ANALYSIS
https://doi.org/10.1038/s41560-019-0386-2

nature energy

An evaluation of air quality, home heating and well-being under Beijing's programme to eliminate household coal use

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To mitigate health and environmental effects from coal-based home heating, the Beijing Municipality has implemented a programme in 3,700 villages that subsidizes electric heat pumps and electricity, and bans coal. Here, we estimate this programme's impact on household energy use and expenditure, well-being and indoor environmental quality by comparing treated and untreated villages in three districts that vary in socioeconomic conditions. We find that, under this programme, households in high- and middle-income districts eliminated coal use with benefits to indoor temperature, indoor air pollution and life satisfaction. In a low-income district, the policy had partial effectiveness: coal use was contingent on household wealth, and there were fewer benefits to the indoor environment and negative impacts on well-being. These results suggest that a rapid household energy transition can be effective, but it is essential to appropriately control subsidies and fine-tune supports to limit transitional hardships for the less affluent.

The transition of households from coal-based to electric heating is emblematic of the convergence of three global grand challenges: the mitigation of greenhouse gas (GHG) emissions, the reduction of regional and household air pollution as major causes of disease and mortality, and access to affordable, reliable, sustainable and modern energy. At this nexus, China lies possibly most prominent of all, with 30% of global GHG emissions—70% of which are from coal[1]—an estimated 1.6 million yearly premature deaths due to air pollution[2], and over one-third of Chinese homes using coal-heating stoves[3].

In response, China is undertaking an ambitious plan to transition up to 70% of all households in northern China to clean space heating (see Supplementary Note 1 for more context). If the integrated programme proves effective, it will lie in sharp contrast to the many past household energy intervention programmes in China and globally (often for cooking) that have had limited impacts on air pollution and health, despite large allocations of resources[4–7].

Residential coal burning emits a mixture of harmful air pollutants, including high concentrations of particulate matter, into homes and surrounding communities, and also substantially contributes to ambient air pollution, thus impacting populations over large areas[8]. Residential coal burning can account for nearly half (45%) of the monthly averaged outdoor fine particulate matter ($PM_{2.5}$) in winter months in northern China, and up to 57% during winter haze episodes (one to several days), exceeding the combined contribution of the transportation and power sectors[9–11].

In response to severe and persistent haze episodes in northern China, the Chinese State Council released an 'Air Pollution Prevention and Control Action Plan' that set regional coal consumption caps in key regions, including Beijing, Tianjin and Hebei, and ambitious new air quality targets, such as a 25% reduction in annual mean $PM_{2.5}$ concentrations from the 2012 level by 2017[12] (recently updated to make further reductions by 2020[13]). In the effort to meet this target, the Beijing municipal government announced in 2016 an ambitious two-pronged 'coal to electricity' programme (and a parallel 'coal to natural gas' programme) that designates coal-restricted areas and, simultaneously, offers subsidies to night-time electricity rates and for the purchase and installation of electric-powered, air-source heat pumps to replace traditional coal-heating stoves (Fig. 1).

The policy is being rolled out rapidly, village by village, with seeming geographic uniformity. While there is some evidence that the extended mountainous regions within the municipality will systematically receive the policy at later times, there is little that predicts whether villages have these programmes in peri-urban Beijing, and village leaders themselves are unsure when they will receive the policy. From anecdotal discussions with policy implementers, the rationale for when the policy is applied in a village may include considerations for the road network, political feasibility, geographic equity and energy infrastructure, among others. These reasons vary considerably and unsystematically, allowing us to treat the roll-out of the programme as a quasi-randomized intervention.

Various contextual factors, such as financial constraints, preferences and social capital, can determine how households might be impacted by this type of programme. Even just considering simple budget constraints suggests that, when household affluence and subsidies are high enough, households under the coal ban programme will embrace the benefits of convenience and improved indoor air quality, and pay the higher cost of electric heating. When affordability

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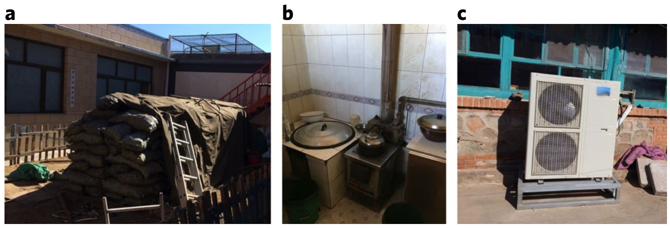

Fig. 1 | Coal storage and heating equipment. a, Coal storage for one household's winter needs is typically conspicuous. **b**, A cook stove (left) and coal heating stove (middle) are both vented to the outside. The coal stove heats water for consumption, as well as for distribution through radiators. **c**, A typical compressor for air-source water-heating heat-pump systems is also conspicuous outside a home in a treated village.

is questionable, households should substitute consumption away from other goods, or possibly increase labour-market participation to fund the transition and higher heating cost. Finally, when household finances are insufficient to cover the cost of the transition, households may cut back on heating and possibly continue burning coal. When enforcement is imperfect, the second and third cases may also be characterized by lesser compliance.

In our study, we compared treated (coal ban in place with installed, subsidized heat pumps and subsidized night-time electricity) and untreated (no ban nor subsidy) villages to assess three types of outcomes of this policy: fuel use and economic behaviour, subjective well-being and indoor environmental conditions. Our study design consisted of 302 door-to-door surveys in six villages, with one treated and one untreated village in each of the three districts chosen to represent the different socioeconomic and geographic conditions present in peri-urban Beijing (Fig. 2). Demographic variables were similar between village pairs, but income differences separated the three districts (Haidian is high income, Fangshan is middle income and Yanqing is lower income). We found evidence that the policy is successful in reducing or eliminating the use of coal for household heating, that these reductions lead to lower exposure to indoor $PM_{2.5}$, and that households generally experience warmer and better-regulated temperatures under the policy. More affluent households reported higher or similar subjective well-being under the treatment, while in the low-income district, satisfaction was lower and the elimination of coal was not entirely effective.

Impacts on household fuel use, expenditure and behaviour

The primary goal of the policy is to eliminate coal from rural household heating. This is intended to occur through fuel substitution, but an overall reduction of heating is also a possible consequence of the policy since the cost of operating a heat pump is greater than that of purchasing coal. Therefore, in addition to surveying households' total expenditures on energy, we also estimated the amount of coal burned in each house, as well as how much indoor space heating was being carried out, room by room.

We found that coal use was entirely absent in treated villages in Haidian and Fangshan, and significantly lower in the treated versus untreated village in Yanqing (Fig. 3). Both types of subsidized technologies (that is, air-to-water heat pumps and air-to-air heat pumps) made significant contributions to the replacement of coal. In addition, in all three districts, heat pumps may have compensated for less efficient resistive electrical heating, as evidenced by the lower (or zero) reported use of resistive heating in treated villages compared with untreated ones.

Total contributions to heating by six different energy sources or technologies, measured as room-hours per day (Fig. 3a), were greater in treated villages compared with their untreated counterparts. In Haidian, total mean heating was significantly higher ($\Delta = 45$ room-hours; $P = 0.002$; $n = 87$) in the treated versus untreated village, as were the fractions of heated house area ($\Delta = 12\%$; $P = 2\times10^{-4}$; $n = 91$) and heated rooms ($\Delta = 7\%$; $P = 0.03$; $n = 87$). Similarly, a higher fraction of rooms was heated in the treated village in Fangshan ($\Delta = 9\%$; $P = 0.04$; $n = 93$) and a higher fraction of house area was heated in the treated village in Yanqing ($\Delta = 14\%$; $P = 0.005$; $n = 87$) compared with their untreated counterparts (Supplementary Table 1), even though treated villages were generally similar, or less affluent, than their untreated counterparts on a variety of objective measures (see Supplementary Note 2 and Supplementary Table 2 for pooled estimates of treatment effects).

These differences are independently corroborated by the expenditures that households reported for coal and electricity (Fig. 3b). The average combined expenditures on electricity (and coal in Yanqing) were higher in treated villages compared with untreated villages (Haidian: $\Delta = \text{RMB}2{,}500\ \text{season}^{-1}$; $P = 0.0001$; $n = 90$; Fangshan: $\Delta = \text{RMB}1{,}700\ \text{season}^{-1}$; $P = 10^{-5}$; $n = 89$; Yanqing: $\Delta = \text{RMB}200\ \text{season}^{-1}$; $P = 0.36$; $n = 87$). In Fangshan, the difference in electricity expenditure was twice the amount spent on coal in the untreated village. In Yanqing, expenditures on coal persisted after the subsidized installation of heat pumps, but were half as high as in the untreated village ($\Delta = \text{RMB}{-670}\ \text{season}^{-1}$; $P = 10^{-7}$; $n = 87$). Treated households in Yanqing used a mix of heat-pump technologies, coal stoves and (to a limited extent) biomass for heating.

The incomplete enforcement of the coal ban in one of our treated study villages (Yanqing district) presents an opportunity for a further examination of household behaviour. Because heat pumps were installed in this village, we are able to examine the dependence of fuel substitution on household financial resources in the case of a subsidized but seemingly voluntary transition away from coal use. Figure 4a shows the relationship within the treated village in Yanqing between the fraction of expenditure on coal and an index of household wealth. The index is constructed as the first principal component of a set of measures of household income, expenditures and assets (see Methods). The relationship between coal use and household wealth is strongly negative ($P = 0.005$; $n = 38$), and nearly all incidences of coal-free households are in the upper half of the wealth distribution (Fig. 4b). Regardless of how much of the electricity expenditure is actually for non-heating needs, this constitutes evidence of a wealth substitution effect away from coal.

We found no differences between village pairs for the number or fraction of household occupants engaged in the labour market, for the monthly consumption of meat or for reported household incomes (Supplementary Table 1).

Impacts on well-being

Dimensions of human well-being, such as comfort, convenience and financial hardship, are often difficult to capture. Households heating with coal are faced with procurement, storage, shovelling and monitoring tasks, in addition to breathing polluted air. However, this is a lower financial burden than electric heating. To try to better account for households' full experience, we asked respondents to report on their overall satisfaction with life (SWL), as a way to quantify their quality of life[14,15].

We found large differences in well-being within two of the districts (Fig. 5). In the middle-income district (Fangshan), where the transition to electric heating was complete, SWL and satisfaction with living conditions (SWC) were higher ($\Delta\text{SWL} = +0.7$ on a 0–10 scale; $P = 0.049$; $n = 93$; $\Delta\text{SWC} = +1.0$; $P = 0.005$; $n = 93$) in the treated versus untreated village. In contrast, in the less affluent (low-income) district, both satisfaction measures were lower ($\Delta\text{SWL} = -1.0$; $P = 0.015$; $n = 87$; $\Delta\text{SWC} = -1.5$; $P = 0.00008$; $n = 87$) in the treated versus untreated village.

These differences are large. In a simple regression explaining SWL as a function of income, the effect on SWL of a doubling of

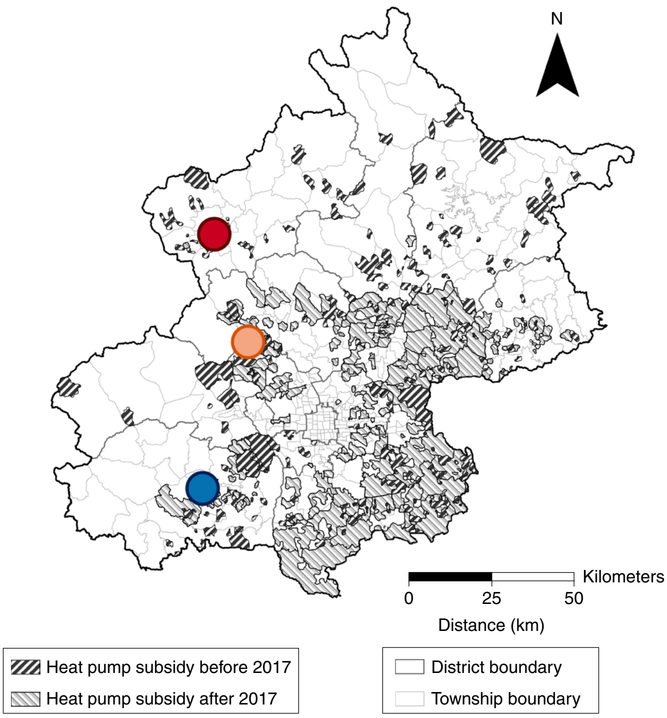

Fig. 2 | Study site locations within Beijing. The study site locations (red, Yanqing; orange, Haidian; blue, Fangshan) contained some villages that had already adopted the coal ban and heat-pump subsidy as of 2017, and some villages that had not. Credit: Beijing Office of Rural Affairs (map outline)

household income was only 0.36 (see Supplementary Note 2 and Supplementary Tables 3–5). The magnitude of this effect is consistent with a large number of studies on SWL and income (for example, ref. [15]). Our observed well-being differences of +0.7 and −1.0 are similar to those one would expect from an income increase of 200% and an income decrease of 85%, respectively. We found no difference in SWL between villages in Haidian, despite larger expenditures on heating and electricity in the treated village.

Impacts on indoor environmental quality

In a randomly selected subsample of 6–12 homes (3–6 d^{-1}) in each village (total $n=55$), we measured the daytime (06:00–20:00) or daily (24 h) indoor air temperature and indoor concentrations of $PM_{2.5}$ in the room where residents reported spending the largest fraction of their awake time (excluding kitchens). For homes with 24-h measurement ($n=26$), we also calculated the average indoor temperature and $PM_{2.5}$ concentration separately for daytime (08:00–18:00) and night-time (18:00–08:00). In addition to indoor sources of $PM_{2.5}$ (for example, combustion of solid fuel and tobacco smoking), indoor air quality was also influenced by $PM_{2.5}$ generated from outdoor sources, such as traffic and local industry, that infiltrated across the residential building envelope, and by the rate at which air moved in and out of the home. Indoor $PM_{2.5}$ concentrations were higher in Haidian than in Fangshan and Yanqing, which probably reflects the higher ambient $PM_{2.5}$ levels on measurement days in Haidian (see Methods). To account for the influence of ambient air pollution, which can vary due to factors independent of coal restriction status, we subtracted time-averaged outdoor $PM_{2.5}$ concentrations from indoor $PM_{2.5}$ concentrations measured and time-averaged over the same time period.

In homes in the two treated villages adhering completely to the coal ban (Haidian and Fangshan), average outdoor-subtracted indoor 24-h $PM_{2.5}$ concentrations (mean ± s.d.: $0.145 \pm 0.218\,mg\,m^{-3}$; $n=7$) were lower compared with untreated homes ($0.275 \pm 0.244\,mg\,m^{-3}$; $n=10$) (Fig. 6a). In Yanqing, where households in both the treated and untreated villages reported using coal, average indoor 24-h $PM_{2.5}$ concentrations were similar (Fig. 6b), with slightly higher concentrations in the treated village ($0.098 \pm 0.117\,mg\,m^{-3}$; $n=4$) than in the untreated village ($0.079 \pm 0.066\,mg\,m^{-3}$; $n=4$). Outdoor-subtracted indoor $PM_{2.5}$ concentrations in Yanqing homes were lower than in homes in Haidian or Fangshan, which may be attributable to higher air change rates in Yanqing homes ($1.9 \pm 0.9\,h^{-1}$) compared with those in Haidian ($0.5 \pm 0.2\,h^{-1}$) and Fangshan ($0.7 \pm 0.3\,h^{-1}$) homes[16,17] (see also the supplementary information files in ref. [17] for full details of the method of estimation). Warmer ambient temperatures on measurement days in Yanqing (16 ± 2 °C) compared with Haidian (9 ± 1 °C) and Fangshan (12 ± 1 °C) may have reduced the demand for heating, and thus coal burning, in Yanqing homes as well.

We observed more pronounced differences in indoor $PM_{2.5}$ levels between homes in treated versus untreated villages (see Methods) at night (18:00–08:00) compared with daytime (08:00–18:00). This may reflect coal burning activity in the evenings for space heating in untreated homes[18,19]. Overall, regardless of time of day, we observed lower indoor $PM_{2.5}$ values in treated versus untreated households, but only in the two districts where treated villages reported adhering to the coal ban. Thus, we interpret these differences to be at least partly attributable to the new household energy-transition policy.

In Fangshan and Haidian, the indoor environment was also warmer in the homes that had transitioned to clean space heating (mean ± s.d.: 18.8 ± 0.7 °C; $n=17$) compared with homes still using coal (17.4 ± 0.5 °C; $n=19$) (Fig. 7). In Yanqing, indoor temperatures were similar, on average, between the two villages (treated: 19.1 ± 0.5 °C; $n=10$; untreated: 19.6 ± 1.3 °C; $n=7$). Treated households in Fangshan and Haidian were consistently warmer than counterpart homes in the untreated villages over the full range of observed temperatures (14–25 °C) during daytime hours. Across the observed temperature range, households in treated villages maintained a narrower range of indoor temperatures, with fewer households experiencing temperatures below the degree-day threshold and more households experiencing temperatures above the degree-day threshold compared with untreated villages in the same district.

One interpretation of these results for Yanqing could be that, at lower temperatures—particularly temperatures below the heating degree-day balance point for China (18 °C)—households in the treated village may have supplemented their clean space heating with coal when their space heating demand could not be met with the new household technology and energy source alone.

Discussion

Four aspects of our findings show that lower indoor air pollution and better convenience associated with the use of heat pumps rather than coal may confer household benefits in the short term that outweigh the higher costs. First, their discretionary use in Yanqing shows that some combination of heat pumps' palpable benefits to health, comfort and convenience are jointly sufficient for households to prefer paying a higher price to heat, at least partially, with electric heat pumps rather than coal. Our most telling finding in the treated village in Yanqing is that wealthier households are the ones that eschew coal entirely. This means that the relationship shown in Fig. 4a is more than a reflection of higher consumption of electricity for non-heating purposes by the wealthy; instead, it constitutes behavioural evidence that, at the existing prices, the switch away from coal to new electric technology is desirable. Second, the undiminished or higher satisfaction of residents in the coal ban villages in Haidian and Fangshan suggests that, despite large increases in expenditures, the transition away from coal is a net benefit. A caveat is that we cannot precisely distinguish between electricity expenditure

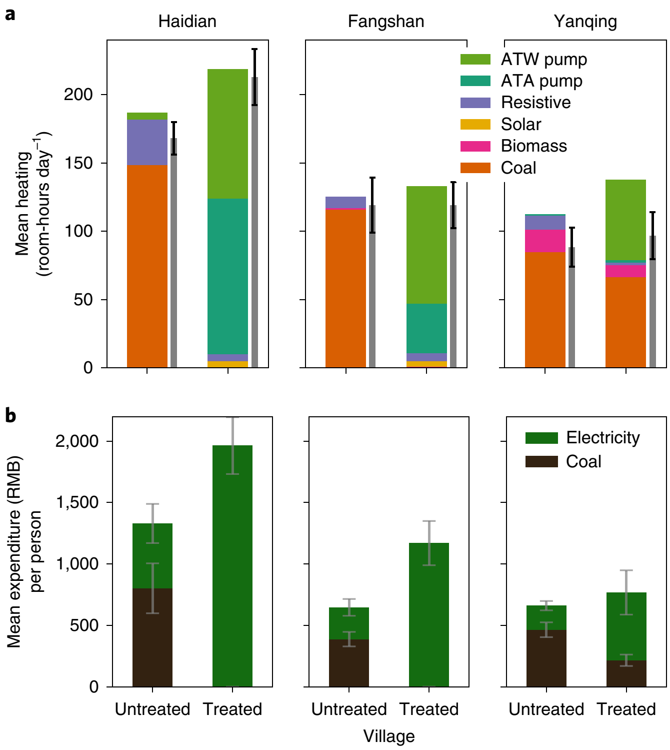

Fig. 3 | Heating and expenditure for coal and electricity. a, Stacked coloured bars show the total contributions to heating by six different energy sources or technologies, measured as room-hours per day per household in treated and untreated villages in Haidan (treated, $n = 42$; untreated, $n = 45$), Fangshan (treated, $n = 48$; untreated, $n = 45$) and Yanqing districts (treated, $n = 39$; untreated, $n = 48$). The grey bars quantify total heating. Means were calculated across households, the majority of which use one method for heating (see Methods). The 'resistive' category includes mobile electric heaters, wall-mounted electric heaters, electric floor heating, thermal storage (electricity), electric blankets, air conditioners used in ohmic heating mode, and hot-water radiators fired by electric heaters. The 'biomass' category refers to wood-fired kangs (under-bed heaters). The 'coal' category includes coal-fired kangs, coal-fired open stoves and coal-fired hot-water radiators, using various grades of coal. ATA, air-to-air heat pumps; ATW, air-to-water heat pumps. **b**, Mean expenditure on coal and electricity for the entire heating season in treated and untreated villages in Haidian, Fangshan and Yanqing districts. Error bars show 95% confidence intervals.

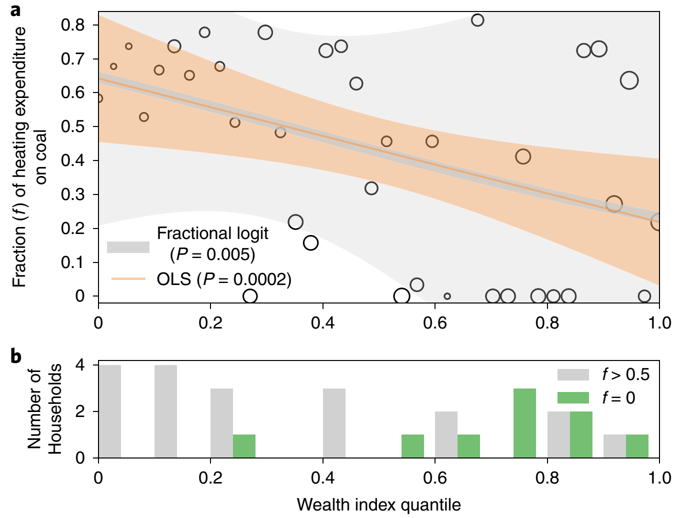

Fig. 4 | Coal use versus wealth. Households are from a village with subsidized, installed heat pumps but incomplete enforcement of the coal ban. Households with a higher wealth index spend less on coal as a fraction of their total heating-related expenditures. **a**, Linear OLS and fractional logit models for this relationship gave nearly identical predictions, with high statistical confidence. The shaded regions show 95% confidence intervals. The circle size indicates the reported household income. **b**, Wealthier households are more likely to eschew coal completely (coal fraction of expenditure $f = 0$), and less likely to spend at least half ($f \geq 0.5$) of their heating/electricity budget on coal. See Methods for details of the household wealth index and estimates.

on heating versus other household appliances. Therefore, some of the programme benefit for these wealthier households may be the subsidized marginal cost, and consequent higher consumption, of other electrified services in the home. Third, in wealthier districts, indoor temperatures were higher, suggesting that the overall benefits of non-coal heating were such that households shifted their expenditures towards it. Fourth, all treated villages heated a higher fraction of rooms or area than their untreated counterparts. This provides further support for our interpretation that the non-pecuniary costs (inconvenience and discomfort) of heating by coal can be more important than the lower price.

These findings are remarkable because most of the programme benefits are likely to come through long-term outcomes such as reduced GHG emissions, improved air quality and better population health outcomes—benefits that are external to the individual affected households. Indeed, even if the overall benefits to rural households under the programme were negligible or slightly negative, the programme could provide net benefits to the region.

The importance of our findings (and this programme) is underscored by ambitions within the United Nations' Sustainable Development Goals (SDGs)—in particular, SDG 13 (climate action), SDG 3 (health and well-being) and SDG 7 (clean energy)—and by the challenges experienced in the past. Previous large-scale rural energy programmes in China were enormously successful in deploying cookstoves into hundreds of millions of homes[4,5], but resulted in low sustained levels of stove use[6] and marginal or no improvements in indoor air quality[7]. In contrast, our results are consistent with Beijing's coal-to-electricity programme changing behaviour while improving well-being, thus achieving its desired social and environmental aims.

Based on evidence from our treated, lower-income village, this appears to be in part a reflection of heat pumps' technological efficiency. With electricity subsidies and heat pumps in place in the lower-income district, we observed heat-pump usage but near-zero use of traditional electric heating ('resistive' in Fig. 3). Thus, the heat pumps' factor of around threefold higher efficiency, possibly along with their better safety and convenience, apparently made their use—but not that of traditional electric heaters—economical in this district with the electricity subsidies in place. Notably, we did not observe higher use of biomass fuel in any of the treated villages, indicating that they did not switch to another inexpensive and polluting solid fuel as a replacement for coal.

As a cross-sectional survey, our study had limitations in its ability to identify causal effects. However, we note that each of our village pairs had similar characteristics, including location, and economic and demographic characteristics. In addition, our ability to leverage within-village variation in the case of the treated Yanqing village complements and corroborates our comparative approach. While our villages generally reflect conditions in greater Beijing, our small sample also limits our ability to generalize to the region. Our study focused on the replacement of coal by electricity, despite the

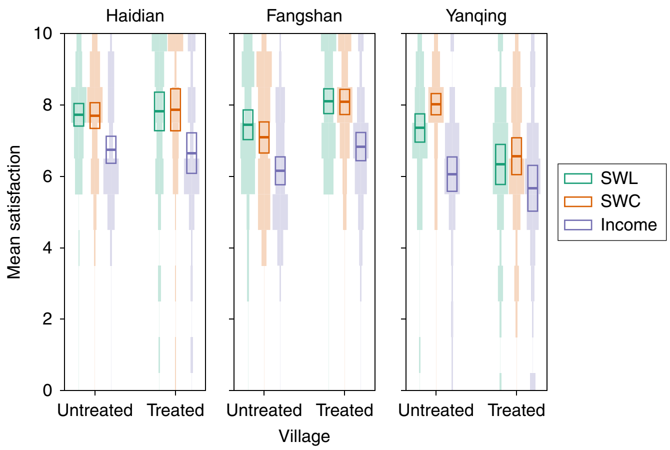

Fig. 5 | Subjective evaluations of well-being. Ratings of SWL (green), SWC (orange) and income (purple) in treated and untreated villages in Haidan (treated, $n=44$; untreated, $n=47$), Fangshan (treated, $n=48$; untreated, $n=45$) and Yanqing districts (treated, $n=39$; untreated, $n=48$). Means and 95% confidence ranges are shown by the boxes. The shaded regions show full distributions over discrete response values.

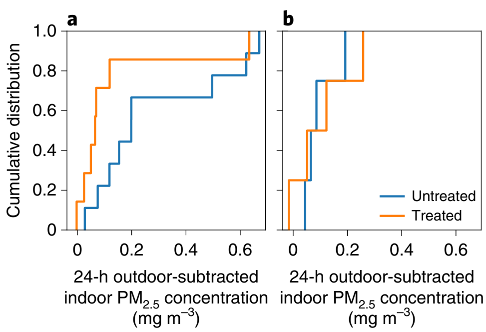

Fig. 6 | Cumulative distributions of indoor 24-h $PM_{2.5}$ concentrations. **a**,**b**, Average 24-h outdoor-subtracted indoor $PM_{2.5}$ concentrations in treated and untreated villages in Fangshan and Haidian (**a**; treated, $n=8$; untreated, $n=9$), where participants in the coal-restricted villages did not report coal use, and Yanqing (**b**; treated, $n=4$; untreated, $n=4$), where participants in the coal-restricted village reported using coal.

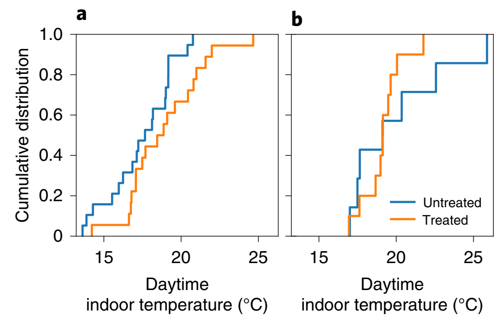

Fig. 7 | Cumulative distributions of observed daytime temperature. **a**,**b**, Average daytime temperature in treated and untreated villages in Fangshan and Haidian (**a**; treated, $n=18$; untreated, $n=19$), where participants in the coal-restricted villages did not report coal use, and Yanqing (**b**; treated, $n=10$; untreated, $n=7$), where participants in the coal-restricted village reported using coal.

existence of a parallel coal-to-natural-gas programme that may not have had an identical geographical distribution[20]. We assessed household concentrations of $PM_{2.5}$ but did not directly measure personal exposures or quantify the programme's acute or long-term health impacts, even though these may be the most important benefits of the programme. Similarly, while a systematic review of randomized evaluations showed that household temperature and energy interventions can improve both physical and mental health outcomes, as well as socioeconomic indicators[21], our study did not measure these benefits directly. Further qualitative work may be able to illuminate other non-financial impacts of the programme.

Untreated villages in our sample burned on average 3.7, 4.2 and 3.4 tonnes of coal per household per winter in Haidian, Fangshan and Yanqing, respectively, while treated villages burned on average 0, 0 and 1.8 tonnes per household. If these are representative effects, it can be expected that the programme might achieve an annual reduction of 6.6 Mt of coal combustion, similar to the total estimated for household heating in Beijing before the coal reduction programme[20], and corresponding to ~13 $MtCO_2e$ of GHG emissions assuming an eventual transition to renewable generation of electricity, and ~6.6–66 kt of particulate matter emissions. Reducing domestic coal burning in China would decrease emissions of important gaseous pollutants, including SO_2 and NO_x, which also contribute to environmental and health impacts through secondary formation of particulate matter, ecosystem acidification and regional climate change. Furthermore, household coal emissions are uniquely hazardous to human health compared with other solid fuels[22], and are classified as carcinogenic to humans[23]. Eliminating emissions from domestic coal combustion in China could reduce annual mortality by over 40,000 premature deaths[24], based only on the contribution of household coal use to ambient air pollution, and reduce exposures for the >200 million Chinese homes using coal stoves[3].

Our positive findings for programme outcomes in terms of indoor daytime temperature, night-time and 24-h air pollution, overall SWL and avoidance of coal burning all hold primarily for wealthier homes. With sufficient resources, households under the policy appear to be willing to pay more for non-coal heating, heat more rooms, keep higher indoor temperatures and have better indicators for their physical and psychological outcomes. However, if many households are economically unable to comply with the coal ban or suffer a reduction in life quality as a result of it, the scalability and political portability of the policy may be questionable, even if the subsidies are sustainable and net benefits to the aggregate population are positive overall. Our findings could be taken to suggest that subsidies may not have been equally necessary in each village or for each household, and may, arguably, have been insufficient in Yanqing (and by the same token, lower subsidies might have achieved the same result in Haidian). We focused on household benefits and costs, but did not evaluate the net benefits in light of the substantial subsidies involved.

As a ground-breaking model for rapid transition and technological 'leap-frogging' to address simultaneously climate, health and development, Beijing's ambitious policy deserves global attention and monitoring. Future research should better quantify the health effects and savings of the policy, and follow households through the transition to better identify causal effects of the natural experiment provided by the distributed roll-out of the programme.

Methods

Sample. We selected three districts (Fig. 2) within the Beijing Municipality that cover a range of economic and geographic conditions (see Supplementary Note 1 for more context). Haidian was selected for its close proximity to Beijing city and relatively high living standards; Fangshan represents a 'typical' peri-urban suburb of Beijing; and Yanqing is a more mountainous area on the fringes of the Beijing Municipality. Within each district, we selected two villages within relatively close proximity to one another. One was a current participant in the coal-to-electricity programme (treated) and the other was not yet enrolled (untreated). In each village, we first met with local village leaders to obtain permission to conduct the surveys.

Within villages, the selection of households was semi-random. While enumerators were instructed to select households randomly, village leaders were often helpful in identifying homes with household members currently present. In some villages, this approach reached a considerable fraction of the total number of households, further minimizing any possible sample bias.

Before data collection, we piloted a preliminary survey instrument with ~25 households in Haidian and Yanqing districts to ensure our instrument accurately reflected the range of situations we might encounter. Our survey instrument and procedures complied with, and were approved by, the research ethics board at McGill University. Informed consent for the study was obtained from all participants.

Sampling was carried out in March and April of 2017. Surveys included a complete roster of heating methods and their contributions in each room. All survey data were collected via handheld electronic tablets using Surveybe data collection software, which facilitated secure data transmission and archiving, and minimized input errors, with a field team hired locally. Visual surveys of the home were also conducted to assess household amenities and verify respondent reports regarding fuel use; signs of coal storage and use are generally clearly discernible (Fig. 1).

Our overall sample included 302 households, distributed across six villages in Haidian (treated, $n=50$; untreated, $n=52$), Fangshan (treated, $n=50$; untreated, $n=50$) and Yanqing (treated, $n=50$; untreated, $n=50$). Supplementary Table 6 shows descriptive statistics for our main survey variables. Due to some non-responses, our sample sizes are slightly smaller than 302 for most statistics; exact values are listed in Supplementary Table 6.

Due to our cross-sectional design, we compare villages both to show similarity and to estimate treatment effects, through simple t-tests of village means. Supplementary Table 1 shows comparisons between village pairs for a number of variables that are roughly grouped into those we considered to be independent (slow to change) and those we considered to be possible response variables. Supplementary Fig. 1 illustrates two independent variables and four response variables.

Measurements. In households selected (randomly) for instrumentation, sensors for indoor temperature (Thermochron iButtons; models DS1922L and DS1921G; Berkeley Air) and $PM_{2.5}$ concentration (DustTrak Model 8520; TSI) were deployed at a height of approximately 1.0–1.5 m in a common occupied room (not a kitchen) at a location that would not interfere with household activities. In these locations, temperature sensors were attached to an internal wall of the home. Measurements were averaged over ten-minute intervals, recorded on the device and downloaded at the end of the measurement onto a project computer. Time-weighted means for temperature were computed over the sampling period in each home ($n=55$). Time-weighted means for indoor $PM_{2.5}$ concentrations were computed in each home ($n=55$) with and without subtracting hourly outdoor $PM_{2.5}$ concentrations[25], which were obtained from the nearest environmental air quality monitoring stations (Supplementary Table 7) operated by the Beijing Municipal Environmental Monitoring Center in each district in Beijing. The average distance of our study villages to the nearest outdoor monitoring station was 6.3 ± 1.9 km.

Temperature measurements. Supplementary Fig. 2 provides comparisons of the cumulative distribution functions of observed indoor temperature for mean daytime temperatures, mean night-time temperatures and 24-h mean temperatures. As described in the main text, we grouped the middle- and high-income districts together to maximize the sample size.

$PM_{2.5}$ measurements. The air pollution estimates from the light-scattering laser photometers used in this study were subject to measurement error, and were thus calibrated against indoor and outdoor 'gold-standard' gravimetric $PM_{2.5}$ measurements conducted in settings where household solid fuel burning contributes to air pollution (see below for more detail on the calibration of light-scattering measurements).

We removed one household observation with an indoor $PM_{2.5}$ concentration $>1\,mg\,m^{-3}$ (or $1{,}000\,\mu g\,m^{-3}$) because the continuous measurement was indicative of potential instrument failure. Supplementary Fig. 3 shows daytime, night-time and 24-h distributions of $PM_{2.5}$ with this observation excluded, while Supplementary Fig. 4 shows the same distributions without the exclusion.

Indoor $PM_{2.5}$ concentrations may be influenced by particulate matter of outdoor origin that infiltrates across the residential building envelope. In our study, daily average outdoor air pollution levels were higher on days when measurements were conducted in Haidian compared with days when measurements were conducted in Fangshan or Yanqing (Supplementary Table 8). Indoor $PM_{2.5}$ concentrations (Supplementary Fig. 5) were also higher in Haidian compared with indoor $PM_{2.5}$ concentrations in Fangshan and Yanqing, which we interpret to be partially attributable to the infiltration of $PM_{2.5}$ of outdoor origin. Supplementary Fig. 6 shows the indoor and outdoor concentrations on sampling days.

Subjective measures. Our survey included three questions soliciting subjective evaluations in the form of overall SWL, SWC and satisfaction with household income. The wordings/translations are as follows: "总的来说, 您对现在的生活满意程度评价如何? 请选择0–10的整数" ("Taking all things into account, how satisfied are you with life as a whole these days? (0–10)"); "总的来说, 您对现在的居住环境满意程度评价如何? 请选择0–10的整数" ("How satisfied are you with your living conditions as a whole? (0–10)"); and "总的来说, 您对现在的家庭收入满意程度评价如何? 请选择0–10的整数" ("How satisfied are you with the income of your household? (0–10)"). These questions were answered on an 11-point numerical scale with end points anchored at "Completely unsatisfied (0)" and "Completely satisfied (10)".

These questions (in particular, the first one) are semi-standardized[26,27] and the subject of a large number of studies. SWL is typically used to assess the integrated impact, or costs and benefits, of all social and material conditions of life, including environmental and other outcomes not accessible by revealed preference (choice) or market measures. Studies can simultaneously resolve variation due to income and small variations in environmental pollutants[15,28].

Statistical tests and inference. Due to the small sample sizes for temperature and $PM_{2.5}$ concentrations, we did not carry out formal difference tests, but instead report means and standard deviations of comparison groups.

For other statistics where we report standard errors for regression coefficients or means, intervals can be calculated for a desired confidence level by assuming normality of errors.

While we could not statistically identify causal effects in our sample, the interpretation of reduced or zero coal use as outcomes of the coal ban policy is reasonable even in principle. Our estimates of the resultant particulate and GHG emission impacts of the programme make use of emission factors of ~2 tCO_2e per tonne of coal[1,29] and ~1–10 kg of particulate matter per tonne of coal[1,30–32]. Our extrapolation assumes 2.1 million rural households (7.9 million residents, with an average household size of 3.8 residents) and, from our sample, a reduction in coal use of 3.17 tonnes per household.

Wealth index. Although we asked for self-reported income, savings and loans, enumerators reported resistance and unreliability for these questions. To supplement these self-reported measures, we took an inventory of certain appliances in each sampled home and categorized them heuristically into three groups. Class 1 represents major investments (cars and stoves); class 2 represents large convenience appliances and investments (motorbikes, scooters, fridges, washing machines and freezers); and class 3 represents smaller appliances and luxury items (computers, televisions, air cleaners, microwaves and air conditioners). Our variables describing each category were the total number of appliances observed.

To discriminate between different levels of affluence within and between villages, we constructed an index from the available information on household assets, expenditures and income, using a principal components analysis following the asset index literature[33]. We treated this combination of measures as complementary components of wealth. Especially in light of China's notoriously high savings rates[34,35], we chose not to rely simply on assets alone (as does much of the asset index literature). We further used the heuristic categorization for assets to avoid problems of high dimensionality with low sample sizes in principle components analysis[36].

Supplementary Fig. 7 shows that the first component captured 40% of the overall variance, and we therefore took it as a scalar measure of wealth. The constituent variables and coefficients comprising the first three components are given in Supplementary Table 9. The first component has positive and uniformly large coefficients on all of our proxies for wealth. Moreover, as a further check on the meaningfulness of our wealth index, we plotted mean values of each constituent measure for households grouped by the wealth index, and found quasi-monotonicity for every measure (Supplementary Fig. 8).

Supplementary Fig. 9 shows the distributions of household asset inventories for assets comprising our three groups. Our asset counts were capped at four (for 'four or more'). Except for motorbikes, there were no rare assets nor outlier counts. When aggregated into our three classes, the asset counts were well distributed.

Characterization of household heating. Our survey recorded for each household a roster of all methods used to heat each room, and for how long each method contributed to heating. In addition, when a room's heating methods included a wall-mounted or under-the-floor hot water radiator, we considered it to be heated by the methods used to power the radiator system in the household. In some cases (Supplementary Table 10), radiator systems were heated by more than one method. In these cases, we obtained no record of which radiator heat source was being used during the time when a given room was heated. To minimize double counting of heat sources, we made the following simplifying assumptions: (1) when electrical resistive heating and an air-to-water heat pump were both connected to a hot water radiator system, the resistive heater was considered not to be used; and (2) when a solar heater was connected to a radiator also heated by either coal or an air-to-water heat pump, the solar heater was considered not to be used. The resulting simplified distribution of radiator heat sources still contained some multiple-heating cases, but they constitute a small fraction of the total (Supplementary Table 11).

In the majority of households, one heating method accounted for all of the room heating. In some cases, houses used more than one method (Supplementary Table 12) to heat, and in some cases individual rooms were considered to be heated by more than one method. When two methods were recorded as heating the same room, we assumed that the heating times overlapped. Thus, we attributed the largest daily heating times among methods used for a given room as the room's heating time when estimating total room heating for a household (grey bars in Fig. 3). This overlap accounts for the fact that the grey bars in Fig. 3 are shorter than the stacked coloured ones.

Calibration of light-scattering laser photometers. Our real-time indoor $PM_{2.5}$ measurements were conducted using laser photometers, which are subject to measurement error. However, we applied a correction factor based on co-location of these instruments with 'gold-standard' gravimetric measurements in previous studies where household solid fuel burning contributed to air pollution, and the residual error in $PM_{2.5}$ measurement due to monitors should be randomly distributed across our study households. Similarly, while there was probably some measurement error in our estimated village-level outdoor $PM_{2.5}$ concentrations, by using the nearest outdoor air monitoring station as a surrogate, the distance to the nearest station was similar for treated (4.0–8.0 km) and untreated (3.0–7.5 km) villages. Thus, while the absolute values of indoor $PM_{2.5}$ and outdoor-subtracted indoor $PM_{2.5}$ concentrations may slightly change with the use of different air-quality instruments or with local measurement of outdoor particulate matter with the same instruments, our overall findings on the differences in indoor $PM_{2.5}$ between treated and untreated villages should not be impacted or would be underestimated.

The light-scattering laser photometers (DustTrak 8520; TSI) used in this study were calibrated against 'gold-standard' gravimetric monitors in separate studies that observed very similar levels of instrument bias. The first study involved winter and summer measurements of indoor (household) and outdoor $PM_{2.5}$ levels in Windsor, Ontario (Canada)—a moderate-pollution setting where industrial coal burning and household wood-burning stoves contribute to outdoor particulate matter (pooled positive bias of a factor of 2.64 for outdoor $PM_{2.5}$, estimated using ordinary least squares (OLS) regression; $n = 799$ measurement days). The level of positive bias in that study was similar for indoor particulate matter (factor of 2.39)[37]. The second study using the same laser photometers also included indoor $PM_{2.5}$ measurements that were conducted in urban and peri-urban Bucaramanga (Colombia) where solid fuel burning and traffic contribute to moderate particulate matter levels (positive bias of a factor of 2.49, estimated using OLS regression; $n = 23$ measurement days; unpublished data). The average bias-corrected precisions in those studies were within 10%, indicating that a proper correction for bias brought the same instruments used in this study into very good agreement with standard reference methods. Notably, the instrument bias factors observed in the Canada and Colombia studies were nearly identical to the factor estimated for the same Model 8520 DustTrak instruments after co-location with gravimetric instruments in our previous study of household solid fuel burning in rural China (positive bias of a factor of 2.67, estimated using OLS regression; $n = 424$ measurement days)[17]. Together, these studies show that the laser photometers used in this study are consistent in their instrument bias factors across diverse indoor and outdoor study settings and air pollution ranges, and that correction for that bias can lead to estimates of $PM_{2.5}$ concentrations that are similar to those obtained by 'gold-standard' instruments.

To further evaluate the use of a single correction factor in a setting where coal burning is a contributor to particulate matter, we co-located four of the DustTrak instruments used in this study with an outdoor reference monitor (Thermo Scientific Model 5030 SHARP) located on the roof of a building on the Peking University (Beijing) campus in the winter season when household coal burning is estimated to be a large contributor (30–50%) to ambient air pollution[9,11,24]. The DustTrak instruments and reference monitor were simultaneously run for a period of five consecutive days, and we compared the average within-day bias across monitors. The within-day coefficient of variation for the instrument bias factors ranged from 6–13% (median = 9%), indicating very good consistency in the degree of measurement error across monitors.

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

Data availability

Datasets generated and analysed during this study will be made available on a case-by-case basis on request to the corresponding author, with input from the co-authors, subject to compliance with Research Ethics Board restrictions for the survey data.

Received: 3 October 2018; Accepted: 1 April 2019;
Published online: 13 May 2019

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Acknowledgements
We are grateful to A. Ballyk and M. Smailes for research assistance, and S. Harper and R. Ravishankara for comments on a draft of the manuscript. This work was supported by a McGill University Emerging Scholars Accelerator grant and by Canada's Social Sciences and Humanities Research Council grants 435-2016-0531 and 430-2017-00998.

Author contributions
C.B.-L., J.B., E.C. and B.R. designed the study, led the field work and wrote the paper. C.B.-L. and E.C. carried out the analysis. C.B.-L., J.B., E.C., B.R., S.T. and Y.Z. discussed the results and commented on the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Supplementary information is available for this paper at https://doi.org/10.1038/s41560-019-0386-2.

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Last updated by author(s): Mar 27, 2019

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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Surveybe Implementer v8 was used on tablets, running Android, for household surveys
Data analysis	Stata v14 was used for some estimates, along with numerous standard open source tools in Python for data analysis.

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

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Datasets generated and analysed during the current study will be made available on a case-by-case basis by the corresponding author with input from co-authors, subject to compliance with Research Ethics Board restrictions for the survey data.

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☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

Behavioural & social sciences study design

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

Study description	Quantitative cross-sectional
Research sample	Village residents, age greater than 18, able to represent the household. Sample is roughly representative of households in each village. Our design was chosen to allow for variation across districts / income levels but to rough match treated /untreated villages within a district.
Sampling strategy	Our sampling within villages was quasirandom. Our choice of villages incorporated convenience. Our sample sizes are ex post justified by the statistical significance of our findings. Fifty per village was considered to be a minimum sample size for estimation of mean subjective well-being.
Data collection	Field leaders knew the intent of the project; enumerators were not specifically briefed in any hypotheses. All surveys were conducted using tablet computers and our own survey, designed and implemented using Surveybe software. Instrumentation data were collected as described in methods.
Timing	Data were collected between March 20 and April 9, 2017.
Data exclusions	One data point was excluded in some PM analysis in the main text, but the analysis is repeated without exclusion in the SI.
Non-participation	No participants were recorded as completely refusing the survey.
Randomization	Treatment of villages was exogenously selected by higher levels of government.

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Materials & experimental systems

n/a	Involved in the study	
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☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology
☒	☐	Animals and other organisms
☐	☒	Human research participants
☒	☐	Clinical data

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics	See above.
Recruitment	Participants were recruited by knocking on their doors while walking around the village. Villagers who were not present were not included. We cannot evaluate the bias associated with this selection (it could go either way).
Ethics oversight	McGill University's research ethics board approved this work.

Note that full information on the approval of the study protocol must also be provided in the manuscript.