Supporting Information

Health benefits and costs of clean heating renovation: An integrated assessment in a major Chinese city

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1. Details of the household energy survey

We applied the following procedure to ensure the representativeness of our survey sample for studying the winter heating renovation that has been rolled out in North China in recent years and is planned to continue in the years to come (i.e., the next five to ten years). Our budget allowed us to survey no more than three thousand households (or less than 375 villages if we interviewed eight households in each village) in the Linfen prefecture-level city. We leveraged one key variable, population density, which is highly correlated with the cost of renovation (and hence, the propensity of receiving renovation sooner), as a threshold to create our study sample. This is because villages with high population density are usually close to the existing infrastructure, reducing the cost of utility network extension, whereas townships with too sparse population would be too costly to implement the renovation. Since population density data were only available at the township level (the lowest administrative level in China), we used a population density threshold (184 km^{-2}) to identify rural towns (*xiangzhen* in Chinese) in North China that are likely to be prioritized for renovation. Areas above this threshold cover 70% of the rural population in North China, consistent with the overall goal of the renovation. Out of 151 towns in Linfen, 67 towns are above the threshold, constituting 72% of Linfen's total rural population (3.6 million). The average population density of sampled towns in Linfen is 527 km^{-2}, comparable to 595 km^{-2} for the average value in North China. Eighty-five percent of Linfen's villages that had renovation by the end of 2018 are in these towns. We then acquired a full list of villages in the 67 towns and randomly selected 345 villages to survey (the number of villages that we sample from a given town is calculated by dividing the town population by 75,000). In the selection procedure, we put a double weight on the villages that have already been renovated, because only 28% of the villages were renovated by the end of 2018 and we needed a sufficient sample size of renovated households to study the cost of completed renovation.

We successfully visited 338 out of 345 villages and surveyed 2,660 households (7.87 households per village on average, close to the planned eight households per village) in two rounds (first round: 328 households in December 2018; second round: 2,332 households in February 2019). We further surveyed 210 households when conducting household exposure measurements in early March. Among all the 2,870 surveyed households, 21 households were not willing or able to provide certain key information, e.g., renovation status and heating equipment type, and 88 households claimed that they completed renovation without government support before 2017, leaving 2,761 valid sample households (96%) for our study.

We recruited 60 local university students as enumerators and organized a training workshop with a mock survey section before starting the survey. To gain trust and solicit real information from surveyed households, we encouraged the enumerators to use local dialect during the interview and explained that the survey was anonymous for a pure research project, so the interviewees should respond truthfully and not worry that their identity would be revealed or their opinions would affect any local policy changes in the future. During the interview, we required the enumerator to verify whether the key information about heating and cooking equipment in use (e.g., type, size, and location) was consistent with the description by the interviewee. The indoor and outdoor temperature and humidity were also recorded by the enumerator.

2. Supplementary information of air pollutant emissions

As described in the main text, we use the 2017 anthropogenic emission inventory developed by Tsinghua University School of Environment[1-3] except for the household sector in Linfen, for which the emissions before and after renovation are updated using the household energy consumption obtained from our survey (Figure S1). Due to the limitation of resources, we did not measure the emission factors in this area but used the existing emission factors in the Tsinghua University School of Environment inventory[1-3]. Note that the SO_2 emission factors from coal stove vary with region-specific sulfur content, which to some extent captures local characteristics in the region of interest. Local measurements of emission factors in future studies could enable a more accurate assessment of the emission reduction caused by the renovation. In our inventory, the NO_x emission factors for residential coal stove, biomass stove, and natural gas stove are 90 g/GJ, 79 g/GJ, and 37 g/GJ, respectively[1, 4]. This means that natural gas stove has a lower emission factor than coal and biomass stoves. We also examined the emission factors used in two widely used databases, the AP-42 emission factor database[5] developed by U.S. Environmental Protection Agency, and the Greenhouse gas – Air pollution Interactions and Synergies Asia (GAINS-Asia) model[6] developed by the International Institute for Applied Systems Analysis (IIASA). In AP-42, the NO_x emission factors for residential coal stove, biomass stove, and natural gas stove are 193 g/GJ, 90 g/GJ, and 39 g/GJ, respectively, and the corresponding values in GAINS-Asia are 100 g/GJ, 72 g/GJ, and 23 g/GJ, respectively. Besides these widely used databases, Cai et al.[7] summarized the emission factors for coal and biomass stoves used in many other studies in China and found that the emission factors for coal stove range between 31 and 126 g/GJ (86 g/GJ on average) while those for biomass stove range between 49 and 176 g/GJ (118 g/GJ on average). Traynor et al.[8] summarized the emission measurements of a series of residential natural gas appliances and found that the NO_x emission factors range between 26 and 53 g/GJ (42 g/GJ on average). Based on the above data, we conclude that the emission factor of natural gas stove is most likely lower than those of coal or biomass stoves. Note that all these emission factors are based on the heat value of fuels. Considering that natural gas stove usually has a higher thermal efficiency than coal and biomass stoves, the replacement of coal or biomass with natural gas may bring an even larger fractional reduction in NO_x emissions than that expected from the difference in emission factors.

We estimate the emission increase from power plants due to the electricity renovation based on the increased electricity usage obtained in our survey. We assume that the additional electricity is generated locally in Linfen. Considering a transmission loss of 6.5%, the average rate in 2017[9], the increase of electricity generation due to the projected electricity renovation accounts for 14% of the 2017 total electricity generation in Linfen. For the added power generation capacity, the power mix (96.7% electricity from coal-fired power plants[10]) and emission factors[1, 2] are assumed to be the same as the average levels in Linfen. Our estimate shows that the increase of any air pollutant emissions due to the increased power generation represents less than 1.5% of the total emissions in Linfen.

Figure S3 shows air pollutant emissions in Linfen before and after the renovation. The emissions from projected natural gas renovation and electricity renovation are generally similar, though there are certain small differences. The main reason is that the emission increases due to either natural gas combustion in the gas renovation scenario or power generation in the electricity renovation scenario are usually much smaller than the emission reductions due to the elimination of solid fuels. Specifically, for gas renovation, the emissions of $PM_{2.5}$, SO_2, and NMVOCs from natural gas combustion are negligible compared with those from solid-fuel use. The NO_x emissions from natural gas combustion could account for about 30% of those from solid-fuel use (this has accounted for the effect of lower emission factor and high energy efficiency of natural gas combustion), but the resulting difference in total NO_x emissions between gas and electricity renovation is small since household-fuel use constitutes only less than 10% of the total NO_x emissions. For electricity renovation, the emission increase of any air pollutant due to increased power generation represents less than 1.5% of the total emissions in Linfen. As a result, the air pollutant emissions after the renovation are quite similar regardless of the selected technology pathway.

3. Configuration and evaluation of the CMAQ simulations

As described in the main text, we use the Community Multiscale Air Quality Model (CMAQ) configured with the Two-Dimensional Volatility Basis Set (2D-VBS) to simulate the ambient $PM_{2.5}$ concentrations before and after the heating renovation. It is noted that, while the heating renovation only rolled out in rural areas and hence our survey was only conducted in the countryside, the renovation changes the emissions of air pollutants which affect the $PM_{2.5}$ concentrations in both urban and rural areas through atmospheric transport and diffusion. The CMAQ model thus captures the changes in $PM_{2.5}$ concentrations in both urban and rural areas. This version of CMAQ model we use was developed in our previous study[11] by incorporating the 2D-VBS model framework into the default CMAQ model. Compared with the default CMAQ, this version explicitly simulates aging of secondary organic aerosol (SOA) formed from non-methane volatile organic compounds (NMVOCs), aging of primary organic aerosol (POA), and photooxidation of intermediate-volatility organic compounds (IVOCs), thereby significantly improving the simulation results of organic aerosol (OA), particularly SOA. We use the SAPRC99 gas-phase chemistry module and the AERO6 aerosol module except that the treatment of OA is replaced with the 2D-VBS framework. The aerosol thermodynamics is based on ISORROPIA-II. The chemical initial and boundary conditions for Domain 1 are kept constant as the model default profile, and those for Domains 2 and 3 are extracted from the outputs of their immediate outer domains. A 5-day spin-up period is used to reduce the influence of initial conditions on modeling results. The biogenic emissions are calculated online using the Model of Emissions of Gases and

Aerosols from Nature (MEGAN)[12]. The Weather Research and Forecasting Model (WRF, version 3.7) is used to generate the meteorological fields. The meteorological initial and boundary conditions are generated from the Final Operational Global Analysis data (ds083.2) of the National Center for Environmental Prediction (NCEP) at a 1.0º×1.0º and 6-h resolution. The NCEP's Automated Data Processing (ADP) data (ds351.0 and ds461.0) are used in objective analysis (i.e., grid nudging). The physical options and vertical resolution of WRF and CMAQ are the same as Zhao et al.[13].

We compare the meteorological predictions with observational data obtained from the National Climatic Data Center (NCDC), where hourly or 3-hour observations of wind speed at 10 m (WS10), temperature at 2 m (T2), and water vapor mixing ratio at 2 m (Q2) are available for surface meteorological sites. We apply a number of statistical indices to quantitatively evaluate the model performance, as summarized in Supplementary Table 3. These indices include mean observation (Mean OBS), mean simulation (Mean SIM), mean bias (MB), gross error (GE), root mean square error (RMSE), systematic RMSE (sys RMSE), unsystematic RMSE (unsys RMSE), and index of agreement (IOA), which are defined in Emery et al.[14]. In general, the model predictions agree fairly well with surface meteorological observations. The performance statistics for WS10, T2, and Q2 are all within the benchmark ranges proposed by Emery et al.[14] except that the MB and GE of summertime Q2 (-1.18 and 2.18 g kg^{-1}) slightly exceed the benchmarks ($\leq \pm 1$ and ≤ 2 g kg^{-1}).

We evaluate simulated concentrations of $PM_{2.5}$, SO_2, NO_2, and O_3 using surface observations from the Ministry of Ecology and Environment of China (MEE) obtained through a repository website (http://beijingair.sinaapp.com). There are 117 sites in 2017 within the innermost modeling domain (Domain 3), which are used for model evaluation. Statistics of model performance are summarized in Supplementary Table 4. The statistical indices used include Mean OBS, Mean SIM, normalized mean bias (NMB), normalized mean error (NME), mean fractional bias (MFB), and mean fractional error (MFE), as documented in previous studies[15, 16]. The CMAQ-simulated $PM_{2.5}$ concentrations agree reasonably well with observations, with an annual NMB of −0.4% and seasonal NMBs within ±30%. The performance statistics for $PM_{2.5}$ generally meet the model performance goal (i.e., MFB within ±30% and MFE ≤ 50%) proposed by Boylan and Russell[16], indicating an overall good model-measurement agreement.

Regarding the chemical compositions of $PM_{2.5}$, we do not have access to observational data within the inner modeling domain during the simulation period. However, in a recent study[3] we compared simulation results based on exactly the same model configurations with $PM_{2.5}$ composition observations in Beijing (which is located in the outer domain) during the same simulation period and showed reasonably good model-measurement agreement. We also compared simulation results based on the same configurations with composition observations at more sites across China during 2010 and 2011 and further demonstrated the reliability of the model in simulating $PM_{2.5}$ compositions[11].

4. Details of the household $PM_{2.5}$ measurements

The measurements were carried out according to the following procedures. The enumerator first explained the instructions and requirements for participating in our research, and the participant had to read and sign the consent form before the measurement. The enumerator then turned on the wearable $PM_{2.5}$ sensor and recorded the outdoor $PM_{2.5}$ concentration. The participant was then required to wear the sensor (or keep the sensor beside his/her bed during sleep) in the next 24 hours and record the time intervals they were located in each of eight microenvironments (i.e., outdoor, outside kitchen, inside kitchen, living room, bedroom, outside bathroom, inside bathroom, and other indoor). In the next day, the enumerator returned to the surveyed household and again recorded the outdoor $PM_{2.5}$ concentration.

We conducted measurements in 210 households in the 2019 winter (early March), and the participants in 188 of them followed our instructions closely and generated valid $PM_{2.5}$ data. We successfully paid back-visits and collected valid $PM_{2.5}$ measurements in the 2019 summer (mid-August) from 138 households. We monitored the $PM_{2.5}$ exposure concentrations using the Oneair CP-15-A4 sensor—a small, lightweight, and portable sensor based on light scattering technique (see Liu et al.[17] for more details). It measures $PM_{2.5}$ concentrations in real-time and records data every minute. We carefully calibrated the sensors before being used to measure $PM_{2.5}$ mass concentrations, as detailed below. After each sampling, we exported the data to a computer and checked and recharged the instruments before the next measurement.

We calculate the daily average exposure concentration of each participant from time-resolved $PM_{2.5}$ concentration measurements for 24 hours and estimate the mean exposure concentration in winter and summer for each population group (Figure 2). We attribute the time-resolved $PM_{2.5}$ exposure concentrations to different microenvironments based on the time-activity pattern recorded by the participants during the tests to arrive at exposure concentrations that take into account the time spent in different microenvironments. For calculation of HAP_k, we subtract the ambient concentrations from the concentrations in all microenvironments (see Eq. 1 and explanations). We estimate the HAP_k for three population groups, including those using clean energy for both heating and cooking, those using solid fuels for heating but clean energy for cooking, and those using solid fuels for both heating and cooking. Very few households use solid fuels for cooking but clean energy for heating according to our survey, thus such households are included in the category that uses solid fuels for both heating and cooking. We estimate annual mean HAP_k based on winter (heating season) and summer (non-heating season) values by assuming that the heating season lasts five months a year.

We do the calibration of the Oneair CP-15-A4 sensor in the following two steps. First, we challenge all 40 sensors used in this study with laboratory-generated particles with a concentration increasing gradually from about 20 to 700 μg m^{-3}. The results indicate that the measured concentrations by different sensors have a strong linear correlation, with a correlation coefficient larger than 0.985 between any two sensors, indicating good stability of the sensors. We calculate the relative scale factors between different sensors. We then sort all sensors according to their average measured concentrations and select seven sensors with concentrations falling in the 8th, 22th, 36th, 50th, 64th, 78th, and 92nd percentiles. In the second step, we use the seven selected sensors to measure ambient $PM_{2.5}$ concentrations for 11 days next to a state-controlled monitoring site in Linfen. The state-controlled site monitors $PM_{2.5}$ concentrations with a scientific Tapered Element Oscillating Microbalance (TEOM), a U.S. Environmental Protection Agency-approved instrument, and releases hourly concentrations to the public in real-time. We compare the $PM_{2.5}$ concentrations measured by our sensors and the state-controlled site and find that the correlation coefficient between the measurements of any sensor and the state-controlled site is larger than 0.83. We then calculate the calibration factors for the seven sensors by using the state-controlled site as a reference and use these factors to correct the measurements of the seven sensors. Figure S5 shows that the sensor measurements after calibration agree very well with those of the state-controlled site. Finally, we combine the calibration factors of the seven sensors with the relative scale factors of all sensors derived in the first step to obtain calibration factors for all sensors, which are subsequently applied to correct the $PM_{2.5}$ exposure measurements in this study.

5. Details of the health impact analysis

$PM_{2.5}$ and ozone are the most prominent pollutants that have been quantitatively associated with premature deaths[18, 19], though adverse health effects have also been reported for other pollutants[20, 21]. Most studies have shown that the premature deaths attributed to O_3 exposure are much fewer than those attributed to $PM_{2.5}$[22-24]. For example, the Global Burden of Diseases, Injuries, and Risk Factors Study 2015[22] shows that the premature deaths due to ambient O_3 account for only 6% of those due to ambient $PM_{2.5}$. Besides, compared with O_3, the health impact of $PM_{2.5}$ is more affected by heating renovation since household-fuel use has large emissions of primary $PM_{2.5}$ (Figure S3) and often dominates indoor $PM_{2.5}$ concentrations. For these reasons, we focus on the health impact of $PM_{2.5}$ in this study. We estimate premature deaths caused by long-term $PM_{2.5}$ exposure before and after renovation based on relative risks of mortality, baseline mortality rates, and population[22, 25]. We calculate the relative risks of mortality as a function of IPWE using the age and sex-specific IER functions developed by Cohen et al.[22], which is an updated version of Burnett et al.[25]. The IER functions were constructed by combining risk estimates from studies of AAP, HAP, and active and second-hand smoking that cover a full $PM_{2.5}$ exposure concentration range from very small to about 30000 mg m^{-3} in many different countries across the world. Therefore, they are suitable for calculating the overall health risks due to both AAP and HAP[22, 25]. The IER functions assume that the health impacts of $PM_{2.5}$ depend only on the inhaled amount of $PM_{2.5}$ and are independent of the chemical composition, which appears reasonable in view of the available quantitative epidemiological studies.[22, 25, 26] However, some studies have reported that the carbonaceous aerosols could be more toxic than other aerosol species.[23, 27] Since carbonaceous aerosols (BC and POA) account for most of the $PM_{2.5}$ emissions from household-fuel use while contributing only about 27% of $PM_{2.5}$ emissions from non-household sources, assuming carbonaceous aerosols being more toxic could result in a larger health benefit of the renovation, as compared to our current results. Nevertheless, this will not change our key conclusion that the heating renovation brings a larger monetized health benefit than the renovation cost. We consider five health endpoints, including ischaemic heart disease, stroke, bronchus and lung cancer, chronic obstructive pulmonary diseases for adults, and lower respiratory infections for children and adults. We obtain the provincial-level disease-specific baseline mortality rates by age and gender from the Institute of Health Metrics and Evaluation[28].

We monetize mortality cases using the values of a statistical life (VSL). Three approaches are typically used in the literature to obtain a VSL estimate for a developing country: scaling, meta-analysis, and direct estimation[29]. Previous studies have obtained a wide range of Chinese VSL values for health risks from air pollution[30-34]. Deriving the VSL based on direct estimation, e.g., domestic survey, is ideal. However, some studies were conducted many years ago and may not reflect people’s current willingness to pay for reducing health risks. To partly address this issue, Aunan et al.[33] reviewed relevant domestic surveys on Chinese VSL and reported the Chinese VSL as a ratio to annual earning, which ranges between 50 and 150 in most studies. We follow their findings and assume a normal distribution for the VSL with a mean of 100 times of annual earning (7.1 million CNY in 2019) and a 95% confidence interval covering 50 to 150 times of annual earning (3.5 to 10.6 million CNY). We have also noticed some VSL estimates adopted in recent studies are also based on earlier domestic surveys. We compared our results with their values and found those values comparable. For example, Liang et al.[35] refer to a VSL based on Chinese survey conducted in 2004[36], which corresponds to a 2019 VSL of 3.8 million CNY with an income elasticity of 1. Li et al.[37] refer to a VSL based on another Chinese survey conducted in 2000[38], which corresponds to a 2019 VSL of 7.1 million CNY with an income elasticity of 1. Finally, we find that the value (5.1 million CNY in 2019) estimated in a recent study based on interviews in six representative cities[39] is also in the same order of magnitude as ours.

Since we do not set an exact timeline for the completion of the heating renovation, we ignore the future increase in VSL due to income growth or the discount of VSL due to the delay of chronic disease onset. Therefore, our health benefit estimates can be more accurately interpreted as the benefits that the household would enjoy had the heating renovation been accomplished. Note that we do not include the monetized benefits due to avoided morbidity (e.g., respiratory and cardiovascular diseases and workday losses) as mortality usually accounts for about 80% of the total monetized health impacts in China[40, 41]. Inclusion of the morbidity impacts would increase the estimated benefit-to-cost ratios to some extent.

6. Uncertainty analysis

We calculate uncertainties in the integrated population-weighted exposure to $PM_{2.5}$ (IPWE), the health impacts, and the benefit-to-cost ratios using 50,000 Monte Carlo runs based on uncertainties associated with the input data, including household energy consumption, size of the population using solid fuels for heating/cooking, household exposure concentrations, integrated exposure-response (IER) functions, value of a statistical life (VSL), and renovation costs. The household energy consumption is assumed to follow a normal distribution, and the uncertainty range is derived from statistical analyses of our survey data. The resulting uncertainty in the AAP exposure simulated by the CMAQ model is estimated by performing a number of sensitivity simulations with perturbed household fuel consumption. The uncertainties in activity data of non-household sources, the emission factors, as well as the model schemes are not considered because they are not supposed to be major factors affecting the impact of heating renovation on $PM_{2.5}$ exposure and public health.

The size of the population using solid fuels for heating/cooking and the renovation costs are also assumed to follow normal distributions with uncertainty range achieved from statistical analyses of the survey data. The uncertainty in mean household exposure concentrations of each population group (i.e., HAP_k in Eq. 2 of Methods) is estimated using our $PM_{2.5}$ exposure measurements in Linfen and is shown in Figure 2. Regarding the IER functions, Cohen et al.[22] provided 1,000 sets of IER parameters for each health endpoint. In each of the 50,000 Monte Carlo runs, a set of IER parameter is randomly chosen together with other randomly sampled inputs from their respective probability distributions. The uncertainty in VSL is determined by summarizing values reported in the literature, as described in Methods. The Monte Carlo simulation results constitute the probability distributions of the IPWE, premature deaths, and benefit-to-cost ratios, from which the 95% confidence intervals are derived.

7. Impact of future natural gas/electricity renovation

The households that have already received heating renovation possess different characteristics from those that are not yet renovated. Specifically, villages that have completed clean heating renovation are usually in closer proximity to the urban area and more densely populated. Average income, living area, and household size for heating of renovated households are significantly higher compared to unrenovated households. In contrast, coal consumption for heating of renovated households (before the renovation) is significantly lower because more clean fuels are used (see Supplementary Table 1). Therefore, the costs and benefits of clean heating renovation might also be different for these two types of households. Hence, we apply the propensity score matching (PSM) method and match each unrenovated household with a renovated one of similar characteristics. By assuming the impact of a future renovation on an unrenovated household is equal to the "treatment effect" of renovation on its matched renovated household, we can obtain more reasonable estimates for expected costs and benefits of the future renovation.

The propensity score is defined as the conditional probability of receiving a treatment given pre-treatment characteristics[42]. As discussed above, this probability is also correlated with the costs and benefits of receiving the "treatment" (clean heating renovation). We use key household characteristics, including income, size of family, heating areas, and energy consumption for winter heating, as matching covariates in a classic logit model to estimate the propensity score[43]:

$$p_i(X_n) = P\left(D_{i,n} = 1 \middle| X_n\right) = \frac{\exp(\beta X_n)}{1+\exp(\beta X_n)} \qquad (6)$$

where X_n is the covariate vector of characteristics of household n; $D_{i,n}$ is the indicator of receiving type i renovation by the end of 2018, which equals 1 for renovated households with natural gas or electricity and 0 for unrenovated households; β is the estimated coefficient for each covariate.

With the propensity score $p_i(X_n)$ estimated, we then use the nearest-neighbor matching method[44] to search the most similar renovated household $m(i)$ for each unrenovated household n and apply the surveyed information (usage time, energy consumption, and cost of heating/cooking equipment and energy after the renovation) of household $m(i)$ to household n, where $m(i) = \text{argmin}\|p_i(X_m) - p_i(X_n)\|$. Furthermore, to avoid matched pairs with large difference in the propensity score, we set a radius ($r = 0.05$) and require that the propensity score of matched renovated household should fall within the radius from the propensity score of the unrenovated household.

Under the policy scenario of future renovation with natural gas (electricity), 1,374 (1,348) out of 1,640 unrenovated households are matched successfully with a household that had natural gas renovation before the end of 2018. 256 unrenovated households are not matched due to missing value in covariates, and 10 (36) unrenovated households are not matched for not satisfying the radius requirement. Figure S6 shows the pre- and post-matching kernel density functions of unrenovated and renovated households under two policy scenarios. Kernel density functions of two groups of households are closer after matching, indicating that unrenovated households are matched with similar renovated households.

8. Changes in chemical compositions of ambient $PM_{2.5}$

Figure S7 illustrates the compositions of ambient $PM_{2.5}$ before and after the renovation in Linfen. Among all components, the concentrations of elemental carbon (EC) and primary organic aerosol (POA) exhibit the largest decrease after the completed renovation (16–18%) and the projected renovation by natural gas or electricity (45–51%), relative to the levels before the renovation. This is because 1) the emissions of black carbon (BC) and POA are most reduced among all pollutants since most of these emissions originate from household solid-fuel combustion (Figure S3), and 2) the EC and POA concentrations are more affected by local emissions in Linfen and less affected by regional transport, as compared to secondary $PM_{2.5}$ components. Besides, secondary organic aerosol (SOA) and sulfate experience a moderate decrease of about 3% after the completed renovation and 10–11% after the projected renovation, owing to the emission reductions of various SOA precursors (VOC, POA, and intermediate volatility organic compounds) and SO_2. The other $PM_{2.5}$ components (nitrate and “Others”) change only slightly due to relatively small emission reductions in these components or their precursors. As a result of the above concentration changes, the relative fractions of EC and POA decrease while those of nitrate and “Others” increase after the completed or projected renovation.

9. Questionnaire of the Implementation of the Clean Heating Renovation

Dear interviewee:

We are investigators from the research team to study the implementation of the clean heating renovation, organized by researchers at Tsinghua University and Beijing Normal University. Following a random sampling process, we have chosen you as an interviewee. Your support is crucial for us to understand the implementation of the clean heating renovation and provide recommendations for future policy designs.

There is no single right answer to any of the questions in this survey. You only need to provide real information based on your personal experience. The interview will take about half an hour. We will keep your personal information and answers strictly confidential and only conduct statistical analyses without revealing any of your personal information. Please feel free to ask any questions during the interview.

Thank you very much for your cooperation!

Basic Information:

Investigator name: ____________ Investigator code: ____________

Village name: ________________ Village code: ____________

Householder name: _______ Street number: ________ Telephone number： _______

Indoor temperature: _________ Outdoor temperature: __________

Indoor humidity: _________ Outdoor humidity: __________

House type:

☐ multi-storey apartment ☐ multi-storey house

☐ single-storey house ☐others, please indicate ____________;

Your house has ______ floor(s) and ______ room(s), with a total living area of ______ square meters.

Your house was built in year _____, and the original living area is ____ square meters.

If it was expanded, the expansion was completed in year _____, and the expanded living area is ____ square meters.

Before the clean heating renovation, there are ___ rooms and a total area of ___ square meters with heating, and after the clean heating renovation, there are (would be) ___ rooms and a total area of ___ square meters with heating.

Exterior wall of your house:
☐solid clay brick ☐sintered hollow brick ☐solid cement brick
☐hollow cement brick ☐clay cave dwelling ☐brick cave dwelling
Any insulation measures for the exterior wall?
☐none, never considered
☐none, considered but not adopted because ________________________
☐yes, the measures are______________, completed in year _______ and cost _________yuan

Doors and windows of your house:
☐wooden doors and windows ☐aluminum-alloy doors and windows
☐others, please indicate _________________________

Any insulation measures for doors and windows?
☐none, never considered
☐none, considered but not adopted because ______________________
☐Yes, the measures are: ☐double glass ☐insulation curtain ☐others, please indicate _________, completed in year_______ and cost _________yuan

Roof of your house:
☐tile roof ☐flat roof ☐others, please indicate _________________________

Any insulation measures for the roof?
☐none, never considered
☐none, considered but not adopted because ________________________
☐Yes, the measures are: ☐insulation film / plastic ☐soil cushion ☐soil cushion with brick top ☐others, please indicate __________, completed in year _______ and cost _________yuan

Family assets and appliances:

__ cars __ scooters __ motorcycles __ electric bicycles __ tractors

__ TVs __ refrigerators __ washing machines __ air conditioners __ computers

The monthly electricity fee in spring and fall is ____ yuan on average, and the monthly electricity fee in summer is ____ yuan on average.

Annual net family income is ______ (in ten thousand yuan, to one decimal place) on average, including ________ (in ten thousand yuan) transfer from non-resident family members.

Is the income of your family stable?

☐ yes, relatively stable

☐not stable, the annual income is about ___ (in ten thousand yuan) at good times, or about ____ (in ten thousand yuan) at bad times.

I. Information on the heating and cooking/hot water equipment before and after the renovation

Note: Heating equipment ID shall be filled following the order of 1, 2, …; Heating equipment type includes [A traditional stove (without chimney); B traditional stove (with chimney); C improved stove; D heatable brick bed; E gas heater; F gas boiler (in the village); G heat pump (at home); H heat pump (centralized); I electric heating furnace; J electric heater; K electric blanket; L geothermal heating; M other (please indicate); N district heating (industrial waste heat); O district heating (other)]; Fuel type includes [A bulk coal; B honeycomb briquette; C straw/corn cob; D firewood; E liquefied petroleum gas (LPG); F natural gas; G coal gas (including coalbed methane); H biogas; I electricity; J geothermal; K other (please indicate); L district heating]; Equipment location includes: [A outdoor; B independent kitchen; C in-house kitchen; D bathroom outside the house; E in-house bathroom; F living room; G bedroom (including dual-use living room and bedroom); H other (please indicate)]; For fuel consumption, please fill in how many tons per year for coal, how many m^3 per year for gas, how many tanks for liquefied gas, how many kWh per year for electricity, and leave the district heating blank. If the energy consumption of certain equipment cannot be estimated, please provide an estimate for the total consumption at the end of the form.

Cooking/hot water equipment ID shall be filled following the order of 1, 2,... (if a certain equipment is used for both heating and cooking/hot water, please make a mark and use the same equipment ID); The equipment type includes [A traditional stove (without chimney); B traditional stove (with chimney); C improved stove; D LPG stove; E natural gas stove; F coal gas stove; G biogas stove; H electric rice cooker; I induction cooker; J gas water heater; K electric water heater; L solar water heater; M other (please indicate)]; Fuel type includes [A bulk coal; B honeycomb briquette; C straw/corn cob; D firewood; E LPG; F natural gas; G coal gas (including coalbed methane); H biogas; I electricity; J geothermal; K solar energy; L other (please indicate)]; Equipment location includes [A outdoor; B independent kitchen outside the house; C in-house kitchen; D bathroom outside the house; E in-house bathroom; F living room; G bedroom (including dual-use living room and bedroom); H other (please indicate)]; Fuel consumption: please fill in how many tons per year for coal, how many m^3 per year for gas, how many tanks for liquefied gas, how many kWh per year for electricity. If the energy consumption of certain equipment cannot be estimated, please provide an estimate for the total consumption at the end of the form.

Equipment ID	**Heating equipment type**	**Fuel type**	**Location**	**Years in use**	**Frequency of use**		**Fuel consumption (in physical unit) and expense (yuan)**			
					Before renovation	After renovation (only for renovated households)	Before renovation		After renovation (only for renovated households)	
					___months every year;	___months every year;				
					___hours every day	___hours every day				
					___months every year;	___months every year;				
					___hours every day	___hours every day				
					___months every year;	___months every year;				
					___hours every day	___hours every day				
					___months every year;	___months every year;				
					___hours every day	___hours every day				
Equipment ID	**Cooking/ hot water equipment type**	**Fuel type**	**Location**	**Years in use**	**Frequency of use**		**Fuel consumption (in physical unit) and expense (yuan)**			
					Before renovation	After renovation (only for renovated households)	Before renovation		After renovation (only for renovated households)	
					___months every year;	___months every year;				
					___hours every day	___hours every day				
					___months every year;	___months every year;				
					___hours every day	___hours every day				
					___months every year;	___months every year;				
					___hours every day	___hours every day				
					___months every year;	___months every year;				
					___hours every day	___hours every day				
Total fuel consumption for heating and cooking/hot water										

II. Clean Heating Renovation Status

1. Has your house completed the clean heating renovation?

☐ Yes, the renovation type is

A☐ coal to natural gas	
B☐ coal to electricity	
C☐ district heating	C1☐ Industrial waste heat C2☐ Thermal (coal) district heating

The renovation started in _______ (month) ______ (year);

The renovation completed in _______ (month) ______ (year)

☐ No，

☐ Other households in our village had a renovation, but my family chose not to.

☐ Renovation is planned (gas/electricity/district heating) to start in year _______

☐ We do not think the renovation will start in the near future.

2. Please provide an overall evaluation of the following heating measures considering comfort, usage cost, convenience, and cleanness：

Overall evaluation	Very bad	Bad	General	Good	Very Good
Heating measure before the renovation: bulk coal/firewood/others（_____）	1	2	3	4	5
Heating measure after the renovation: electricity/natural gas/clean coal/district heating	1	2	3	4	5

3. What is your attitude towards the clean heating renovation：

	Very unsupportive	Unsupportive	Neutral	Supportive	Very supportive	No idea
Coal to natural gas	1	2	3	4	5	
Coal to electricity	1	2	3	4	5	
District heating	1	2	3	4	5	

If you choose "Very unsupportive" or "Unsupportive", please provide your reasons (multiple choices are allowed here):

☐ Do not live in this house for the whole winter

☐ Do not think the renovation is effective as better renovation option is available

☐ One-time cost of renovation is too high

☐ Increased usage cost is too high
☐ Traditional heating measures are more comfortable
☐ Unwilling to change for now and leave the decision later while observing feedback from others
☐Other reason________________

For renovated households

4A. What do you think the comfort of heating after the renovation ☐significantly improved ☐slightly improved ☐no change ☐slightly decreased ☐significantly decreased

Average room temperature before the renovation: ___ centigrade, average room temperature after the renovation: ____ centigrade

5A. What do you think the convenience of heating equipment use (e.g., labor input) after the renovation?

☐significantly improved ☐slightly improved
☐no change ☐slightly decreased ☐significantly decreased

6A. What do you think about the indoor air quality in winter than that in other seasons before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

What do you think about the outdoor air quality in winter than that in other seasons before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

7A. What do you think about your health condition in winter than that in other seasons before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

Do you think coal or firewood are harmful to the health of you and your family?

___ (1-No harm, 2-Little harm, 3-Some harm, 4-Much harm, 5-Great harm)

Do you see a doctor and buy medicine for respiratory diseases more often in winter?

☐Yes, the average medical cost is ______yuan ☐No

8A. What do you think about the indoor air quality in winter after the renovation than that before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

What do you think about your health condition in winter after the renovation than that before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

9A. Renovation expenses (unit: yuan; heating equipment expenses refer to the out-of-pocket expenses for the equipment, such as electric heaters, gas heating stoves, and radiators; network connecting expenses refer to out-of-pocket expenses for connecting to as the main natural gas or grid network; subsidy refers to the subsidy for renovation expenses specifically, excluding subsidies for the usage, asked below)

Equipment ID	Out-of-pocket expenses	Heating equipment expenses	Network connecting expenses	Do you receive subsidies from the government?	Amount of subsidy

10A. Do you feel a budget constraint for the renovation?

☐Yes ☐No.

If so, how did you raise the money for the renovation?

☐borrowing money from relatives and friends

☐public funding from the village

☐ peer-to-peer loans ☐ default ☐ other approaches: ____

11A. Expected usage cost during the heating season (your estimation for the next year):

Fuel cost (gas): Unit price:_______, annual usage: ______, total cost:_______,

Do you receive subsidies from the government? ☐Yes, _____ yuan ☐No

Fuel cost (electricity): Unit price:_______, annual usage: ______, total cost:_______,

Do you receive subsidies from the government? ☐Yes, _____ yuan ☐No

12A. Do you think the usage cost is acceptable?

☐perfectly acceptable ☐acceptable ☐unacceptable ☐very unacceptable

13A. Compared to the heating using coal or firewood, **if the indoor temperature is kept the same,** you can accept an increase in usage expense of ____ yuan per year for the clean heating.

14A. If you could have a chance to reverse the renovation, will you choose to reverse?

☐ Yes ☐No

For unrenovated households or households being renovated

4B. What do you expect the comfort of heating after the renovation?

☐significantly improved ☐slightly improved ☐no change
☐slightly decreased ☐significantly decreased

Average room temperature now:
___ centigrade, expected average room temperature after the renovation: ____ centigrade

5B. What do you expect the convenience of heating equipment use (e.g., labor input) after the renovation?

☐significantly improved ☐slightly improved ☐no change
☐slightly decreased ☐significantly decreased

6B. What do you think about the indoor air quality in winter than that in other seasons before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

What do you think about the outdoor air quality in winter than that in other seasons before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

7B. What do you think about your health condition in winter than that in other seasons before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

Do you think coal or firewood are harmful to the health of you and your family?

___ (1-No harm, 2-Little harm, 3-Some harm, 4-Much harm, 5-Great harm)

Do you see a doctor and buy medicine for respiratory diseases more often in winter?

☐Yes, the average medical cost is ______yuan ☐No

8B. What do you expect the indoor air quality in winter after the renovation than that before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

What do you expect your health condition in winter after the renovation than that before the renovation?

___ (1-much worse, 2-worse, 3-same, 4-better, 5-much better)

9B. Renovation expenses (unit: yuan; heating equipment expenses refer to the out-of-pocket expenses for the equipment, such as electric heaters, gas heating stoves, and radiators; network connecting expenses refer to out-of-pocket expenses for connecting to as the main natural gas or grid network; subsidy refers to the subsidy for renovation expenses specifically, excluding subsidies for the usage, asked below)

Equipment ID	Out-of-pocket expenses	Heating equipment expenses	Network connecting expenses	Do you receive subsidies from the government?	Amount of subsidy

10B. Do you expect a budget constraint for the renovation?

☐Yes ☐No.

If so, how will you raise the money for the renovation?

☐borrowing money from relatives and friends

☐public funding from the village

☐ peer-to-peer loans ☐ default ☐ other approaches: ____

11B. Expected usage cost during the heating season after the renovation:

Fuel cost (gas): Unit price:_______, annual usage: ______, total cost:_______,

Do you expect to receive subsidies from the government? ☐Yes, _____ yuan ☐No

Fuel cost (electricity): Unit price:_______, annual usage: ______, total cost:_______,

Do you expect to receive subsidies from the government? ☐Yes, _____ yuan ☐No

12B. Do you think the expected usage cost is acceptable?

☐perfectly acceptable ☐acceptable ☐unacceptable ☐very unacceptable

13B. Compared to the heating using coal or firewood, **if the indoor temperature is kept the same,** you can accept an increase in usage expense of ____ yuan per year for the clean heating.

Demographic information:

Other family members living with the interviewee (one month per year or above)	Interviewee							
Number of months at home per year								
Year of birth								
Gender								
The highest level of education (1 incomplete primary, 2 primary, 3 junior high school, 4 senior high school, 5 university, 6 graduate students)								
Occupation (1 farming, 2 civil servants, 3 public institutions, 4 state-owned enterprises, 5 temporary workers, 6 individual households, 7 students)								
Party membership								
Urban/rural hukou								
If you work, your working place is in (1 this county, 2 Linfen city, 3 Shanxi province, 4 outside the province)								
If you work, your working industry is (1 coal, 2 steel, 3 clothing, 4 other-please indicate)								

Figures and Tables

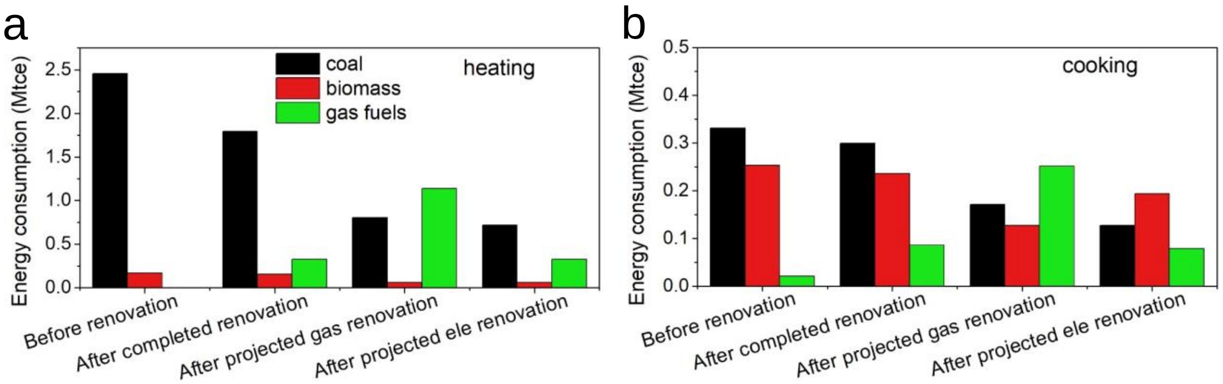

Figure S1. Household fuel consumption in Linfen before and after the renovation: (a) heating and (b) cooking and hot water.

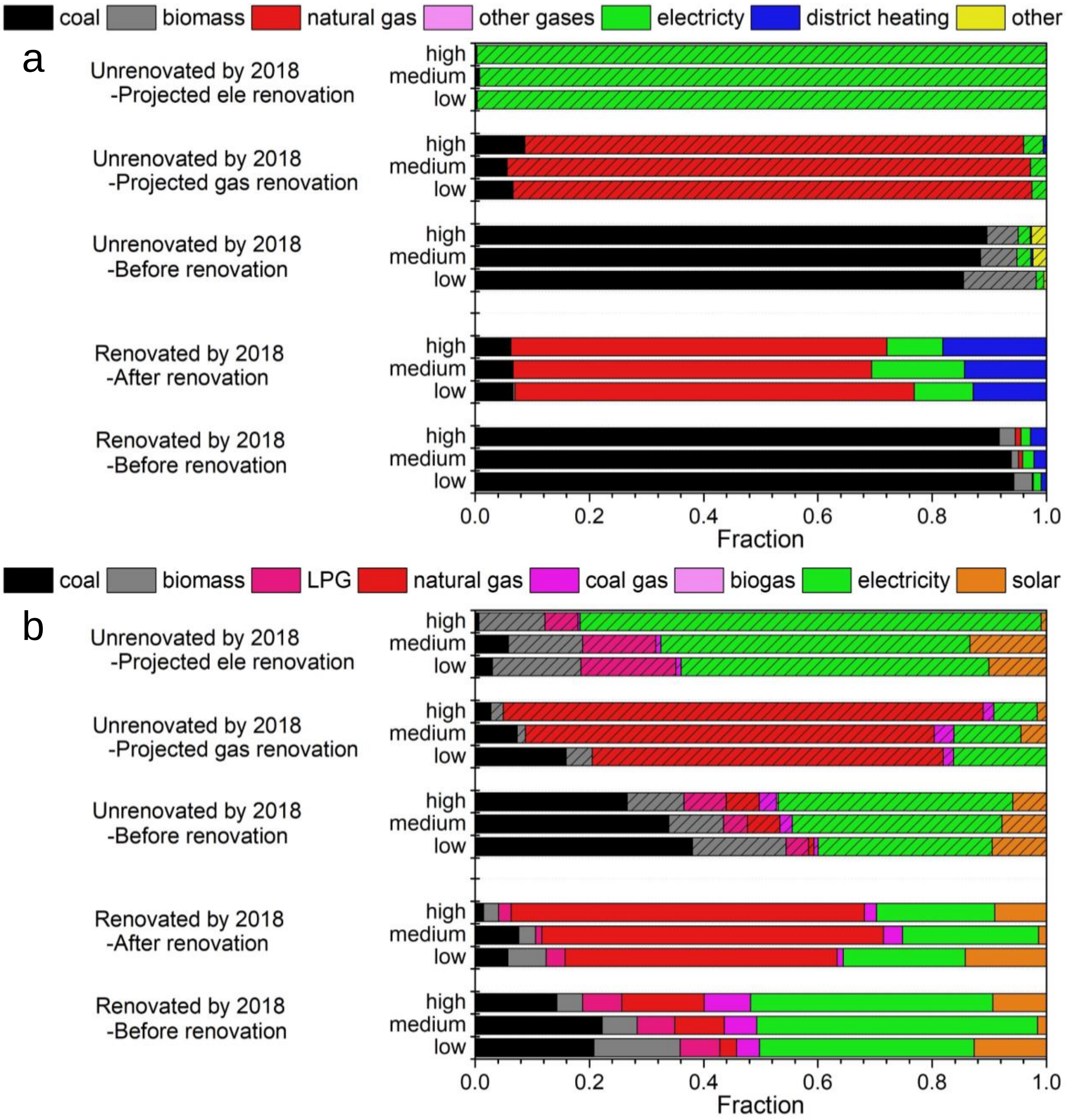

Figure S2. Relative time usage of heating/cooking energy before and after renovation in Linfen as a function of household income. (a) Percentage share of energy type for heating; (b) percentage share of energy type for cooking and hot water. “Low”, “medium”, and “high” in the figure represent surveyed households with the lowest 1/3, the medium 1/3, and the highest 1/3 incomes, respectively. Bars without shadow represent observed values while bars with shadow represent projected values.

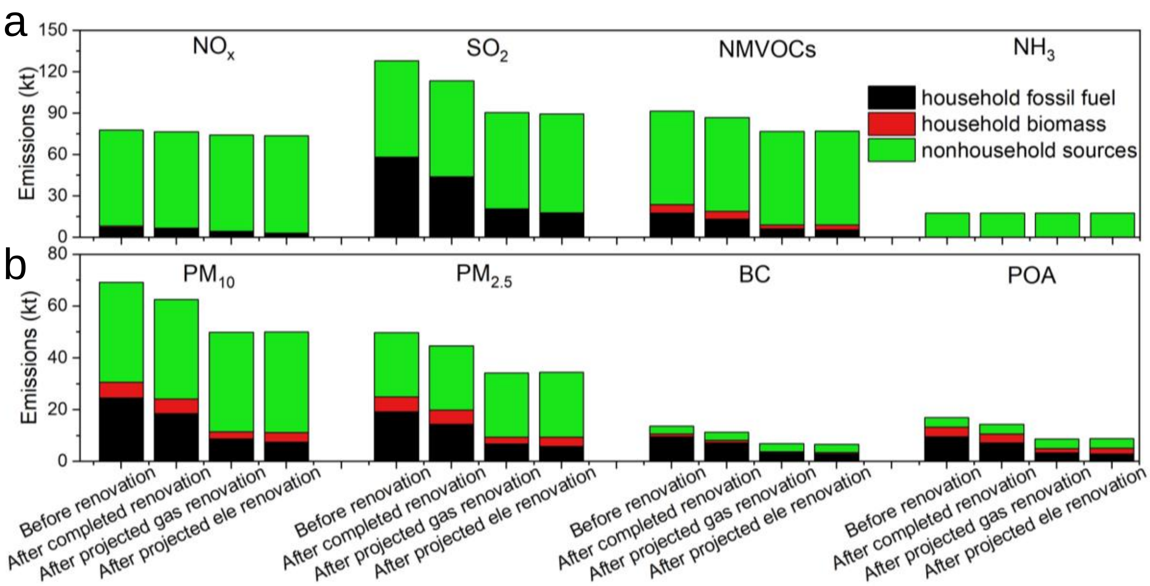

Figure S3. Air pollutant emissions from household and non-household sources in Linfen before and after the renovation: (a) NO$_x$, SO$_2$, NMVOCs, NH$_3$, and (b) PM$_{10}$, PM$_{2.5}$, BC, POA.

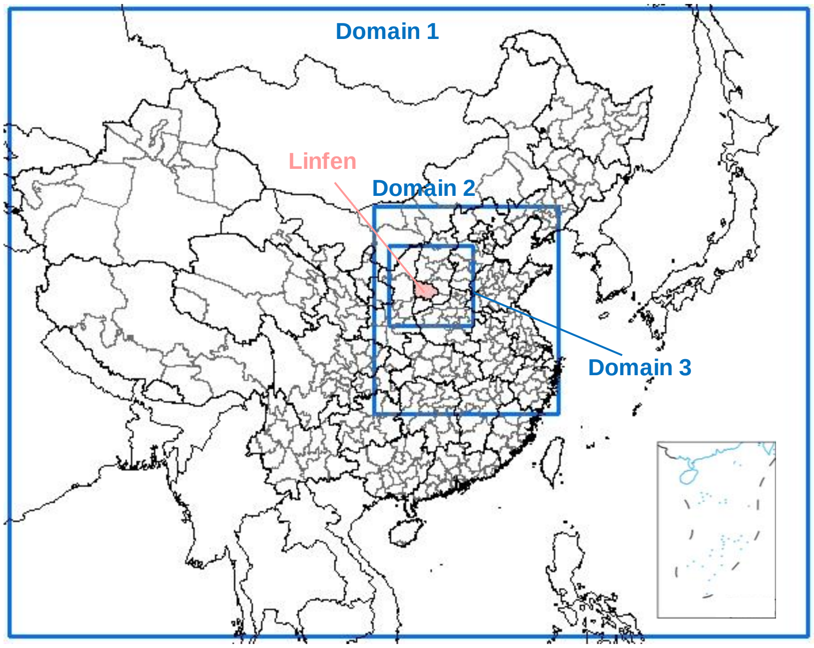

Figure S4. Triple nested modeling domains used in this study.

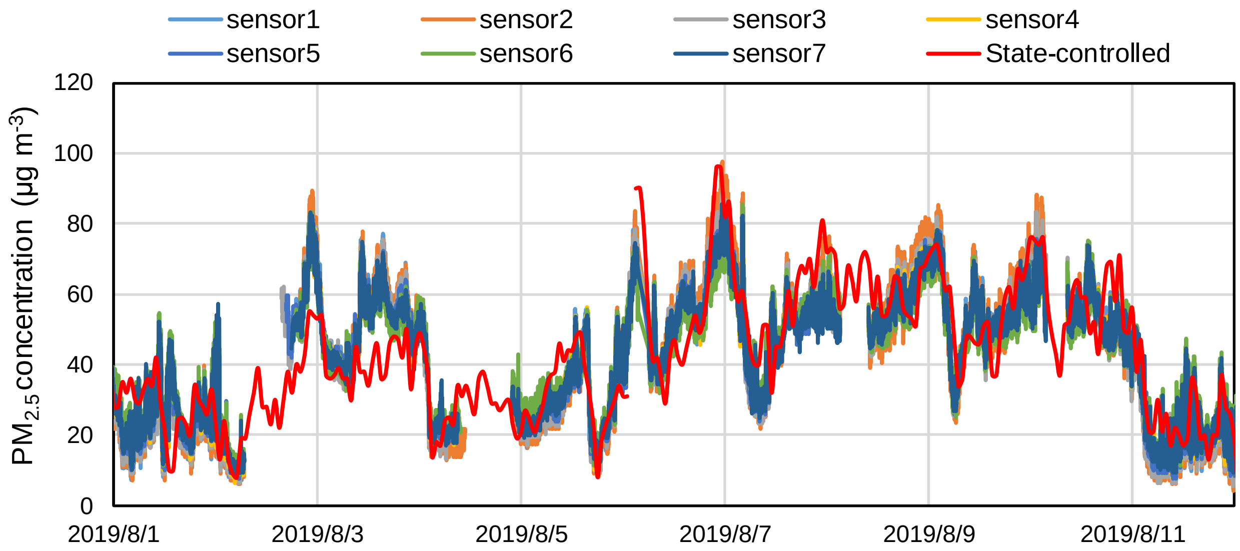

Figure S5. Comparison of $PM_{2.5}$ concentrations measured by the Oneair CP-15-A4 sensors (after calibration) and the state-controlled site in Linfen.

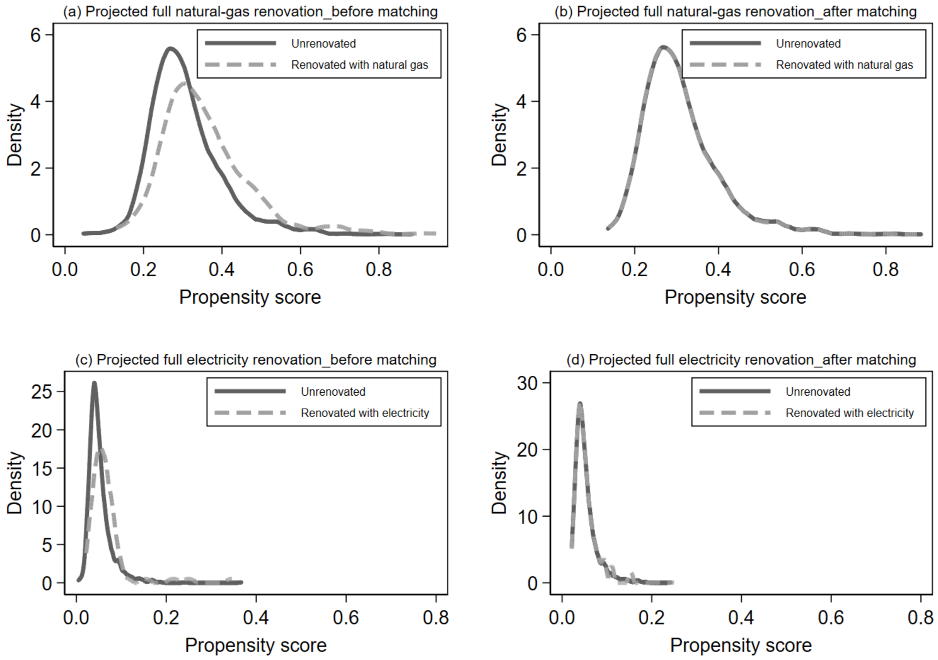

Figure S6. Kernel density of the propensity score by renovation status before and after matching.

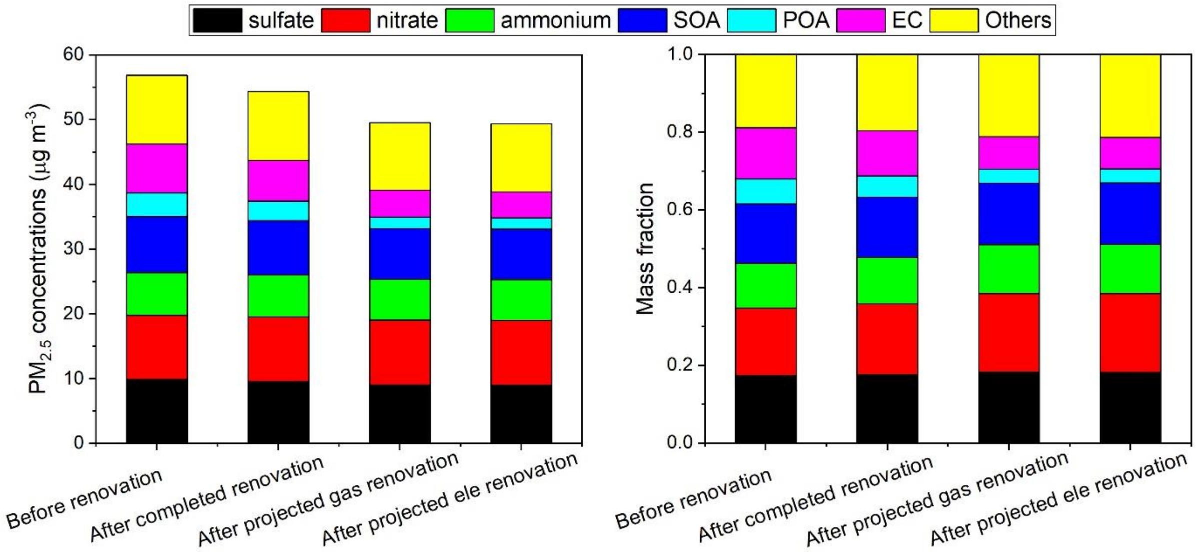

Figure S7. Chemical compositions of ambient $PM_{2.5}$ in Linfen before the renovation, after the completed renovation, and after projected renovation with natural gas or electricity. (a) population-weighted concentrations; (b) relative fractions.

Table S1. Differences of the covariates used in the propensity score matching between renovated households (with natural gas or electricity) and unrenovated households.

	Unrenovated		Renovated with natural gas				Renovated with electricity			
	N=1640		*N*=778				*N*=90			
Covariates	mean	s.d.	mean	s.d.	*t*-statistic[a]	*p*-value	mean	s.d.	*t*-statistic[b]	*p*-value
Net income (CNY)	19540.1	22301.4	25036.6	26160.6	5.201	0.000	20135.6	17783.9	0.248	0.402
Heating area (m^2)	110.8	67.0	135.4	80.6	7.555	0.000	135.7	79.0	3.204	0.001
Size of family	2.9	1.4	3.2	1.6	3.953	0.000	3.3	1.3	2.318	0.010
Coal consumption (CNY)[c]	2147.4	1335.8	2020.0	1313.0	-2.194	0.014	1900.8	1174.3	-1.714	0.043

[a] Two-sided t-test of the difference between renovated households with natural gas and unrenovated households;

[b] Two-sided t-test of the difference between renovated households with electricity and unrenovated households;

[c] For renovated households, this refers to the coal consumption before renovation.

Table S2. Annualized costs and willingness to pay per household for clean heating renovation in Linfen by household income.

Unit: CNY/year	Renovated by 2018			Unrenovated by 2018-Projected gas renovation			Unrenovated by 2018-Projected ele renovation		
	low[a]	medium	high	low	medium	high	low	medium	high
Sample	262	373	427	528	596	467	528	596	467
Increased usage cost (1)	1455±238[b]	1174±252	1278±232	2006±187	1405±179	1289±233	686±143	251±142	-111±160
Subsidy on usage (2)	642±54	686±54	608±46	754±27	734±26	783±26	1405±40	1440±39	1399±46
Equipment cost (3)	727±51	736±47	707±48	646±28	687±28	689±32	903±45	930±43	895±49
Equipment subsidy (4)	282±12	302±13	293±11	255±9±1	256±6±0	256±4±0	551±15	553±14	548±16
Total usage cost (1+2)	2098±269	1860±276	1886±252	2760±196	2138±193	2072±244	2091±165	1691±166	1288±188
Total equipment cost (3+4)	1009±55	1038±52	1000±51	901±28	943±28	945±32	1454±58	1484±54	1443±62
Out-of-pocket cost (1+3)	2183±243	1909±256	1986±237	2651±189	2092±182	1977±235	1590±150	1181±148	784±167
Total subsidy (2+4)	925±55	988±55	900±47	1009±27	989±26	1039±26	1955±43	1993±42	1948±49
Total cost (1+2+3+4)	3107±272	2898±275	2886±257	3661±199	3081±196	3016±249	3545±178	3175±181	2731±204
Willingness to pay	767±106	839±85	933±88	767±75	839±67	933±84	767±75	839±67	933±84

[a] "low", "medium", and "high" represent surveyed households with the lowest 1/3, the medium 1/3, and the highest 1/3 incomes, respectively.

[b] The cost is shown as mean ± standard deviation.

Table S3. Performance statistics for the comparison between simulated and observed meteorological variables.

Variable	Index	Unit	Spring[a]	Summer	Fall	Winter	Benchmark
Wind Speed (WS10)	Mean OBS	(m s^{-1})	2.82	2.53	2.52	2.61	
	Mean SIM	(m s^{-1})	2.64	2.36	2.54	2.48	
	MB	(m s^{-1})	−0.18	−0.18	0.01	−0.13	≤±0.5
	GE	(m s^{-1})	1.06	1.00	0.99	1.01	≤2
	RMSE	(m s^{-1})	1.45	1.37	1.38	1.43	≤2
	Sys RMSE	(m s^{-1})	1.01	0.97	0.90	1.05	
	Unsys RMSE	(m s^{-1})	1.04	0.97	1.04	0.97	
	IOA		0.77	0.73	0.79	0.77	≥0.6
Temperature (T2)	Mean OBS	(K)	287.93	298.57	286.93	274.71	
	Mean SIM	(K)	288.10	298.51	286.78	275.06	
	MB	(K)	0.16	−0.06	−0.15	0.35	≤±0.5
	GE	(K)	1.57	2.18	2.30	1.77	≤2
	RMSE	(K)	2.04	3.15	3.32	2.38	
	Sys RMSE	(K)	0.58	1.39	1.60	1.03	
	Unsys RMSE	(K)	1.94	2.79	2.87	2.09	
	IOA		0.96	0.88	0.88	0.95	≥0.8
Humidity (Q2)	Mean OBS	(g kg^{-1})	7.27	16.62	9.11	3.36	
	Mean SIM	(g kg^{-1})	6.71	15.44	8.74	3.25	
	MB	(g kg^{-1})	−0.56	*−1.18*[b]	−0.37	−0.10	≤±1
	GE	(g kg^{-1})	1.07	*2.18*	1.31	0.50	≤2
	RMSE	(g kg^{-1})	1.38	2.79	1.74	0.67	
	Sys RMSE	(g kg^{-1})	0.74	1.45	0.58	0.27	
	Unsys RMSE	(g kg^{-1})	1.13	2.33	1.62	0.61	
	IOA		0.92	0.84	0.90	0.94	≥0.6

[a] Spring—March, April, May; Summer—June, July, August; Fall—September, October, November; Winter—December, January, February.

[b] The values exceeding the benchmark range are italicized.

Table S4. Performance statistics for the comparison between simulated and observed $PM_{2.5}$, SO_2, NO_2, and O_3 concentrations at state-controlled monitoring sites.

		Annual	Spring[a]	Summer	Fall	Winter	Model performance criteria	Model performance goal
$PM_{2.5}$ (μg/m^3)	Mean OBS	69.2	57.9	43.5	60.1	114.0		
	Mean SIM	68.8	52.1	50.3	78.1	94.8		
	NMB	-0.4	-10.1	15.3	30.0	-16.6		
	NME	17.1	19.6	24.0	34.5	21.1		
	MFB	-3.0	-14.1	10.7	23.5	-19.2	≤ ±60	≤ ±30
	MFE	17.2	21.9	21.7	28.7	22.8	≤ 75	≤ 50
SO_2 (ppb)	Mean OBS	11.3	10.3	5.4	8.3	21.3		
	Mean SIM	15.2	11.3	7.9	15.2	26.4		
	NMB	33.5	10.5	48.9	82.7	23.3		
	NME	56.4	45.5	72.6	95.7	57.3		
	MFB	24.3	1.9	29.2	52.2	23.9		
	MFE	41.5	37.1	50.1	60.9	44.3		
NO_2 (ppb)	Mean OBS	22.4	21.5	15.4	23.7	28.8		
	Mean SIM	30.6	27.6	25.8	33.3	35.8		
	NMB	36.4	27.7	67.0	40.5	24.0		
	NME	51.0	49.0	85.1	54.1	36.0		
	MFB	19.5	11.0	32.2	23.2	14.6		
	MFE	40.1	41.6	56.0	42.2	31.1		
1-hour max O_3 (ppb)	Mean OBS	58.3	66.0	86.0	47.0	35.0		
	Mean SIM	59.0	62.4	91.0	49.4	33.5		
	NMB	1.4	-5.4	5.6	5.0	-3.9		
	NME	8.9	10.8	9.8	13.3	15.6		
	MFB	1.4	-5.5	5.5	4.5	-5.4		
	MFE	9.2	11.4	9.6	13.5	16.7		

[a] Spring—March, April, May; Summer—June, July, August; Fall—September, October, November; Winter—December, January, February.

REFERENCES

1. Zhao, B.; Wang, S. X.; Wang, J. D.; Fu, J. S.; Liu, T. H.; Xu, J. Y.; Fu, X.; Hao, J. M., Impact of national NOx and SO2 control policies on particulate matter pollution in China. *Atmos Environ* **2013,** *77*, 453-463.
2. Zhao, B.; Zheng, H.; Wang, S.; Smith, K. R.; Lu, X.; Aunan, K.; Gu, Y.; Wang, Y.; Ding, D.; Xing, J.; Fu, X.; Yang, X.; Liou, K. N.; Hao, J., Change in household fuels dominates the decrease in PM2.5 exposure and premature mortality in China in 2005-2015. *P Natl Acad Sci USA* **2018,** *115*, (49), 12401-12406.
3. Leung, D. M.; Shi, H.; Zhao, B.; Wang, J.; Ding, E. M.; Gu, Y.; Zheng, H.; Chen, G.; Liou, K. N.; Wang, S.; Fast, J. D.; Zheng, G.; Jiang, J.; Li, X.; Jiang, J. H., Wintertime particulate matter decrease buffered by unfavorable chemical processes despite emission reductions in China. *Geophys Res Lett* **2020,** *47*, (14), e2020GL087721.
4. Hao, J. M.; Tian, H. Z.; Lu, Y. Q., Emission inventories of NOx from commercial energy consumption in China, 1995-1998. *Environ Sci Technol* **2002,** *36*, (4), 552-560.
5. US Environmental Protection Agency AP-42: Compilation of Air Emissions Factors. https://www.epa.gov/air-emissions-factors-and-quantification/ap-42-compilation-air-emissions-factors (March 1, 2021),
6. Liu, J.; Kiesewetter, G.; Klimont, Z.; Cofala, J.; Heyes, C.; Schopp, W.; Zhu, T.; Cao, G. Y.; Sanabria, A. G.; Sander, R.; Guo, F.; Zhang, Q.; Nguyen, B.; Bertok, I.; Rafaj, P.; Amann, M., Mitigation pathways of air pollution from residential emissions in the Beijing-Tianjin-Hebei region in China. *Environ Int* **2019,** *125*, 236-244.
7. Cai, S. Y.; Li, Q.; Wang, S. X.; Chen, J. M.; Ding, D.; Zhao, B.; Yang, D. S.; Hao, J. M., Pollutant emissions from residential combustion and reduction strategies estimated via a village-based emission inventory in Beijing. *Environ Pollut* **2018,** *238*, 230-237.
8. Traynor, G. W.; Apte, M. G.; Chang, G. M. *Pollutant emission factors from residential natural gas appliances: a literature review*; Lawrence Berkeley National Laboratory: Pleasanton, CA, U.S.A., 1996.
9. China Electric Power Yearbook Committee, *China Electric Power Yearbook 2018*. China Electric Power Press: Beijing, China, 2018.
10. Linfen Municipal Bureau of Statistics, *Lin Fen Statistical Yearbook 2019*. China Statistics Press: 2019; p 535.
11. Zhao, B.; Wang, S. X.; Donahue, N. M.; Jathar, S. H.; Huang, X. F.; Wu, W. J.; Hao, J. M.; Robinson, A. L., Quantifying the effect of organic aerosol aging and intermediate-volatility emissions on regional-scale aerosol pollution in China. *Sci Rep-Uk* **2016,** *6*, 28815.
12. Guenther, A.; Karl, T.; Harley, P.; Wiedinmyer, C.; Palmer, P. I.; Geron, C., Estimates of global terrestrial isoprene emissions using MEGAN (Model of Emissions of Gases and Aerosols from Nature). *Atmos Chem Phys* **2006,** *6*, 3181-3210.
13. Zhao, B.; Wu, W. J.; Wang, S. X.; Xing, J.; Chang, X.; Liou, K. N.; Jiang, J. H.; Gu, Y.; Jang, C.; Fu, J. S.; Zhu, Y.; Wang, J. D.; Lin, Y.; Hao, J. M., A modeling study of the nonlinear response of fine particles to air pollutant emissions in the Beijing-Tianjin-Hebei region. *Atmos Chem Phys* **2017,** *17*, 12031-12050.
14. Emery, C.; Tai, E.; Yarwood, G. *Enhanced meteorological modeling and performance evaluation for two texas episodes. Report to the Texas Natural Resources Conservation Commission*; ENVIRON International Corporation: Novato, CA, 2001.

15. Yu, S.; Eder, B.; Dennis, R.; Chu, S. H.; Schwartz, S. E., New unbiased symmetric metrics for evaluation of air quality models. *Atmos Sci Lett* **2006,** *7*, (1), 26-34.

16. Boylan, J. W.; Russell, A. G., PM and light extinction model performance metrics, goals, and criteria for three-dimensional air quality models. *Atmos Environ* **2006,** *40*, 4946-4959.

17. Liu, D.; Zhang, Q.; Jiang, J. K.; Chen, D. R., Performance calibration of low-cost and portable particular matter (PM) sensors. *J Aerosol Sci* **2017,** *112*, 1-10.

18. Dedoussi, I. C.; Eastham, S. D.; Monier, E.; Barrett, S. R. H., Premature mortality related to United States cross-state air pollution. *Nature* **2020,** *578*, (7794), 261-265.

19. Forouzanfar, M. H.; Afshin, A.; Alexander, L. T.; Anderson, H. R.; Bhutta, Z. A.; Biryukov, S.; Brauer, M.; Burnett, R.; Cercy, K.; Charlson, F. J.; Cohen, A. J.; Dandona, L.; Estep, K.; Ferrari, A. J.; Frostad, J. J.; Fullman, N.; Gething, P. W.; Godwin, W. W.; Griswold, M.; Kinfu, Y.; Kyu, H. H.; Larson, H. J.; Liang, X.; Lim, S. S.; Liu, P. Y.; Lopez, A. D.; Lozano, R.; Marczak, L.; Mensah, G. A.; Mokdad, A. H.; Moradi-Lakeh, M.; Naghavi, M.; Neal, B.; Reitsma, M. B.; Roth, G. A.; Salomon, J. A.; Sur, P. J.; Vos, T.; Wagner, J. A.; Wang, H.; Zhao, Y.; Zhou, M.; Aasvang, G. M.; Abajobir, A. A.; Abate, K. H.; Abbafati, C.; Abbas, K. M.; Abd-Allah, F.; Abdulle, A. M.; Abera, S. F.; Abraham, B.; Abu-Raddad, L. J.; Abyu, G. Y.; Adebiyi, A. O.; Adedeji, I. A.; Ademi, Z.; Adou, A. K.; Adsuar, J. C.; Agardh, E. E.; Agarwal, A.; Agrawal, A.; Kiadaliri, A. A.; Ajala, O. N.; Akinyemiju, T. F.; Al-Aly, Z.; Alam, K.; Alam, N. K. M.; Aldhahri, S. F.; Aldridge, R. W.; Alemu, Z. A.; Ali, R.; Alkerwi, A. a.; Alla, F.; Allebeck, P.; Alsharif, U.; Altirkawi, K. A.; Alvarez Martin, E.; Alvis-Guzman, N.; Amare, A. T.; Amberbir, A.; Amegah, A. K.; Amini, H.; Ammar, W.; Amrock, S. M.; Andersen, H. H.; Anderson, B. O.; Antonio, C. A. T.; Anwar, P.; Arnlov, J.; Al, A.; Asayesh, H.; Asghar, R. J.; Assadi, R.; Atique, S.; Avokpaho, E. F. G. A.; Awasthi, A.; Quintanilla, B. P. A.; Azzopardi, P.; Bacha, U.; Badawi, A.; Bahit, M. C.; Balakrishnan, K.; Barac, A.; Barber, R. M.; Barker-Collo, S. L.; Baernighausen, T.; Barquera, S.; Barregard, L.; Barrero, L. H.; Basu, S.; Batis, C.; Bazargan-Hejazi, S.; Beardsley, J.; Bedi, N.; Beghi, E.; Bell, M. L.; Bello, A. K.; Bennett, D. A.; Bensenor, I. M.; Berhane, A.; Bernabe, E.; Betsu, B. D.; Beyene, A. S.; Bhala, N.; Bhansali, A.; Bhatt, S.; Biadgilign, S.; Bikbov, B.; Bisanzio, D.; Bjertness, E.; Blore, J. D.; Borschmann, R.; Boufous, S.; Bourne, R. R. A.; Brainin, M.; Brazinova, A.; Breitborde, N. J. K.; Brenner, H.; Broday, D. M.; Brugha, T. S.; Brunekreef, B.; Butt, Z. A.; Cahill, L. E.; Calabria, B.; Ricardo Campos-Nonato, I.; Cardenas, R.; Carpenter, D.; Casey, D. C.; Castaneda-Oquela, C. A.; Castillo Rivas, J.; Estanislao Castro, R.; Catala-Lopez, F.; Chang, J.-C.; Chiang, P. P.-C.; Chibalabala, M.; Chimed-Ochir, O.; Chisumpa, V. H.; Chitheer, A. A.; Choi, J.-Y. J.; Christensen, H.; Christopher, D. J.; Ciobanu, L. G.; Coates, M. M.; Colquhoun, S. M.; Cooper, L. T.; Cooperrider, K.; Cornaby, L.; Cortinovis, M.; Crump, J. A.; Cuevas-Nasu, L.; Damasceno, A.; Dandona, R.; Darby, S. C.; Dargan, P. I.; das Neves, J.; Davis, A. C.; Davletov, K.; Filipa de Castro, E.; De la Cruz-Gongora, V.; De Leo, D.; Degenhardt, L.; Del Gobbo, L. C.; del Pozo-Cruz, B.; Dellavalle, R. P.; Deribew, A.; Des Jarlais, D. C.; Dharmaratne, S. D.; Dhillon, P. K.; Diaz-Tome, C.; Dicker, D.; Ding, E. L.; Dorsey, E. R.; Doyle, K. E.; Driscoll, T. R.; Duan, L.; Dubey, M.; Duncan, B. B.; Elyazar, I.; Endries, A. Y.; Ermakov, S. P.; Erskine, H. E.; Eshrati, B.; Esteghamati, A.; Fahimi, S.; Aquino Faraon, E. J.; Farid, T. A.; Sofia E Sa Farinha, C.; Faro, A.; Farvid, M. S.; Farzadfar, F.; Feigin, V. L.; Fereshtehnejad, S.-M.; Fernandes, J. G.; Fischer, F.; Fitchett, J. R. A.; Fleming, T.; Foigt, N.; Foreman, K.; Fowkes, F. G. R.; Franklin, R. C.; Fuerst, T.; Futran, N. D.; Gakidou, E.; Garcia-Basteiro, A. L.; Gebrehiwot, T. T.; Gebremedhin, A. T.; Geleijnse, J. M.; Gessner, B. D.; Giref, A. Z.; Giroud, M.; Gishu, M. D.; Goenka, S.; Carmen Gomez-Cabrera, M.; Gomez-Dantes, H.; Gona, P.; Goodridge, A.; Gopalani, S. V.; Gotay, C. C.; Goto, A.; Gouda, H. N.; Gugnani, H. C.; Guillemin, F.; Guo, Y.; Gupta, R.; Gupta, R.; Gutierrez, R. A.; Haagsma, J.

A.; Hafezi-Nejad, N.; Haile, D.; Hailu, G. B.; Halasa, Y. A.; Hamadeh, R. R.; Hamidi, S.; Handal, A. J.; Hankey, G. J.; Hao, Y.; Harb, H. L.; Harikrishnan, S.; Maria Haro, J.; Hassanvand, M. S.; Hassen, T. A.; Havmoeller, R.; Beatriz Heredia-Pi, I.; Francisco Hernandez-Llanes, N.; Heydarpour, P.; Hoek, H. W.; Hoffman, H. J.; Horino, M.; Horita, N.; Hosgood, H. D.; Hoy, D. G.; Hsairi, M.; Htet, A. S.; Hu, G.; Huang, J. J.; Husseini, A.; Hutchings, S. J.; Huybrechts, I.; Iburg, K. M.; Idrisov, B. T.; Ileanu, B. V.; Inoue, M.; Jacobs, T. A.; Jacobsen, K. H.; Jahanmehr, N.; Jakovljevic, M. B.; Jansen, H. A. F. M.; Jassal, S. K.; Javanbakht, M.; Jayatilleke, A. U.; Jee, S. H.; Jeemon, P.; Jha, V.; Jiang, Y.; Jibat, T.; Jin, Y.; Johnson, C. O.; Jonas, J. B.; Kabir, Z.; Kalkonde, Y.; Kamal, R.; Kan, H.; Karch, A.; Karema, C. K.; Karimkhani, C.; Kasaeian, A.; Kaul, A.; Kawakami, N.; Kazi, D. S.; Keiyoro, P. N.; Kemp, A. H.; Kengne, A. P.; Keren, A.; Kesavachandran, C. N.; Khader, Y. S.; Khan, A. R.; Khan, E. A.; Khan, G.; Khang, Y.-H.; Khatibzadeh, S.; Khera, S.; Khoja, T. A. M.; Khubchandani, J.; Kieling, C.; Kim, C.-i.; Kim, D.; Kimokoti, R. W.; Kissoon, N.; Kivipelto, M.; Knibbs, L. D.; Kokubo, Y.; Kopec, J. A.; Koul, P. A.; Koyanagi, A.; Kravchenko, M.; Kromhout, H.; Krueger, H.; Ku, T.; Defo, B. K.; Kuchenbecker, R. S.; Bicer, B. K.; Kuipers, E. J.; Kumar, G. A.; Kwan, G. F.; Lal, D. K.; Lalloo, R.; Lallukka, T.; Lan, Q.; Larsson, A.; Latif, A. A.; Beatriz Lawrynowicz, A. E.; Leasher, J. L.; Leigh, J.; Leung, J.; Levi, M.; Li, X.; Li, Y.; Liang, J.; Liu, S.; Lloyd, B. K.; Logroscino, G.; Lotufo, P. A.; Lunevicius, R.; MacIntyre, M.; Mahdavi, M.; Majdan, M.; Majeed, A.; Malekzadeh, R.; Malta, D. C.; Manamo, W. A. A.; Mapoma, C. C.; Marcenes, W.; Martin, R. V.; Martinez-Raga, J.; Masiye, F.; Matsushita, K.; Matzopoulos, R.; Mayosi, B. M.; McGrath, J. J.; McKee, M.; Meaney, P. A.; Medina, C.; Mehari, A.; Mena-Rodriguez, F.; Mekonnen, A. B.; Melaku, Y. A.; Memish, Z. A.; Mendoza, W.; Mensink, G. B. M.; Meretoja, A.; Meretoja, T. J.; Mesfin, Y. M.; Mhimbira, F. A.; Miller, T. R.; Mills, E. J.; Mirarefin, M.; Misganaw, A.; Mock, C. N.; Mohammadi, A.; Mohammed, S.; Mola, G. L. D.; Monasta, L.; Montanez Hernandez, J. C.; Montico, M.; Morawska, L.; Mori, R.; Mozaffarian, D.; Mueller, U. O.; Mullany, E.; Mumford, J. E.; Murthy, G. V. S.; Nachega, J. B.; Naheed, A.; Nangia, V.; Nassiri, N.; Newton, J. N.; Ng, M.; Quyen Le, N.; Nisar, M. I.; Pete, P. M. N.; Norheim, O. F.; Norman, R. E.; Norrving, B.; Nyakarahuka, L.; Obermeyer, C. M.; Ogbo, F. A.; Oh, I.-H.; Oladimeji, O.; Olivares, P. R.; Olsen, H.; Olusanya, B. O.; Olusanya, J. O.; Opio, J. N.; Oren, E.; Orozco, R.; Ortiz, A.; Ota, E.; Mahesh, P. A.; Pana, A.; Park, E.-K.; Parry, C. D.; Parsaeian, M.; Patel, T.; Caicedo, A. J. P.; Patil, S. T.; Patten, S. B.; Patton, G. C.; Pearce, N.; Pereira, D. M.; Perico, N.; Pesudovs, K.; Petzold, M.; Phillips, M. R.; Piel, F. B.; Pillay, J. D.; Plass, D.; Polinder, S.; Pond, C. D.; Pope, C. A.; Pope, D.; Popova, S.; Poulton, R. G.; Pourmalek, F.; Prasad, N. M.; Qorbani, M.; Rabiee, R. H. S.; Radfar, A.; Rafay, A.; Rahimi-Movaghar, V.; Rahman, M.; Rahman, M. H. U.; Rahman, S. U.; Rai, R. K.; Rajsic, S.; Raju, M.; Ram, U.; Rana, S. M.; Ranganathan, K.; Rao, P.; Razo Garcia, C. A.; Refaat, A. H.; Rehm, C. D.; Rehm, J.; Reinig, N.; Remuzzi, G.; Resnikoff, S.; Ribeiro, A. L.; Rivera, J. A.; Rolm, H. S.; Rodriguez, A.; Rodriguez-Ramirez, S.; Rojas-Rueda, D.; Roman, Y.; Ronfani, L.; Roshandel, G.; Rothenbacher, D.; Roy, A.; Saleh, M. M.; Sanabria, J. R.; Dolores Sanchez-Nino, M.; Sanchez-Pimienta, T. G.; Sandar, L.; Santomauro, D. F.; Santos, I. S.; Sarmiento-Suarez, R.; Sartorius, B.; Satpathy, M.; Savic, M.; Sawhney, M.; Schmidhuber, J.; Schmidt, M. I.; Schneider, I. J. C.; Schoettker, B.; Schutte, A. E.; Schwebel, D. C.; Scott, J. G.; Seedat, S.; Sepanlou, S. G.; Servan-Mori, E. E.; Shaddick, G.; Shaheen, A.; Shahraz, S.; Shaikh, M. A.; Levy, T. S.; Sharma, R.; She, J.; Sheikhbahaei, S.; Shen, J.; Sheth, K. N.; Shi, P.; Shibuya, K.; Shigematsu, M.; Shin, M.-J.; Shiri, R.; Shishani, K.; Shiue, I.; Shrime, M. G.; Sigfusdottir, I. D.; Silva, D. A. S.; Alves Silveira, D. G.; Silverberg, J. I.; Simard, E. P.; Sindi, S.; Singh, A.; Singh, J. A.; Singh, P. K.; Slepak, E. L.; Soljak, M.; Soneji, S.; Sorensen, R. J. D.; Sposato, L. A.; Sreeramareddy, C. T.; Stathopoulou, V.; Steckling, N.; Steel, N.; Stein, D. J.; Stein, M. B.; Stockl, H.; Stranges, S.; Stroumpoulis, K.; Sunguya, B. F.; Swaminathan, S.; Sykes, B. L.; Szoeke, C. E. I.; Tabares-Seisdedos, R.; Takahashi, K.; Talongwa, R. T.; Landon, N.; Tanne, D.; Tavakkoli, M.; Taye, B. W.; Taylor, H. R.; Tedla, B. A.; Tefera, W. M.; Tegegne, T. K.; Tekle, D. Y.; Terkawi, A. S.; Thakur, J. S.; Thomas, B. A.; Thomas, M. L.; Thomson, A. J.; Thorne-Lyman, A. L.; Thrift, A. G.; Thurston, G. D.; Tillmann, T.; Tobe-Gai, R.; Tobollik, M.; Topor-Madry, R.; Topouzis, F.; Towbin, J. A.; Bach Xuan, T.; Dimbuene, Z. T.; Tsilimparis, N.; Tura, A. K.; Tuzcu, E. M.; Tyrovolas, S.; Ukwaja, K. N.; Undurraga, E. A.; Uneke, C. J.; Uthman, O. A.; van Donkelaar, A.; van Os, J.; Varakin, Y. Y.; Vasankari, T.; Veerman, J. L.; Venketasubramanian, N.; Violante, F. S.; Vollset, S. E.; Wagner, G. R.; Waller, S. G.; Wang, J.; Wang, L.; Wang, Y.; Weichenthal, S.; Weiderpass, E.; Weintraub, R. G.; Werdecker, A.; Westerman, R.; Whiteford, H. A.; Wijeratne, T.; Wiysonge, C. S.; Wolfe, C. D. A.; Won, S.; Woolf, A. D.; Wubshet, M.; Xavier, D.; Xu, G.; Yadav, A. K.; Yakob, B.; Yalew, A. Z.; Yano, Y.; Yaseri, M.; Ye, P.; Yip, P.; Yonemoto, N.; Yoon, S.-J.; Younis, M. Z.; Yu, C.; Zaidi, Z.; Zaki, M. E. S.; Zhu, J.; Zipkin, B.; Zodpey, S.; Zuhlke, L. J.; Murray, C. J. L.; Factors, G. B. D. R., Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990-2015: a systematic analysis for the Global Burden of Disease Study 2015. *Lancet* **2016,** *388*, (10053), 1659-1724.

20. Chen, K.; Breitner, S.; Wolf, K.; Stafoggia, M.; Sera, F.; Vicedo-Cabrera, A. M.; Guo, Y.; Tong, S.; Lavigne, E.; Matus, P.; Valdes, N.; Kan, H.; Jaakkola, J. J. K.; Ryti, N. R. I.; Huber, V.; Scortichini, M.; Hashizume, M.; Honda, Y.; Nunes, B.; Madureira, J.; Holobaca, I. H.; Fratianni, S.; Kim, H.; Lee, W.; Tobias, A.; Iniguez, C.; Forsberg, B.; Astrom, C.; Ragettli, M. S.; Guo, Y.-L. L.; Chen, B.-Y.; Li, S.; Milojevic, A.; Zanobetti, A.; Schwartz, J.; Bell, M. L.; Gasparrini, A.; Schneider, A., Ambient carbon monoxide and daily mortality: a global time-series study in 337 cities. *Lancet Planetary Health* **2021,** *5*, (4), E191-E199.

21. Manisalidis, I.; Stavropoulou, E.; Stavropoulos, A.; Bezirtzoglou, E., Environmental and Health Impacts of Air Pollution: A Review. *Frontiers In Public Health* **2020,** *8*, 14.

22. Cohen, A. J.; Brauer, M.; Burnett, R.; Anderson, H. R.; Frostad, J.; Estep, K.; Balakrishnan, K.; Brunekreef, B.; Dandona, L.; Dandona, R.; Feigin, V.; Freedman, G.; Hubbell, B.; Jobling, A.; Kan, H.; Knibbs, L.; Liu, Y.; Martin, R.; Morawska, L.; Pope, C. A.; Shin, H.; Straif, K.; Shaddick, G.; Thomas, M.; van Dingenen, R.; van Donkelaar, A.; Vos, T.; Murray, C. J. L.; Forouzanfar, M. H., Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet* **2017,** *389*, (10082), 1907-1918.

23. Lelieveld, J.; Evans, J. S.; Fnais, M.; Giannadaki, D.; Pozzer, A., The contribution of outdoor air pollution sources to premature mortality on a global scale. *Nature* **2015,** *525*, (7569), 367-371.

24. Fann, N.; Lamson, A. D.; Anenberg, S. C.; Wesson, K.; Risley, D.; Hubbell, B. J., Estimating the National Public Health Burden Associated with Exposure to Ambient PM2.5 and Ozone. *Risk Anal* **2012,** *32*, (1), 81-95.

25. Burnett, R. T.; Pope, C. A., III; Ezzati, M.; Olives, C.; Lim, S. S.; Mehta, S.; Shin, H. H.; Singh, G.; Hubbell, B.; Brauer, M.; Anderson, H. R.; Smith, K. R.; Balmes, J. R.; Bruce, N. G.; Kan, H.; Laden, F.; Pruess-Ustuen, A.; Turner, M. C.; Gapstur, S. M.; Diver, W. R.; Cohen, A., An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. *Environ Health Persp* **2014,** *122*, (4), 397-403.

26. Burnett, R.; Chen, H.; Szyszkowicz, M., Global estimates of mortality associated with long-term exposure to outdoor fine particulate matter. *P Natl Acad Sci USA* **2018,** *115*, (38), 9592-9597.

27. Tuomisto, J. T.; Wilson, A.; Evans, J. S.; Tainio, M., Uncertainty in mortality response to airborne fine particulate matter: Combining European air pollution experts. *Reliability Engineering & System Safety* **2008,** *93*, (5), 732-744.

28. Global Burden of Disease Collaborative Network *Global Burden of Disease Study 2016 (GBD 2016) results tool, available from http://ghdx.healthdata.org/gbd-results-tool*; Institute for Health Metrics and Evaluation (IHME): Seattle, United States, 2017.

29. Bowland, B. J.; Beghin, J. C., Robust estimates of value of a statistical life for developing economies. *Journal Of Policy Modeling* **2001,** *23*, (4), 385-396.

30. Yang, Z.; Liu, P.; Xu, X., Estimation of social value of statistical life using willingness-to-pay method in Nanjing, China. *Accident Analysis And Prevention* **2016,** *95*, 308-316.

31. Bai, R. Q.; Lam, J. C. K.; Li, V. O. K., A review on health cost accounting of air pollution in China. *Environ Int* **2018,** *120*, 279-294.

32. Hammitt, J. K.; Zhou, Y., The economic value of air-pollution-related health risks in China: A contingent valuation study. *Environmental & Resource Economics* **2006,** *33*, (3), 399-423.

33. Aunan, K.; Alnes, L. W. H.; Berger, J.; Dong, Z. Q.; Ma, L. Y.; Mestl, H. E. S.; Vennemo, H.; Wang, S. X.; Zhang, W., Upgrading to cleaner household stoves and reducing chronic obstructive pulmonary disease among women in rural China - A cost-benefit analysis. *Energy for Sustainable Development* **2013,** *17*, (5), 489-496.

34. Wang, H.; Mullahy, J., Willingness to pay for reducing fatal risk by improving air quality: A contingent valuation study in Chongqing, China. *Sci Total Environ* **2006,** *367*, (1), 50-57.

35. Liang, X. Y.; Zhang, S. J.; Wu, Y.; Xing, J.; He, X. Y.; Zhang, K. M.; Wang, S. X.; Hao, J. M., Air quality and health benefits from fleet electrification in China. *Nature Sustainability* **2019,** *2*, (10), 962-971.

36. Zhang, M. S.; Song, Y.; Cai, X. H.; Zhou, J., Economic assessment of the health effects related to particulate matter pollution in 111 Chinese cities by using economic burden of disease analysis. *J Environ Manage* **2008,** *88*, (4), 947-954.

37. Li, M. W.; Zhang, D.; Li, C. T.; Mulvaney, K. M.; Selin, N. E.; Karplus, V. J., Air quality co-benefits of carbon pricing in China. *Nat Clim Change* **2018,** *8*, (5), 398-403.

38. Wang, H.; He, J. J. *The Value of a Statistical Life: A Contingent Investigation in China, Working Paper 5421, available at http://elibrary.worldbank.org/doi/abs/10.1596/1813-9450-5421*; The World Bank Development Research Group: 2010.

39. Cao, C.; Song, X.; Cai, W.; Li, Y.; Cong, J.; Yu, X.; Niu, X.; Gao, M.; Wang, C., Estimating the Value of Statistical Life in China: A Contingent Valuation Study in Six Representative Cities. *Preprint in Research Square* **2021**.

40. Kan, H. D.; Chen, B. H., Particulate air pollution in urban areas of Shanghai, China: health-based economic assessment. *Sci Total Environ* **2004,** *322*, (1-3), 71-79.

41. Wu, W. J. Health Effect Attributed to Ambient Fine Particle Pollution in the Beijing-Tianjin-Hebei Region and its Source Apportionment. Tsinghua University, Beijing, China, 2016.

42. Rosenbaum, P. R.; Rubin, D. B., THE CENTRAL ROLE OF THE PROPENSITY SCORE IN OBSERVATIONAL STUDIES FOR CAUSAL EFFECTS. *Biometrika* **1983,** *70*, (1), 41-55.

43. Dehejia, R. H.; Wahba, S., Propensity score-matching methods for nonexperimental causal studies. *Review Of Economics And Statistics* **2002,** *84*, (1), 151-161.

44. Becker, S. O.; Ichino, A., Estimation of average treatment effects based on propensity scores. *Stata Journal* **2002,** *2*, (4), 358-377.