–38.

(54) Beijing Issues the 2018 Work Plan for Clean Winter Heating in Rural Villages. iGreen News [Internet] (in Chinese); 2018 May 18 [cited 2026 Aug 20]. Available from <https://www.igreen.org/index.php?m=content&c=index&a=show&catid=18&id=12641>.

(55) Weng, Z.; Han, E.; Wu, Y.; Shi, L.; Ma, Z.; Liu, T. Environmental and economic impacts of transitioning to cleaner heating in Northern China. *Resources, Conservation and Recycling*. **2021**, 172, No. 105673.

(56) Hao, J.; Qiao, L. Carbon emissions in the building sector: the effect of clean heating policy in China's "2 + 26" cities. *Energy and Buildings*. **2025**, 348, No. 116393.

(57) Uribe, A.; Chávez, C.; Gómez, W.; Jaime, M.; Bluffstone, R. Private benefits from ambient air pollution reduction policies: Evidence from the household heating stove replacement program in Chile. *Energy for Sustainable Development*. **2023**, 77, No. 101323.