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PRIVATE ACTIONS IN THE PRESENCE OF EXTERNALITIES: THE HEALTH IMPACTS OF REDUCING AIR POLLUTION PEAKS BUT NOT AMBIENT EXPOSURE

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ABSTRACT

Extensive research has documented that elevated air pollution increases mortality and morbidity, with estimates reaching 8 million deaths per year. Many of the world's one billion urban poor face both high ambient concentrations and even higher transient peaks. Should government interventions aimed at improving health prioritize reductions in ambient pollution—for example, regulating industrial emissions—or peak pollution? We conduct a field experiment studying the impacts of reducing a notorious source of peak air pollution exposure—biomass cooking—for three years in an urban environment with high ambient pollution. We collect personal, high-frequency particulate matter and carbon monoxide measurements and extensive quantitative and self-reported health measurements. Cooking increases peak PM2.5 exposure by 125 μg/m³ for the control group, but improved stove ownership reduces this by 52 μg/m³—a sizeable 42% reduction in peak cooking emissions. However, ambient pollution of 37.5 μg/m³ largely negates any impact on average air pollution exposure. The reduction in peak cooking emissions generates a 0.24 standard deviation reduction in short-term self-reported respiratory symptoms. However, we can rule out meaningful improvements in blood pressure, blood oxygen, and a wide array of self-reported diagnoses. Ambient air pollution dampens the health benefits from private technology adoption, and a government seeking to generate chronic health improvements will likely need to address negative externalities through environmental regulation. Still, despite the importance of ambient pollution, the \$40 stove generates \$86 in annual energy savings and reduces CO_2 emissions at \$4.9 per ton when factoring in additionality rates, suggesting government subsidies would generate large societal benefits.

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A data appendix is available at
http://www.nber.org/data-appendix/w31614
A randomized controlled trials registry entry is available at
https://www.socialscienceregistry.org/trials/2484

1 Introduction

According to the World Health Organization (2021) air pollution is "the single biggest environmental threat to human health." The Global Burden of Disease study (Lancet, 2017) estimates that it is responsible for 7–9 million premature deaths annually (10-15% of all deaths). While these figures suggest air pollution is a pressing public health problem, existing research does not distinguish between the health impacts of the most extreme peak pollution events within a day and sustained exposures to ambient pollution. Because the former is largely driven by private actions, optimal policy to address these exposures would focus on frictions that prevent individuals from making privately optimal choices. Addressing the latter would require correcting the significant negative externalities that drive poor ambient air quality. To evaluate how prioritizing the former would impact health, we study the impacts of reducing one of the most notorious sources of peak air pollution—charcoal cooking—in an urban environment with high ambient pollution.[1]

We conduct a randomized field study in Nairobi, Kenya to estimate the impact of improved cookstove adoption on pollution and health. We offer randomized subsidies and access to credit to create random variation in the adoption of an improved cookstove, and follow up with study participants after 3.5 years of daily use. To measure individual pollution exposure, each respondent wears a backpack containing two devices that record particulate matter smaller than 1.0 or $2.5\mu m$ (PM1.0 and PM2.5) and parts-per-million of carbon monoxide (CO ppm) on a minute-by-minute basis for 48 hours. High-frequency monitoring allows us to separately identify impacts on mean and peak pollution exposure. A complementary time use survey records each respondent's indoor or outdoor activity during each of those 48 hours. To measure health, we complement quantitative measurements of blood pressure, pulse oximetry, and anthropometrics with detailed self-reports on health symptoms and diagnoses for adults and children. Finally, we use a socio-economic survey to measure behavioral and financial impacts.

The analyses generate three key findings. First, the improved stove reduces peak cooking emissions by 42%. For the control group, peak emissions while cooking are 125 $\mu g/m^3$ higher than their median daily exposure, but improved stove ownership reduces this by 52 $\mu g/m^3$.[2] Average exposure while cooking is 50 $\mu g/m^3$ among the control group and 33 $\mu g/m^3$ for the treatment group (p-val < 0.01); for comparison, average exposure while not cooking is 36 $\mu g/m^3$ for both groups. These results are stable, and relatively precise in part due to the persistence of the adoption subsidies: 86% of respondents have the same adoption status as 3.5 years ago.

Second, high levels of ambient pollution largely negate the mostly transitory reductions in peak cooking emissions. Study participants report cooking for only two hours per day on average (9% of the time). The large reductions in cooking pollution therefore have negligible impacts on mean

[1] Pervasive charcoal cooking may also be a major contributor to ambient pollution. However, optimal policy still depends on whether the harm from the cookstove is mostly private (arising from the owner's own usage), or due to poor ambient quality driven by others' use of cookstoves. In the latter case, enabling individuals to make privately optimal choices (for example through the loans we study in Berkouwer and Dean (2022a)) will not be sufficient as it does not incentivize them to internalize the externalities.

[2] The EPA (2018) considers >55 $\mu g/m^3$ (150 AQI) to be 'unhealthy' and >150 $\mu g/m^3$ (200 AQI) 'very unhealthy'.

exposure, which averages 38 $\mu g/m^3$ among the control group ($\hat{\beta}$: –0.8, 95% CI: [-7.5, 5.9]).

Given the limited changes in daily average concentrations, does the reduction in peak cooking emissions affect health? We estimate that adoption causes a statistically significant 0.24 standard deviation (SD) reduction in an index of transient self-reported respiratory symptoms such as sore throat, headache, cough, and runny nose. These are likely a direct result of reductions in peak emissions, and an analysis of the mechanisms confirms that these respiratory symptoms are correlated with peak levels and not with average concentrations. However, we see no impacts on an array of clinical, quantitative health measurements (including blood pressure and blood oxygen), medical diagnoses (including pneumonia), or health-related expenditures.[3] In other words, against a backdrop of high ambient air pollution, the large reductions in peak cooking emissions appear to have had negligible impacts on long-term indicators of health during the 3.5 years of ownership. Participants may have already been aware of this: at baseline, 37% of respondents believed that adoption of the improved stove would have no impact on their health (another 20% believed it would have a small impact), and these beliefs did not predict WTP—unlike beliefs about financial savings.[4]

Billions of urban poor are exposed to high levels of both ambient and own-cooking related emissions on a daily basis. More than 90% of pollution-related deaths occur in low- and middle-income countries (WHO, 2021). For the 4 billion people lacking access to improved stoves (World Bank, 2020), intermittent use of traditional cookstoves is a key driver of transient pollution peaks. However, the lack of impact on measurable or chronic health outcomes that we estimate indicates that private actions alone can generate only modest health benefits over the course of 3.5 years. While it is possible that benefits would emerge over a longer term, this suggests government regulation of the economic activities that generate the ambient pollution externality are a more promising approach to generating meaningful health benefits. This is especially the case in cities with the highest ambient air pollution: while average annual ambient PM2.5 concentrations are higher in Nairobi than in many OECD cities, they are higher still in many other cities.[5,6]

Our use of personally wearable PM and CO pollution monitoring devices to collect high-frequency, indoor and outdoor air pollution measurements advances our understanding of how transient peaks in air pollution exposure affect health. Existing research on ambient air pollution almost exclusively evaluates mean daily exposure.[7] Gong et al. (2023), He, Fan, and Zhou

[3]We can rule out a 0.14 SD or greater reduction in health diagnoses, and comparing our cardiovascular impacts with the medical literature we can reject a 12% or greater decrease in major cardiovascular events.

[4]Table 4 of Berkouwer and Dean (2022a) reports health and savings beliefs in different units. Standardizing both outcomes yields the following results: increasing health beliefs by 1 SD decreases WTP by \$0.01 (p=0.988) while increasing savings beliefs by 1 SD increases WTP by \$0.79 (p=0.036).

[5]As examples, annual PM2.5 concentrations average 13 $\mu g/m^3$ in Los Angeles and in Rome, 30 $\mu g/m^3$ in Kampala and in Accra, but 49 $\mu g/m^3$ in Jakarta, 83 $\mu g/m^3$ in Dhaka, and 99 $\mu g/m^3$ in Delhi (IQAir, 2019).

[6]One may be concerned that this poses challenges to the external validity of our study. For example, if ambient concentrations are higher, the subsequent peaks must be even higher and perhaps reducing those has positive health impacts. While we cannot rule this possibility out with our data, it is worth nothing that similarities in cooking technologies likely mean the size of the peaks relative to the ambient concentration are similar across the contexts. This means the peaks are likely to be an even smaller portion of an individuals total pollution exposure in more polluted settings.

[7]See Clay, Lewis, and Severnini, 2022; Deryugina et al., 2019; Graff Zivin and Neidell, 2012; Greenstone and

(2016), and La Nauze and Severnini (2021) do study non-linearity in the dose-response function, however they primarily focus on concavity in daily average pollution exposure. Caplan and Acharya (2019), Cropper et al. (2014), Cutter and Neidell (2009), and Henderson (1996) study how regulations and firm actions affect peaks in pollution (also known as 'episodic pollution' in this literature), but do not measure any health outcomes. Several additional papers document causal links between health and air pollution in unique experimental and quasi-random settings,[8] but the relevance of these relationships for realized exposure in daily life remains unclear. One notable exception is Hansman, Hjort, and León (2018), who find that a given amount of pollution exposure has larger health impacts when emitted over an extended period of time than when concentrated into a short-term period. The dearth of research on short-term exposure creates uncertainty for policy-makers around the optimal targeting of costly environmental regulations, for example, regulating peak hours versus annual average concentrations. Improving our understanding of these relationships is crucial for optimizing environmental regulations, especially if daily averages and transient peaks have heterogeneous health effects. The Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS), for example, targets both 365-day averages and 1-hour peaks, which could have significant heterogeneity in both regulatory costs as well as economic costs and benefits (EPA, 2023).

This paper also contributes rigorous causal evidence to the ongoing policy debate around the transition towards cleaner cooking technologies (Gill-Wiehl and Kammen, 2022). Extensive research has associated a wide range of health problems with energy-intensive cookstove usage, but most papers are correlational rather than causal, or focus on adoption rather than on the impacts of improved cookstoves.[9] A recent meta-analysis in *The Lancet* identified 437 studies on the health impacts of cookstoves: only six were randomized trials (Lee et al., 2020). The article identified an "urgent need for clinical trials evaluating cleaner fuel interventions on health outcomes to underpin evidence-based policy and decision making." Randomized studies on improved cookstoves often are limited to short-term outcomes, lack quantitative measurements of pollution exposure, or rely exclusively on self-reported health measures (Table A1 provides an overview of the causal evidence). The large RESPIRE trial conducted in a poor, rural community in Guatemala in 2002–2005 and the ongoing HAPIN trial being conducted in rural communities in Guatemala, India, Peru and Rwanda are valuable exceptions to this (T. F. Clasen et al., 2022; Smith et al., 2011). However, these trials focus exclusively on rural communities. There is almost no evidence evaluating cooking exposure in contexts with high ambient pollution, even though the 1 billion urban poor who live in slums are simultaneously chronically exposed to both: 80% of urban African residents use biomass as their primary cooking energy (FAO, 2017). In a 2018 review of the cookstove literature, Thakur et al. (2018) identified no urban papers.[10] Papers that do evaluate the health impact of ambient

Hanna, 2014; Isen, Rossin-Slater, and Walker, 2017; Schlenker and Walker, 2015.

[8]See Adhvaryu, Kala, and Nyshadham (2022), Archsmith, Heyes, and Saberian (2018), Ebenstein, Lavy, and Roth (2016), Kubesch et al. (2015), Künn, Palacios, and Pestel (2023), Soppa et al. (2014), and Wen and Burke (2022).

[9]See Bensch, Grimm, and Peters (2015), Bensch and Peters (2019), Burwen and Levine (2012), Chowdhury et al. (2019), Levine et al. (2018), Miller and Mobarak (2013), Mobarak et al. (2012), and Pattanayak et al. (2019).

[10]More recently, Alexander et al. (2018) measured peak and duration of exposure to estimate the pollution and

air pollution in low- and middle-income countries (LMICs) rarely evaluate personal exposure.[11] Our findings furthermore depart from some earlier research asserting own-household generated air pollution plays a dominant role in aggregate pollution exposure (WHO, 2014; Fisher et al., 2021).

Finally, our results on the persistence of cookstove adoption has important implications for climate and international development policy. The subsidies have high additionality: even after 3.5 years, ownership is 72 percentage points higher among those who were offered a \$30–\$40 subsidy for the stove than among those who were offered only a \$10-\$15 subsidy.[12] In addition to providing a strong first stage with which to study the health impacts, the adoption gap demonstrates that the subsidies were marginal on the decision to adopt the stove. We also do not find evidence of crowd out of the adoption of other cleaner cooking technologies. Combining the results on persistence with the impacts on emissions from Berkouwer and Dean (2022a), we estimate an upper bound on the abatement cost of distributing stoves for free of around \$4.9 per ton of carbon dioxide equivalent (tCO_2e)—significantly lower than most alternative abatement technologies available today.[13] Improved cookstove users in urban areas furthermore continue to save \$86 per year in charcoal spending (44% of control group spending, which is similar to the estimate in Berkouwer and Dean, 2022a). This provides additional evidence that high-income countries and multilateral agencies could achieve higher impact carbon mitigation when investing in LMICs (Glennerster and Jayachandran, 2023).

2 Background: Cookstoves and pollution among the urban poor

Traditional charcoal cookstoves produce indoor air pollution that causes millions of deaths each year (WHO, 2017; Bailis et al., 2015; Pattanayak et al., 2019). More than 4 billion people still do not have access to modern cooking methods (WB, 2020).

Three billion people are expected to live in slums in Africa and Asia by 2050, which experience unhealthy PM2.5 levels on a daily basis (WHO, 2021; UN, 2022). In Africa, 80% of households living in African cities still primarily use biomass (wood or charcoal) for cooking (FAO, 2017). As a result, urban LMIC residents suffer disproportionately from both ambient air pollution (AAP) and own household-generated (HAP), yet there is effectively no causal evidence assessing AAP and HAP simultaneously.

health impacts of improved stove adoption in an urban setting, but their sample is restricted to pregnant women, they do not separately measure ambient pollution, and they examine relatively modest variation in air pollution (a 5–13% reduction in peak—and no impact on mean—PM2.5).

[11] For example, Adhvaryu, Kala, and Nyshadham (2022), Adhvaryu et al. (2023), Barrows, Garg, and Jha (2019), Ebenstein et al. (2017), Greenstone and Hanna (2014), and Gupta and Spears (2017).

[12] For equity reasons, all participants received at least a \$10 subsidy. Given that the stoves were easily accessible at shops, it is reasonable to assume that adoption at or near market prices (\$0 subsidy) would have been almost zero.

[13] For example, U.S. CAFE standards cost \$48-\$310 per tCO_2e abated (Gillingham and Stock, 2018) and solar panel subsidies in Spain and Germany reduced emissions at a cost of €411-1,944 (\$574-\$1,492) per tCO_2e abated (Abrell, Kosch, and Rausch, 2019).

2.1 Cookstoves in Kenya

Two-thirds of Kenyan households rely on biomass (wood and charcoal) as their primary household fuel (KNBS, 2019; WB, 2019). Around 42 percent of Kenyan households use a Kenyan ceramic *'jiko'* for daily cooking, with the primary alternatives being wood stoves (in rural areas) and liquefied petroleum gas (LPG) and kerosene stoves (in urban areas) (Ministry of Energy, 2019). According to the World Bank's Kenya Country Environmental Analysis (2019), "Those who cook inside with poor ventilation have 400–600 $\mu g/m^3$ average annual concentration of PM2.5 in their household." These levels are extremely high: the WHO (2021) defines its 'healthy' threshold to be 5 $\mu g/m^3$. Furthermore, Pope et al. (2018) document that average PM2.5 and PM1.0 in Kenya are on average 2.8 times higher in urban roadside locations than in rural locations. They estimate urban roadside air pollution levels of 36.6 $\mu g/m^3$ and urban background levels of 24.8 $\mu g/m^3$.

Figure 1 displays a *jiko* as well as the Jikokoa, an energy efficient charcoal stove produced by Burn Manufacturing ('Burn'), which has sold more than two million energy efficient cookstoves since 2014. Berkouwer and Dean (2022a) provides more detail on charcoal consumption, barriers to adoption, and access to credit among potential adopters in Nairobi.

Figure 1: Traditional *jiko* ('stove') and energy efficient stove

Reproduced from Berkouwer and Dean (2022a). On the left is the traditional *jiko*. On the right is the energy efficient stove. The two stoves use the same type of charcoal and the same process for cooking food, hence the energy efficient stove requires essentially no learning to adopt. After usage, the user disposes of the ash using the tray at the bottom. The central chamber of the energy efficient stove is constructed using insulating materials.

The primary difference between the Jikokoa and the *jiko* is that the Jikokoa's main charcoal combustion chamber is constructed using improved insulation material and designed for optimized fuel-air mixing. It is made of a metal alloy that better withstands heat, and a layer of ceramic wool insulates the chamber to cut heat loss. To maximize the charcoal-to-heat conversion rate, parts are made to strict specifications, and components fit tightly to minimize air leakage. These features were designed and tested by laboratories in Nairobi and Berkeley. Adoption of the energy efficient stove does not require any behavioral adaptation or learning as the cooking processes are identical. In line with lab estimates, Berkouwer and Dean (2022a) find that adoption of the Jikokoa reduces charcoal usage (as measured through charcoal expenditures and ash generation) by 39%. Most adopters continue cooking the same types and quantities of food as before, using the same type of charcoal.

2.2 Health measurement methodology

Our health-related outcome variables and the surveying methodology we use to measure them are informed by an extensive public health literature. Chang et al. (2015), Kubesch et al. (2015), and Soppa et al. (2014) document an association between air pollution and blood pressure within 1–2 hours of high pollution exposure. The Guatemala RESPIRE trial found impacts on blood pressure (McCracken et al., 2007), and more recently an experiment in urban Nigeria found that an improved stove can reduce blood pressure among pregnant women (Alexander et al., 2018). For children aged 5 and under, who are more likely than older children to spend more of their days with the primary cookstove user, frequent exposure to cooking-associated pollution may have negative health impacts, and for this reason our surveys include questions regarding adult and child health. Recent RCTs in rural Malawi and rural Guatemala found that improved stove adoption can reduce pneumonia in adults as well as in children (Mortimer et al., 2016; Smith-Sivertsen et al., 2009).

In settings where the technology to formally diagnose pneumonia is unavailable, the literature recommends three methodologies to diagnose pneumonia. The first is to inquire about diagnoses made by health professionals. The second is to ask about symptoms related to respiratory distress in order to make an attempted diagnoses of an acute respiratory infection (ARI), which can then be cautiously interpreted as a presumed pneumonia diagnoses. This methodology is standard for, among others, the World Health Organization, the USAID Demographic and Health Survey (DHS) program, and UNICEF.[14] Finally, oximetry readings have been found to be a cost-effective approach to screening for respiratory infections (Floyd et al., 2015; National Library of Medicine, 2021; Van Son and Eti, 2021).

One challenge when trying to identify the health impacts of improved stoves, experienced by for example Beltramo and Levine (2013) and Hanna, Duflo, and Greenstone (2016), is lack of stove usage. Berkouwer and Dean (2022a) rules this out in this paper's study context.

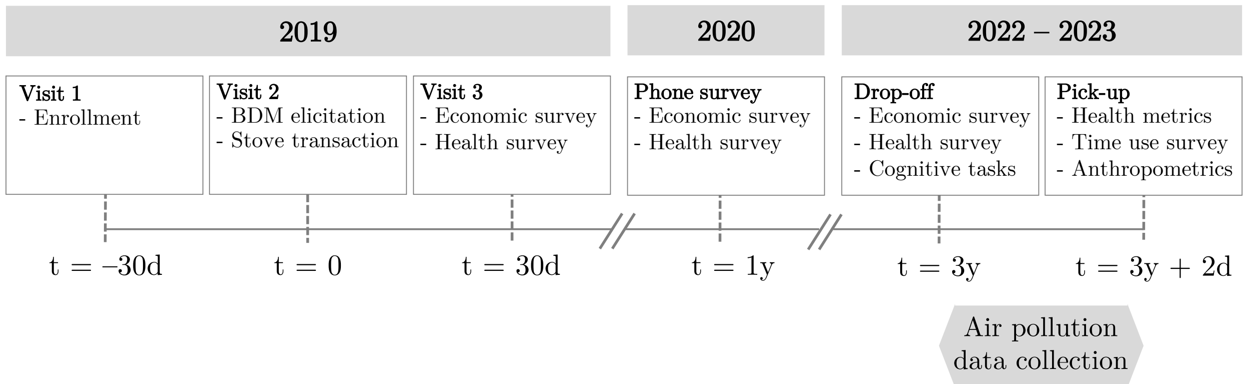
3 Study design and methodology

The study consists of three surveys conducted in 2019, a medium-term follow-up conducted in 2020, and a long-term follow-up conducted in 2022–2023. Figure 2 presents an overview of the study elements included in each survey round.

In the initial baseline enrolment survey activity conducted in April-May 2019, enumerators enrolled respondents residing in urban settlement areas around Nairobi, Kenya who used a traditional charcoal stove as their primary daily cooking technology and who spent at least $3 per week buying charcoal. Within each household they enrolled the primary cookstove user. To elicit baseline levels of health, enumerators asked respondents whether they had experienced a persistent cough or

[14] For example, UNICEF MICS6 (2020) identifies ARI if a child had fast, short, rapid breaths or difficulty breathing in combination with chest problems.

Figure 2: Timeline of field activities



Participants who adopted the stove did so during Visit 2 ($t = 0$). For 89% of respondents the long-term endline was conducted between 3.4–3.7 years after Visit 2. Cognitive tasks and anthropometrics of household members were collected on either drop-off or pickup depending on attendance. Due to COVID-19 related health restrictions, the 2020 follow-up survey was conducted over the phone.

breathlessness in the past week. If they had any children under 16 who lived with them, we asked the same about the child(ren). Enumerators then elicited beliefs about the potential health impacts of an improved stove using methodologies from the health literature (Hooper et al., 2018; Usmani, Steele, and Jeuland, 2017). Specifically, in an unprompted manner they asked respondents what they perceived to be the main benefits of the improved stove—62 percent stated 'reduced smoke' (95 percent said 'saving money'). They then asked several Likert scale questions about the extent to which the respondent thought usage of a traditional stove has had negative impacts on their health, and how much adoption of an energy efficient stove might improve their health.

The main visit—Visit 2, completed by 955 respondents—took place approximately one month after each respondent's baseline enrolment visit. During this visit, respondents received at least a $10 subsidy off the retail price and were able to buy the stove using the subsidy. Of the 955 respondents who completed the main visit, 570 (60 percent) adopted the Jikokoa stove.

In June–July 2019, approximately one month after the main visit, enumerators conducted a short-term endline survey. In 2020, enumerators conducted a medium-term survey.[15] These surveys ask about a range of socioeconomic outcomes, including charcoal expenditures, savings (in bank accounts, mobile money accounts, or rotating savings groups), as well as the same health symptoms questions asked during the baseline surveys.

In 2022-2023 enumerators conducted a long-term survey round, which consisted of two surveys, the second approximately 48 hours after the first. The surveys were designed to take quantitative measurements of three long-term outcomes: air pollution, physical health, and cognition. An accompanying socioeconomic survey included questions on charcoal expenditures, cooking technology ownership and usage, maintenance, food cooked, home heating, in-network Jikokoa purchases, savings, income, and work activities. Table 1 presents summary statistics. Enumerators were able to

[15]Due to COVID-19, all surveys conducted in 2020 were conducted over the phone.

Table 1: Summary statistics from respondent surveys

	N	Mean	SD	25^{th}	50^{th}	75^{th}
Female respondent	702	0.96				
Completed primary education	702	0.70				
Completed secondary education	702	0.26				
Age	702	41.46	11.8	33.0	40.0	48.0
Children under 5 in home	702	0.50	0.7	0.0	0.0	1.0
Daily earnings (USD)	563	2.77	5.8	1.0	1.7	3.1
Daily charcoal expenditure (USD)	702	0.48	0.6	0.2	0.3	0.6
Minutes spent cooking per day	702	127.54	59.5	90.0	120.0	150.0
... of which indoor	702	111.80	61.3	70.0	109.0	150.0
Owns Jikokoa	702	0.52				
Owns traditional wood or charcoal jiko	702	0.57				
Owns LPG stove	702	0.59				
Owns electric stove	702	0.01				
Mostly uses modern stove	702	0.53				
Blood oxygen	696	96.74	2.4	96.0	97.0	98.0
Average systolic blood pressure	696	123.46	22.0	108.3	118.5	131.7
Average diastolic blood pressure	696	81.75	12.9	73.0	79.3	89.0
Number of health symptoms	702	2.47	2.6	0.0	2.0	4.0
In the past month, have you experienced...						
Fever	702	0.22				
Headache	702	0.48				
Persistent cough	702	0.23				
Runny nose	702	0.22				
Sore throat	702	0.15				
Always feeling tired	702	0.28				

Standard deviation and 25^{th}, 50^{th}, 75^{th} reported for all non-binary variables. Blood pressure is averaged over three readings taken consecutively.

reach 775 of the 942 respondents they attempted to reach, and successfully surveyed 702 (75%).[16] 95% of respondents were surveyed between 3.4–3.7 years after the original main visit.

To match high-frequency pollution data to specific activities, the second survey included a time use module inquiring about which activities the respondent was engaged in for each hour between the two surveys, whether they were indoors or outdoors during each hour, and if they were cooking,

[16] 13 of the 955 respondents completed the main visit in 2019 but removed themselves from the study between 2019 and 2022. 167 respondents could not be contacted in 2022-2023 despite repeated phone calls to their phone numbers or any other phone numbers they had used for earlier SMS surveys or MPESA payments. Physical attempts to track individuals residing in the study areas were hampered by the recent demolitions of housing in Nairobi's settlement areas (The Star, 2023). Respondents who were contacted but who did not complete a 2022-2023 survey did not do so for various reasons, including nonconsent, migration, physical incapacitation, or death. As a rule we attempted to survey any respondent still residing in Kenya. Attrition is balanced by treatment assignment, take-up, and baseline health (Table A24).

which stove(s) they were using. Most respondents cook primarily between the morning hours of 5–8am and the evening hours of 6–9pm.[17]

The time use data indicate that households primarily cook indoors: 89% of time spent cooking takes place indoors, on average. Improved cookstove adoption does not meaningfully affect the propensity to cook indoors (Table A9). However, there is some heterogeneity in behavior correlated with stove usage. For the 278 households who report using an LPG or electric stove at least once in the time use survey, on average only 5% of the time spent cooking with such a stove is spent outdoors. Conversely, for the nearly 500 households who report using a wood or charcoal stove at least once in the time use survey, more than 20% of time spent cooking with such a stove is spent outdoors. It is plausible that respondents are more likely to choose to cook indoors when using a relatively cleaner stove, and that this reduces the benefits of an improved stove, as emissions are more likely to build up when cooking indoors. Our results should be interpreted as factoring in relevant behavior changes such as location choice, or opening doors or windows in order to increase household ventilation rates.

3.1 Causal identification

After completing the initial baseline enrolment survey, each respondent was randomly assigned a subsidy of between $10-39 for the energy efficient Jikokoa stove, which cost $40 in stores at the time. The random assignment of subsidies was stratified on baseline charcoal usage. The subsidy assignment was cross-randomized with a random credit treatment allowing recipients to pay for the stove in installments over a 3-month period, as well as an attention treatment designed to increase the salience of long-term charcoal savings.

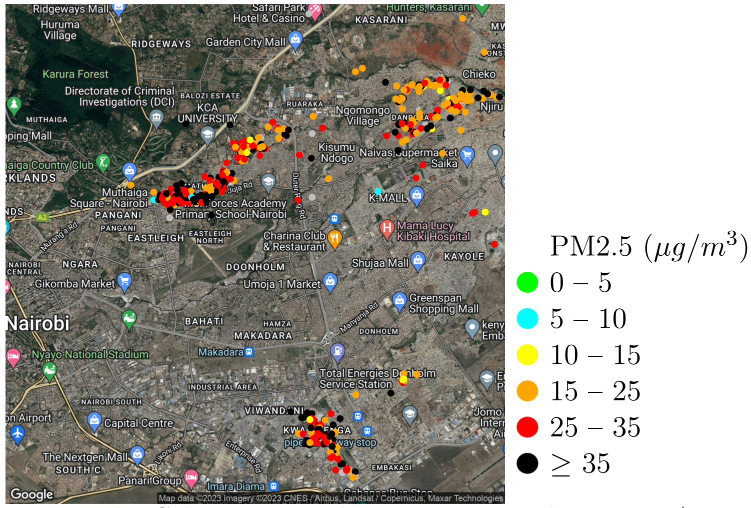
During visit 2, enumerators used a Becker, Degroot, and Marschak (1964) mechanism (BDM) to elicit WTP for the Jikokoa stove. Respondents whose WTP was at least as high as their randomly assigned price (the market price of $40 minus the randomly assigned subsidy) then adopted the stove.[18]

The credit treatment doubled WTP, while the attention treatment had no effect on WTP (Figure A2 shows the full WTP distributions by treatment group). The randomized credit and subsidy treatments were highly predictive of improved stove adoption: among those in both the high subsidy and the credit treatment group 93% adopted the Jikokoa, whereas among those in both the low subsidy and the credit control group only 8% did. To estimate the causal effect of improved stove adoption on long-term outcomes we use the randomly assigned subsidy, the credit treatment assignment, and their interaction as instruments for adoption. We report weak instrument F-statistics where relevant—the first stage is generally strong.

[17] There are modest differences in the types of technologies used during different types of day, with LPG used more in the mornings and a charcoal jiko or Jikokoa used more in the evenings (Figure A1). Anecdotally, this is due to a preference for a fast-lighting stove (which the LPG stove is, in comparison to biomass) in the morning, for a small meal or hot beverage, and a longer-cooking stove when preparing larger meals.

[18] 98.6% of respondents who 'won' the stove through the BDM actually adopted the stove.

Figure 3: Average air pollution (PM 2.5) for participants by their home locations



Distribution of respondents across Nairobi. Colors correspond to average particulate matter (PM 2.5) exposure. Respondents for whom pollution was not recorded are shown in gray. The WHO air quality guideline (AQG) is 5 $\mu g/m^3$ (WHO, 2021). WHO interim targets 1 through 4 correspond to 10, 15, 25, and 35 $\mu g/m^3$. Some respondents were surveyed outside the visible area.

3.2 Air pollution exposure concentrations

We use two different devices to measure air pollution. A Purple Air II Air Quality Sensor (PA-II) takes one measurement of Particulate Matter (PM) every two minutes (Panel A of Figure A3),[19] and a Lascar EL-USB-CO Data Logger takes one measurement of Carbon Monoxide (CO) per minute (Panel B of Figure A3).[20] A test of co-located readings shows that devices are strongly correlated and that there is a small and generally stable gap between some devices (Figure A4). For this reason we include device fixed effects in all regressions.[21] Figure 3 maps respondents' interview locations and average air pollution exposure.[22]

Following best practices (Gordon et al., 2014; Gould et al., 2022), we designed the deployment methodology to collect exposure as experienced by respondents rather than stationary monitoring of kitchen concentrations. Collecting pollution exposure over a 48-hour period captures HAP as well as AAP generated by industrial facilities, traffic, or other sources in urban Nairobi.

To achieve this, we used procedures developed by the Berkeley Air Monitoring Group (Johnson et al., 2021). During the first endline survey we provided each respondent with a small mesh backpack containing the two devices (Panels C and D of Figure A3). 48 hours later the enumerators then picked up the devices, downloaded the data, recharged the 48-hour battery pack, and placed them

[19] We average the PA-II a and b readings, and top-code data at 419 $\mu g/m^3$ above which the device saturates. We apply the PA-II calibration methodology from Giordano et al. (2021) and Ward et al. (2021) to correct for humidity and local air composition. Building on Tryner et al. (2020), if the difference between the a and b readings is at least 25% and at least 15 $\mu g/m^3$ the reading is removed from the sample (1.7% of readings).

[20] Each CO device has an independent calibration factor. Devices were re-calibrated every two months, between survey breaks. We include device FE in all regressions.

[21] Interacting device fixed effects with a linear time trends could account for heterogeneous trends across devices. Doing so introduces noise and therefore increases standard errors, but does not qualitatively change the results.

[22] 60 survey respondents were located elsewhere in Nairobi or in rural areas and are not shown in Figure 3.

in a new backpack to be deployed with a different respondent.[23] Respondents were asked to wear this backpack continuously whenever feasible, or to keep it within one meter, at waist level, when wearing it was infeasible. We did not quantitatively monitor backpack wearing, as this would have required installing GPS trackers on the backpacks which we felt could be perceived as violating participants' privacy and increase attrition. However, qualitatively, enumerators reported generally high backpack wearing.[24] Our methodology is in line with best practices from the air pollution monitoring literature (Burrowes et al., 2020; Chillrud et al., 2021; Gould et al., 2023).

One concern with deploying conspicuous sensors is that respondents may be more self-conscious of their own cookstove usage and alter their cookstove use in response, biasing our estimates—a concern known as the Hawthorne effect. Existing research has identified this effect in the monitoring of health technologies such as cookstoves or latrines (e.g. T. Clasen et al., 2012; Simons et al., 2017). For this reason we administer questions about charcoal expenditures and cookstove usage during the first survey, before deploying the devices.

To better understand peak pollution patterns we compute average exposure during each 10-minute window for each respondent in our data. Panel B of Figure 4 shows the cumulative distributions of each respondent's 50th (median) and 99th percentile 10-minute average, with the 99th percentile 10-minute average representing approximately the worst 15 minutes of one's day. Median 10-minute average is below 50 $\mu g/m^3$ for 89% of respondents. However, the worst 15 minutes of the day is above 100 $\mu g/m^3$ for half of respondents, and exceeds 200 $\mu g/m^3$ for 23% of respondents.

Panel A of Figure 4 presents average pollution over the hours of the day by whether or not the respondent owned a Jikokoa. The levels and diurnal patterns of PM2.5 and PM1.0 follow the air pollution patterns documented by Pope et al. (2018) in urban Kenya. We do not observe any meaningful seasonal heterogeneity in air pollution over our sample period. Matching hourly time use data and hourly pollution data indicates that PM2.5 is lowest in the hours when sleeping (32 $\mu g/m^3$) and highest in the hours when cooking (46 $\mu g/m^3$) on average (Table A2).

3.3 Physical health

Enumerators record systolic and diastolic blood pressures using a sphygmomanometer, following procedures set by the Centers for Disease Control and Prevention NHANES (2019).[25] The analysis uses direct measures of systolic and diastolic blood pressure as well as indicators for having hypotension (low blood pressure, defined as <90/60 mmHg), stage 1 hypertension (130-139/80-89 mmHg), and stage 2 hypertension ($\geq 140/\geq 90$ mmHg), as defined by the American Heart Association and

[23] 85% of respondents held the device between 45–50 hours. Air pollution data are missing for 45 respondents who only had time to complete a single survey.

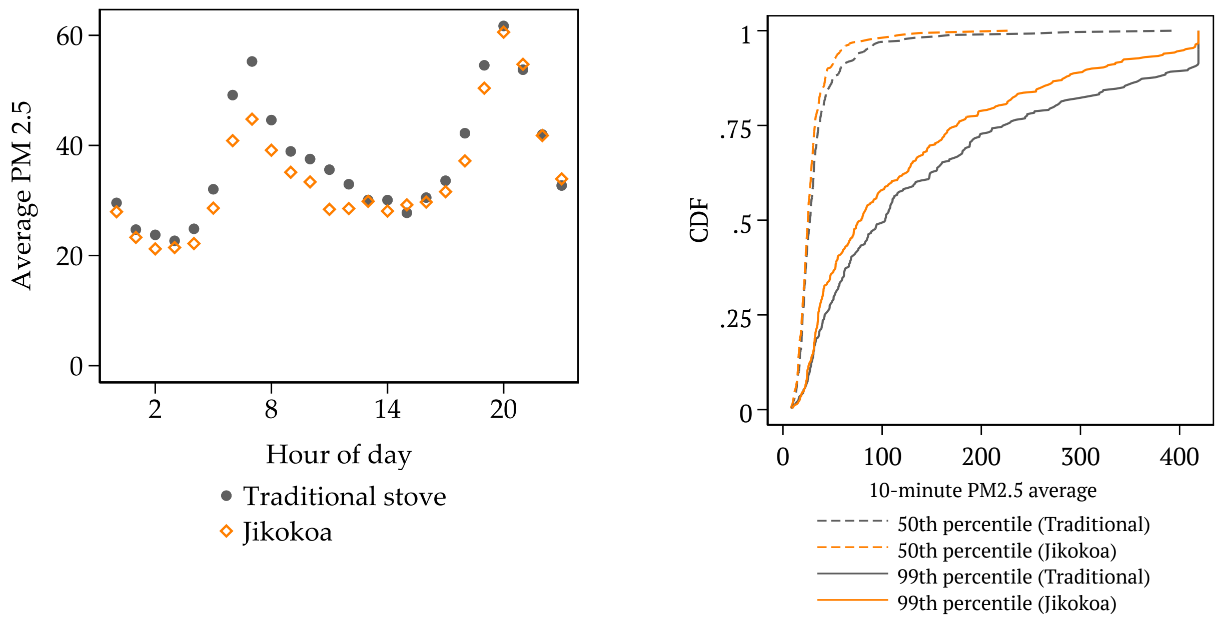
[24] Enumerators were attentive to this: for example, they raised concerns about a lack of continuous backpack wearing as respondents would take off the backpack for example while sleeping it (placing it next to their beds) or while working statically (placing it on a table), which we agreed was acceptable as long as the backpack was within one meter of the respondent. That enumerators were attentive enough to identify this issue suggests they likely would have noticed any widespread more severe non-compliance.

[25] Respondents are asked to sit still, upright, and not engage in affecting behaviors (cooking, smoking, etc.) in the 30 minutes prior to the blood pressure readings. In line with guidelines, blood pressure is recorded three times and the analysis uses the average of the three readings.

Figure 4: Particulate matter (PM2.5, in $\mu g/m^3$) pollution by Jikokoa ownership

A) Over the hours of the day

B) Distributions of 50th and 99th percentiles of 10-minute averages (by household)



Panel A shows average PM2.5 air pollution, by hour and endline Jikokoa ownership, as collected by respondents wearing backpacks for on average 48 hours. Figure A5 presents the same for PM1.0 and CO.

the American College of Cardiology (Goetsch et al., 2021). Enumerators use pulse oximeters (blood oxygen saturation monitors) to record haemoglobin oxygen saturation.[26]

The survey furthermore asks a large set of health questions, following the methodology from field experiments in the public health literature (see for example Checkley et al., 2021; Smith-Sivertsen et al., 2009; Tielsch et al., 2016 and others). This includes a set of 10 yes/no questions asking if a medical professional had diagnosed the respondent with various medical diagnoses (including pneumonia, asthma, or other lung disease), of which we only keep diagnoses that were made in the past three years (since the original experiment). It includes a set of 29 yes/no questions asking if the respondent experienced specific symptoms in the past 4 weeks (including fever, persistent cough, stomach pain, or rapid weight loss, as well as symptoms required to make a presumed pneumonia diagnosis). The survey also asks about perceptions of health impacts, and frequency and financial costs of hospital visits. For female respondents, the enumerator also inquired about recent pregnancies, birth outcomes, and any recent newborns' weight and length. We use these self-reports to generate several standardized adult physical health indices.

The adult respondent is asked similar questions about symptoms any children under 10 who live in the home, including questions about overall health, basic health symptoms (specifically those that permit a presumed pneumonia diagnoses, including fever, vomiting, and cough), school atten-

[26]While we considered collecting spirometry or peak expiratory flow data, discussions with medical consultants in Kenya and the U.S. suggested that these run the risk of generating noisy and unusable data. We therefore chose to focus on improving the quality of the personal exposure, blood pressure, and blood oxygen measurements.

dance, and medical diagnoses. Subsets of these are then combined into several standardized child physical health indices. The enumerator finally measured child and adult height, weight, and arm circumference as indicators for physical child development and for parental controls, respectively.

17% of respondents report having been diagnosed with pneumonia by a doctor at least once in their lives, including 12% who report having been diagnosed in the past three years. Table 1 presents additional summary statistics on health outcomes. To control for diurnal patterns in health outcomes such as blood pressure, health regressions control for the hour of day during which each survey was administered.

3.4 Cognition

To assess basic adult and child cognitive functions, we use three instruments. First, we use the Reverse Corsi Block task to measure working memory (Brunetti, Del Gatto, and Delogu, 2014). Second, we use Hearts and Flowers to measure response inhibition (Davidson et al., 2006). Third, we use the d2 task for sustained attention (Bates and Lemay Jr., 2004; Brickenkamp and Zillmer, 1998). Appendix C provides detail on these assessments. The analysis uses a standardized adult cognitive ability index.

4 Causal impacts

To estimate the causal effect of adoption of the energy efficient charcoal cookstove on pollution, health, and socioeconomic outcomes, we employ an instrumental variables (IV) approach where we use the randomly assigned BDM price (P_i), the randomly assigned credit treatment status (C_i), and their interaction (P_iC_i) as instruments for stove ownership d_i. These were the two random treatments found to have a statistically and economically large effect on stove adoption in Berkouwer and Dean (2022a).[27] Since P_i and C_i are both randomly assigned, this regression identifies the causal effect of stove adoption on the outcomes of interest. Econometrically, this proceeds as follows:

$$y_i = \beta_0 + \beta_1[\hat{d}_i \sim P_i, C_i, P_iC_i] + \beta_2 X_i + \epsilon_i \tag{1}$$

where $\hat{d}_i$ is a dummy for (endogenous) adoption. As appropriate, regressions include socioeconomic controls[28] and panel data fixed effects.[29] Note that $\hat{d}_i$ could represent either initial adoption in 2019, or ownership status as of the 2022–2023 endline survey. Using initial adoption represents the longer-term effects of adoption, factoring in potential breakage or other subsequent changes

[27] We omit a third random treatment, attention to energy savings, as it had no impact on adoption.

[28] Socioeconomic controls used in each regression are the respondent's attention treatment status (a treatment designed to increase attention to energy savings), age, gender, savings in 2019, income in 2019, number of residents in the household in 2019, number of children in the household in 2019, prevalence of a cough or breathlessness at night in 2019, hours of work/homework missed due to poor health, education level completed in 2019, charcoal expenditures in 2019, level of risk aversion in 2019, status of credit constraint in 2019, living situation as rural or urban, age as decade binary variables (designed to capture non-linear impacts of age), as well as field officer fixed effects.

[29] Panel data fixed effects include week FE, device FE, and the interaction of and hour-of-day by day-of-week by neighborhood FE.

in stove ownership, but underestimates contemporaneous effects as some treated individuals are no longer benefiting from the treatment. Long-term adoption status better estimates contemporaneous differences, but could result in an overestimated IV coefficient if changes experienced by respondents who initially adopted the stove but no longer own one at endline are attributed to the (smaller) treatment group. We present both estimates where relevant but use ownership as of the long-term follow-up in most regressions.

4.1 Impacts of random treatments on stove ownership

Panel (A) of Table 2 shows the causal impact of 2019 Jikokoa adoption on long-term ownership of various stove types. 90% of respondents who did not adopt a Jikokoa during the main visit also do not own one during the long term endline, and 83% of respondents who adopted a Jikokoa initially also own one three years later. This persistence generates a strong first stage to study the impacts of the Jikokoa on other outcomes, with weak IV F-statistics between 20 and 50 depending on the specification (Table A3 presents the first stage).

Jikokoa adoption does not appear to meaningfully affect adoption of other modern cooking technologies such as liquefied petroleum gas (LPG), bio-ethanol, or electric stove ownership, though we cannot rule out modest increases. We thus find limited evidence of the 'energy ladder' mechanism whereby initial adoption of an improved biomass stoves can act as a stepping stone towards even cleaner cooking technologies (Hanna and Oliva, 2015), nor of the converse, that adoption of an intermediary technology can slow adoption of a more energy efficient technology (Armitage, 2022). The median household owns two unique stove types, indicating some degree of 'fuel stacking' (simultaneous ownership of cooking technologies that use multiple types of cooking fuel). LPG ownership has risen sharply in recent years, with 57% of respondents reporting owning an LPG stove, potentially as a result of a government LPG subsidy program (IEA, 2022). The estimates should be interpreted as the aggregate causal effect of improved cookstove adoption, allowing for any continued use of existing stove (rather than an estimate of a strict switch from an existing stove to an improved stove).

The results on the persistence of stove ownership imply that a subsidy for the Jikokoa is an extremely cost-effective means of reducing carbon emissions because the subsidies were marginal for the decision of the vast majority of households while not crowding out adoption of other emissions reducing options.

To illustrate, focus on the two mass points in our subsidy distribution ($13-15 and $28-30) which encompasses 86% of our sample. 161 (36.6%) of those with the small subsidy purchased a Jikokoa during the study while 290 (77.13%) of those with the larger subsidy did. The low-subsidy group cost a total of $2,263 while the high-subsidy group cost $8,413. Thus the additional $6,150 in subsidies yielded the purchase of an additional 129 stoves. At the one year endline, the shares of improved stove ownership remain essentially constant at 35.9% and 77.19%, thus for the first year the subsidies bought 129 stove years. Now, conservatively assume that immediately after the one year endline the ownership shares change to what we observe 3.5 years later (37% and 65%). Applying these shares

Table 2: Primary socio-economic outcomes

	Control Mean (1)	Treatment Effect (2022 Ownership) (2)	Treatment Effect (2019 Ownership) (3)	N
Panel A				
Owns other wood or charcoal stove	0.88		-0.54***	702
	[0.33]		(0.05)	
Owns Jikokoa	0.10		0.74***	702
	[0.31]		(0.04)	
Owns LPG stove	0.57		0.05	702
	[0.50]		(0.06)	
Owns bio-ethanol stove	0.15		0.01	702
	[0.36]		(0.04)	
Owns electric stove	0.00		0.02*	702
	[0.06]		(0.01)	
Panel B				
Charcoal expenditures past 7 days (USD)	3.65	-1.50***	-1.12***	702
	[2.93]	(0.47)	(0.35)	
Charcoal expenditures past 7 days (urban)	3.79	-1.65***	-1.20***	649
	[2.94]	(0.52)	(0.37)	
Charcoal expenditures past 7 days (rural)	1.82	1.22	1.16	53
	[2.09]	(1.00)	(0.81)	
Earnings past 2 weeks (USD)	32.20	4.73	3.45	563
	[35.31]	(7.83)	(5.38)	
Total savings (USD)	57.70	-8.63	-7.07	701
	[94.87]	(19.88)	(14.67)	
Has formal bank account (=1)	0.12	0.11	0.08	702
	[0.33]	(0.07)	(0.05)	
Minutes cooking per day	133.79	3.49	2.60	702
	[57.29]	(8.32)	(6.15)	
People in network who adopted Jikokoa	0.75	1.13***	0.84***	702
	[2.03]	(0.40)	(0.29)	

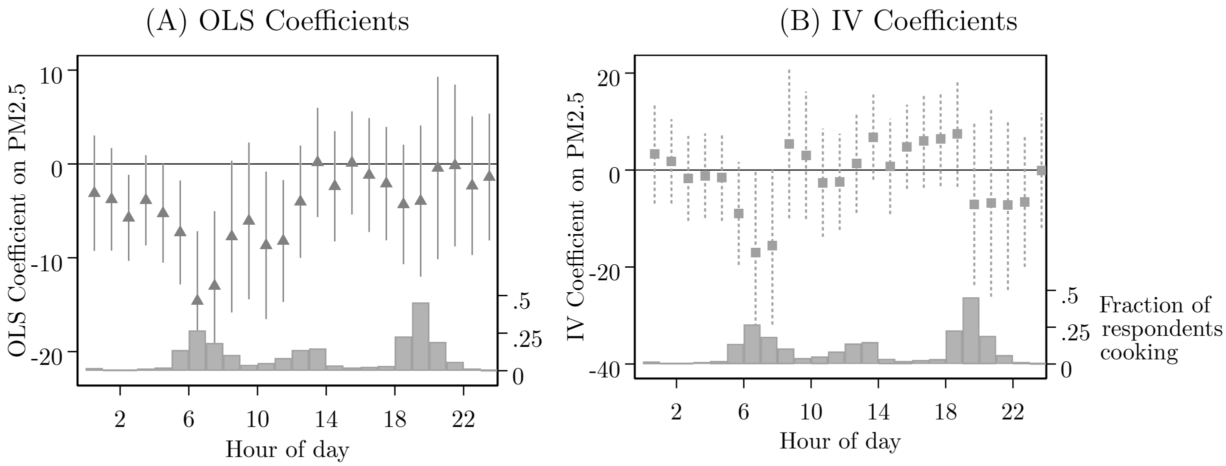
Panel A presents the causal impact of 2019 Jikokoa adoption on 2022–2023 cookstove ownership. Panel B presents the causal impact of 2022 Jikokoa ownership and 2019 Jikokoa adoption (Columns 1 and 2 respectively) on outcomes recorded during the 2022–2023 endline surveys. Each row is an IV regression that uses the randomly assigned price, credit treatment status, and their interaction as instruments for the endogenous variables. Regressions include socioeconomic controls. Table A4 presents additional socio-economic outcomes relating to savings and in-network adoptions.

to the size of the original groups gives a net increase of 92 stoves per year for the subsequent 2.5 years. Thus in total, the additional \$6,150 in subsidies conservatively increased stove-years by 358. In Berkouwer and Dean (2022a) we estimate that adopting a Jikokoa reduces household emissions by 3.5 tons of carbon dioxide equivalent per year. Thus these additional subsidies reduced emissions by 1,254 metric tons of CO_2e at a cost of \$4.9 per ton.

4.2 Impacts of stove ownership on air pollution

The relationship between stove ownership and air pollution varies significantly across hours in the day. Panel (A) of Figure 5 presents a standard OLS panel fixed effects regression, estimating a separate coefficient for each hour of the day. Panel (B) uses the IV approach to similarly estimate a separate causal estimate for each hour of the day. For comparability, both panels also present a histogram of the number of people who reported cooking during a given hour in the time use survey. Improved stove ownership reduces air pollution between 5–8am, which lines up well with when respondents generally report to be cooking breakfast.

Figure 5: Impact of Jikokoa ownership on average hourly particulate matter (PM2.5, in $\mu g/m^3$)



Panel (A) reports coefficients from an OLS regression of PM2.5 on Jikokoa ownership. Panel (B) reports coefficients from an equivalent IV regression, using subsidy, credit treatment status, their interaction, and their interaction with hour of day dummies as instruments. Both regressions include socioeconomic controls and panel data fixed effects. The gray bars report the fraction of respondents who report cooking during any given hour in the time use survey. Table 3 presents regressions pooling data across respondents, for PM2.5 (Panel A) and CO (Panel B).

Figure 5 also reveals a modest reduction in air pollution concentrations during dinnertime between 7–9pm, though this reduction is significantly smaller than the effect during breakfast time. The lack of effect during dinnertime is not driven by differences in cooking technologies used during the different meals: during all daytime hours, a Jikokoa is being used by approximately 30% of respondents that are cooking, a traditional Jiko by approximately 27%, and an LPG stove by approximately 23% (Figure A1). There is a slight difference in temperature, with a 10^{th}–90^{th} percentile range of 26–33°C between 5–7am and 29–36°C between 7–9pm (according to the PA-II devices), however this difference is sufficiently small that it is unlikely to account for the differences in treatment effects we see. Instead, we hypothesize that the lack of reduction in dinnertime pollution exposure is due to diurnal variation in planetary boundary layer height (PBLh). A lower PBLh weakens the exchange of air between the earth's boundary layer and the free atmosphere, trapping particles closer to earth's surface. NASA MERRA-2 satellite measurements indicate that PBLh in Nairobi is on average 1,600 meters during the morning hours of 5–8am but on average 60 meters during the evening hours of 7–9pm (Figure A6). Previous research has documented a strong relationship between PM2.5 and PBLh (Dhammapala, 2019; Dobson et al., 2021; Manning et al.,

Table 3: Causal impact of cookstove adoption on pollution exposure

Panel A) All hours

	PM2.5				CO			
	(1) Median	(2) Mean	(3) Max Hour	(4) 99th	(5) Median	(6) Mean	(7) Max Hour	(8) 99th
Own Jikokoa	0.1	-0.8	-16.4	-8.3	-0.5	2.2	21.5*	25.6*
	(1.7)	(3.4)	(19.0)	(23.0)	(0.4)	(1.7)	(12.8)	(15.1)
Control Mean	25.2	37.8	153.3	200.3	1.8	6.5	49.6	61.6
Weak IV F-Statistic	53	53	53	53	52	52	52	52
Observations	651	651	651	651	656	656	656	656

Panel B) When self-reporting cooking

	PM2.5				CO			
	(1) Median	(2) Mean	(3) Max Hour	(4) 99th	(5) Median	(6) Mean	(7) Max Hour	(8) 99th
Own Jikokoa	-11.0**	-16.6***	-31.0**	-52.0**	1.1	1.4	8.3	6.2
	(5.2)	(6.4)	(15.4)	(22.5)	(2.1)	(3.1)	(9.9)	(14.2)
Control Mean	35.9	49.7	92.6	150.3	4.2	9.2	25.3	41.3
Weak IV F-Statistic	48	48	48	48	47	47	47	47
Observations	598	598	595	598	609	609	608	609

Each column is an IV regression where the randomly assigned price, credit treatment status, and their interaction are used as instruments for endline Jikokoa ownership. Columns (1) and (5) use median exposure, (2) and (6) use mean exposure, (3) and (7) use maximum 1-hour average exposure, and (4) and (8) use 99th percentile of 10-min average exposure. Regressions include socioeconomic controls and a fixed effect for the specific LASCAR or PA-II device used for that respondent. Table A7 presents the same for when self-reporting not cooking as well as for the hours between 6–8am and 6–9pm specifically, which is less prone to recall bias. Table A6 presents all four outcomes in logs.

2018). Low PBLh during the evening may saturate the boundary layer and reduce the marginal impact of cookstove emissions reductions, but more research is needed to confirm this channel.

Table 3 aggregates pollution exposure data for each individual and estimates the causal impact of stove adoption on three key moments of pollution exposure, again following the IV approach outlined in Equation 1. Columns (1) and (5) estimate the causal impact on median exposure while Columns (2) and (6) estimate the causal impact on mean exposure, taken over all (minute- or 2-minute level) readings. Columns (3) and (7) consider the maximum of hourly average exposure while Columns (4) and (8) consider the 99th percentile of 10-minute averages. Panel A considers the full 45–50 hours during which the respondent was wearing the device, while Panel B limits the data to the hours during which the respondent self-reported cooking in the time use survey (Table A7 also presents results on all non-cooking hours and on cooking hours defined uniformly as 6–8am and 6–9pm, when most respondents report cooking).

Two key patterns emerge. First, there is a large and statistically significant reduction of 52 $\mu g/m^3$ in the 99th percentile of 10-minute means while cooking (Column 4 of Panel B), which corresponds to around a 40% reduction in the marginal emissions increase from cooking (over median non-cooking exposure) when compared with the control group. In other words, Jikokoa reduces the peak emissions from cooking by around 40%, which closely matches the 41% reduction in charcoal expenditures identified in Table 2. PM2.5 emissions from cooking appear to decrease approximately linearly in proportion to charcoal usage. These patterns are economically and statistically similar when the data are analyzed in logs (Table A6).

Improved cookstove adoption also reduces the time spent cooking (Column (1) of Table A8); anecdotally this is likely driven by the fact that the improved stove takes less time to heat up. As a result, the reduction in pollution in maximum hourly average is even larger—48%—as this factors in both the reduced peak levels as well as a reduction in the time spent near the stove during the most polluted cooking hour (Column 3 of Panel B in Table 3). We see no impact on the propensity to cook indoors (Table A9).

Second, however, there are no detectable effects on any of the other hours of the day, when ambient pollution remains high (Panel B of Table A7). As a result, despite large emissions reductions during cooking, there is only a 2% reduction in aggregate average exposure, and it is not statistically significantly different from zero (Column 2 of Panel A in Table 3). The lack of impact on aggregate average air pollution can be reconciled with the relatively small amount of time spent cooking daily: respondents cook for 9% of the day (2 hours) on average. Median non-cooking exposure to PM2.5 is around 25 $\mu g/m^3$. Indeed, we cannot reject that the coefficient in Column (2) of Panel A is 9% of that reported in Column (2) of Panel B. In this context, the reduction in cooking-related pollution causes only a small and statistically undetectable reduction in total pollution exposure.

Cooking hours are non-uniformly distributed across the day. Using hourly data on self-reported cooking activity and pollution allows us to include hour-of-day fixed effects in the regressions. This is in some ways preferred as it accounts for spurious correlations between diurnal patterns in pollution and in cooking. However we lose significant variation since there is indeed significant correlation between hour of day and propensity to be cooking. We estimate this regression using both IV and OLS specifications (Table A8). While the IV estimates are noisier than the OLS estimates, the results present a similar story: improved stove adoption does not affect PM during non-cooking hours but reduces average PM2.5 by around 8 $\mu g/m^3$ (and PM1.0 by around 4 $\mu g/m^3$) during cooking hours. To factor in that adoption reduces the time spent cooking, we conduct a complementary analysis of pollution during 'cooking hours', which we define as 6-8am and 7-9pm following Figure 5. In line with the results above, improved cookstove ownership causes an environmentally and statistically large reduction in average PM2.5 air pollution during cooking hours. However, as with the individual-level results, the high ambient pollution levels dampen any impact on aggregate exposure.

We can conduct a back-of-the-envelope exercise to get a sense for what pollution exposure reduction might be in rural areas, where ambient air pollution is 9 $\mu g/m^3$ (Pope et al., 2018). Even conservatively supposing that participants cook for twice as long in rural areas as in urban areas, this would still only generate a 22% reduction in aggregate exposure.[30]

[30]Due to logistical surveying constraints in rural areas, most study participants residing in rural areas did not

Columns (5)–(8) of Table 3 indicate no impacts on CO. This is in line with recent independent laboratory tests scoring the Jikokoa Tier 3 for PM2.5 but Tier 1 for CO (CREEC, 2022). A stove's CO output generally depends on its rate of oxygenation: higher oxygen inflow increases the production of CO_2 and reduces the production of CO while cooking. Per the company's engineers, the lack of reduction in CO output results from a desire to increase the durability of the stove by limiting peak cooking temperatures to 700°C. While this improves durability, it limits oxygenation.

It is worth noting that inverting these statistics to be represented as time above thresholds (for example, 'minutes per day where a participant is exposed to PM2.5 in excess of 100 $\mu g/m^3$') dramatically reduces the power of the estimation, as big changes that happen entirely below or entirely above the threshold will be ignored and only movements across the threshold will generate a treatment effect (Table A10). When trying to answer regulatory or health questions, looking at averages or other moments in the distribution can often generate more precise statistical results than relying on data on thresholds.

4.3 Impacts of stove ownership on health

Table 4 presents the primary estimates from the IV approach described in Equation 1, of the impact of stove adoption on health outcomes, controlling flexibly for age and linearly for other socioeconomic outcomes measured at baseline. Column (2) uses 2022 Jikokoa ownership as the endogenous variable while Column (3) uses 2019 Jikokoa adoption as the endogenous variable. The first outcome is an index of quantitative health measurements, while the next six outcomes are indices and counts of self-reported health outcomes. Following our pre-analysis plan (Berkouwer and Dean, 2022b) we separate self-reported health symptoms into those related to the respiratory system and those not.

The results indicate a 0.24 standard deviation reduction in self-reported symptoms directly related to pollution, such as sore throat, headache, and cough (Table A12 present more detailed results on pollution-related symptoms). Section 4.6 presents evidence for why these results are unlikely to be driven by experimenter demand.

However, we identify no long-term health improvements in quantitatively measured outcomes such as blood oxygen and blood pressure, self-reported non-respiratory symptoms, and self-reports about any diagnoses made by a medical professional during a hospital visit (Table A13 and Table A14 present more detailed results on non-pollution related symptoms and medical diagnoses, respectively). Specifically, we can reject that owning a stove in 2019 decreased our diagnoses index by more than 0.14 SD and that it increased our physiological health index (composed of blood pressure and pulse oximetry) by more than 0.27 SD. In order to understand what this means clinically, it's useful to focus on the systolic component where we can reject a decrease of 5.97 mm Hg. Ettehad et al. (2016) conducted a metanalysis of 123 randomized controlled trials examining the health impacts of reducing systolic blood pressure. They find a 10 mm Hg reduction is associated with a 20% reduction in the risk of a major cardiovascular event off a base of 11%. Applying this estimate to our results suggests we can reject a change large enough to reduce major cardiovascular events

receive air pollution monitoring devices.

Table 4: Primary health outcomes

	Control Mean (1)	Treatment Effect (2022 Ownership) (2)	Treatment Effect (2019 ownership) (3)	N
Physiological health index (blood oxygen and blood pressure)	-0.00	0.02	0.02	696
	[1.00]	(0.17)	(0.13)	
Number of non-respiratory health symptoms	1.09	-0.24	-0.18	702
	[1.54]	(0.25)	(0.19)	
Non-respiratory health symptom index	-0.00	-0.03	-0.03	702
	[1.00]	(0.19)	(0.14)	
Number of respiratory health symptoms	1.70	-0.48**	-0.36**	702
	[1.76]	(0.23)	(0.17)	
Respiratory health symptom index	-0.00	-0.24*	-0.18*	702
	[1.00]	(0.13)	(0.10)	
Health diagnoses index	0.00	0.13	0.10	702
	[1.00]	(0.16)	(0.12)	
Number of health diagnoses	0.30	0.13	0.10	702
	[0.58]	(0.09)	(0.07)	
Cognitive index	-0.00	-0.01	-0.02	587
	[1.00]	(0.15)	(0.12)	
Healthcare utilization index (spending and visits)	0.00	0.08	0.05	702
	[1.00]	(0.14)	(0.11)	

Each row is an instrumental regression wherein endline modern stove use is instrumented for with randomly assigned price, credit treatment status, and their interaction. Regressions include socioeconomic controls and control for hour of day of the second visit, where blood pressure and blood oxygen were recorded. Table A11, Table A12, Table A13, Table A14, Table A15, and Table A16 present detailed results on the components of the physiological, symptoms, diagnoses, cognitive, and healthcare utilization indices. Outcomes for children are presented in Table A17 and Table A18.

by 12%. Similarly, we find no effect on the number of hospital visits, hospital-related expenditures, or any of the cognition outcomes (Table A15).[31]

These results point to important heterogeneity in the impacts of pollution exposure on health. The significant reduction in intense, short-term peaks likely contributed to the reduction of self-reported and largely transient health symptoms. At the same time, the lack of reduction in aggregate average pollution exposure may explain the lack of impacts on chronic or quantitative health outcomes, despite 3.5 years of sustained use of reduced peaks in air pollution. Taken together, this suggests that while reductions in peak exposure can generate important short-term health improvements, improvements in long-term measures of health may require reductions in ambient air pollution exposure. Section 5 explores the direct link between pollution exposure and health in more detail.

We cannot detect a statistically significant impact on a range of child health outcomes, including weight, height, and arm circumference, a range of self- or parent-reported symptoms, and two

[31] Due to a technical issue with the tablets the sample size for some of the cognition outcomes is smaller than in other outcome tables. Since this was a technical issue, and since the order of follow-up surveys was randomized, it is unlikely that this biased the results in any meaningful way.

types of attempted pneumonia diagnoses (Table A17), neither among children under 10 nor when restricting the sample to just children age 5 or under, who are more likely to stay at home during the day (Table A18).

One way to reconcile the impacts on self-reported symptoms directly related to pollution with the lack of impact on more objective outcomes is that the self-reports are driven by the "peak-end" effect. A classic psychology finding is that when evaluating experiences, individuals attend primarily to the peak intensity of the experience and the end of the experience (Fredrickson and Kahneman, 1993; Kahneman et al., 1993; Redelmeier and Kahneman, 1996). In our context, this means that when asking someone about their symptoms, they may pay disproportionate attention to the symptoms experienced during peak smoke exposure. Because the intensity of the peaks is reduced by the Jikokoa, these salient experiences may be reduced even without an effect on more enduring measures of health. It is important to note that this does not mean the self reports contain no signal of health experiences, but that they may be driven by peak experiences which may not translate into non-transitory health impacts.

4.4 Heterogeneity of health impacts

We do not find evidence of heterogeneity in treatment impacts along the lines of baseline health, baseline beliefs about future health impacts, age, WTP, or baseline charcoal expenditures (Table A19). Ambient pollution is a potentially important source of heterogeneity, as some previous research has found air pollution improvements to be non-linear—either concave or convex—in average pollution. We test for heterogeneity in the primary treatment effect on health by whether the respondent has above or below median ambient air pollution. To avoid bias due to adoption endogeneity and noise in the time use data, we define a respondent's ambient pollution as average pollution among the five respondents residing nearest that respondent. We then test whether the health impacts differ by whether respondents' ambient exposure is above vs the median. We find no difference of heterogeneity along this dimension, at least over the range of pollution levels we observe (Table A20).

Since ambient pollution levels are generally lower in rural areas than in urban areas, study participants residing in rural areas may experience larger proportional pollution improvements. To examine whether health impacts are different for study participants residing in rural areas, we estimate the causal impact of adoption on health outcomes just among this sample. We do not find evidence of health improvements among this sub-sample—in fact, most point estimates point in the opposite (Table A21). We refrain from over-interpreting this result because the rural sample is very small ($n = 53$) and because moving to a rural area is an endogenous choice that may significantly bias the estimation.

4.5 Impacts of stove ownership on socio-economic outcomes

Panel (B) of Table 2 presents the impact of stove adoption on various socioeconomic outcomes (Table A4 presents a more detailed version). Among the urban sample, improved cookstove ownership causes a \$1.65 reduction in weekly charcoal expenditures, about a 44 percent reduction relative to the control group (Table A4). This adds up to approximately \$86 per year—a statistically and economically significant result, though the estimate is slightly lower than short- and medium-term impacts (Berkouwer and Dean, 2022a). Rural residents spend less than half as much on charcoal per week as urban residents.[32] The combined treatment effect for the full sample is therefore slightly lower; \$1.50 per week on average. These results demonstrate that the stoves have both large private and social benefits.

In addition, Jikokoa adoption increases the propensity of individuals in an adopter's network to adopt the stove. Specifically, it roughly doubles the number of Jikokoa stoves owned by members in a respondent's network such as friends, family, and in particular neighbors (Table A4). We see no impacts on earnings, savings, or formal banking access, suggesting the financial savings may have been spent on consumption. In terms of other behavioral outcomes, we see no impacts on time spent on various activities such as sleeping, working, eating, or walking (Table A5).

4.6 Robustness tests

A critical concern when using self-reported data is whether self-reports are driven by experimenter demand. Participants who received a (sometimes very heavily) subsidized cookstove might be more inclined to report better health than those who did not. While we cannot rule out some amount of experimenter demand, several factors weigh against this fully explaining the effects. First, we test whether those with higher subsidies are more likely to report positive health even after controlling for stove adoption. If respondents with a lower price (higher subsidy) were more likely to self-report better health, price would correlate directly with self-reported symptoms rather than purely through the adoption channel ('owns Jikokoa'). We do not find evidence of this (Table A22). Second, self-reported health improvements arise primarily through respiratory rather than non-respiratory symptoms: participants would thus have to be sophisticated about which types of health symptoms they report improvements in. Third, the relationship between health and pollution is similar in magnitude when constraining the sample to non-adopters only (Table A27).

702 of the 942 respondents (75%) were surveyed successfully during the three-year follow-up survey. Attrition is not correlated with their randomly assigned BDM price, credit treatment assignment, initial Jikokoa stove adoption, or baseline health outcomes (Table A24). 53 of the respondents who did not complete the three-year follow-up survey had moved outside to locations the three study areas—either elsewhere in Nairobi or elsewhere in Kenya—but where our survey team could still reach them. 65% of those who were not surveyed could not be contacted; the remainder were not surveyed because they said they were unavailable, withdrew from the study, or relocated to locations outside of the survey team's reach (Table A23). Attrition is slightly higher among respondents with fewer children, fewer household members, and younger respondents (such respondents may more easily move around, making them harder to track).

[32] Households living in rural areas are more likely to use firewood to cook as this can often be gathered at little to no cost.

Table 5: Correlation between health and mean, median, maximum, and duration of PM2.5 exposure

	Mean	Mean Pollution in SD	Median Pollution in SD	Max Hourly Pollution in SD	Hours Above $100\mu g/m^3$	N
	(1)	(2)	(3)	(4)	(5)	(6)
Hypertension (>130/80)	0.51	0.01	-0.02	0.00	0.00	645
	[0.50]	(0.02)	(0.02)	(0.02)	(0.01)	
Blood oxygen	96.72	0.12	0.12	-0.03	0.03	645
	[2.43]	(0.10)	(0.11)	(0.10)	(0.06)	
Health symptoms index (z-score)	-0.09	0.01	-0.01	0.07**	0.01	651
	[0.92]	(0.04)	(0.04)	(0.04)	(0.02)	
Number of health symptoms	2.52	0.02	-0.00	0.23**	0.02	651
	[2.66]	(0.11)	(0.11)	(0.10)	(0.06)	
Health diagnoses index	-0.04	-0.04	-0.05	0.00	-0.03	651
	[0.89]	(0.04)	(0.04)	(0.04)	(0.02)	
Number of health diagnoses	0.29	-0.03	-0.02	-0.00	-0.02	651
	[0.56]	(0.02)	(0.03)	(0.02)	(0.01)	
Hospital visits in past 30 days	0.30	-0.01	-0.01	0.01	-0.00	651
	[0.55]	(0.02)	(0.02)	(0.02)	(0.01)	
Hospital visit expenditures (USD)	2.82	0.66	0.40	0.62	0.26	651
	[10.14]	(0.44)	(0.45)	(0.42)	(0.24)	

Each row and column cell in columns (2)–(5) is a separate OLS regression. All regressions include socioeconomic controls, fixed effects for the specific PA-II device used, month of survey, and willingness to pay for the Jikokoa in 2019. Hypertension refers to stage 1. Table A26 provides the same for CO. Table A25 provides a version with additional detail. Table A12, Table A13, and Table A14 present detailed results on symptoms and diagnoses.

5 The relationship between pollution and health

There is uncertainty in the literature about which moments of the pollution exposure matter for health. Unfortunately, using an instrumental variables approach to estimate the impacts of these different moments causally lacks precision (the Cragg-Donald Wald F-statistic on a weak identification test is 1.4) and also potentially violates the exclusion restriction as there are multiple channels through which stove adoption could affect health outcomes.

Instead, we provide some evidence by using standard OLS regressions to estimate the correlation between health and three key moments of pollution: average pollution exposure (in 100 $\mu g/m^3$), peak pollution exposure (defined as the highest hourly average recorded, in 100 $\mu g/m^3$), and the duration of high pollution exposure (defined as the number of hours pollution was above in 100 $\mu g/m^3$). Table 5 presents the results. Table A25 provides a version with additional detail, and also provides specifications that control for average pollution to look at the effect of peakiness as distinct from higher average pollution.

Mean and median PM2.5 air pollution are not correlated with self-reported health symptoms, while maximum hourly pollution is. Peaks in air pollution exposure may have very different health impacts than the mean daily levels that were investigated in much of the literature studying ambient air pollution (Chay and Greenstone (2003), Clay, Lewis, and Severnini (2022), Currie and Walker (2011), Deryugina et al. (2019), Ebenstein et al. (2017), Greenstone and Hanna (2014), Isen, Rossin-Slater, and Walker (2017), and Schlenker and Walker (2015)).

6 Conclusion

Air pollution is a significant contributor to global morbidity and mortality. Most air pollution falls broadly into one of two categories: peak pollution exposures—primarily generated by a household's private actions, such as cooking—and ambient pollution—primarily generated by other actors, such as factories, industry, power plants, or even neighbors' cookstove usage. Billions of the world's urban poor face both types of air pollution on a daily basis, yet there is little evidence on which policy makers seeking to improve health should prioritize. To fill this gap, we investigate the impacts of reducing peak pollution exposures in the presence of high ambient air pollution, using a randomized experiment studying an improved biomass cookstove in Kenya. Randomized subsidies and access to credit yield a persistent increase in adoption of a more energy efficient biomass cookstove. This allows us to asses the health impacts of owning an improved stove for three and a half years.

We find that improved stove ownership causes a large reduction in peak air pollution generated during cooking hours. As a result, households experience a 0.24 standard deviation improvement in self-reported respiratory symptoms.

However, since we observe no reduction during the remaining 22 hours of the day, and given the high levels of ambient pollution in this urban context, we see only a very small and statistically insignificant effect on average air pollution exposure. This can explain the comprehensive lack of impacts on a host of quantitative health measurements (including blood pressure and blood oxygen) and self-reported diagnoses of chronic diseases such as pneumonia, as well as several key health outcomes for children.

These results suggest that the urban poor have only limited ability to improve their health through the private adoption of improved technologies. Instead, improving chronic and long-term health will depend on the reduction of ambient air pollution, which will require government intervention addressing the negative pollution externality caused by economic activity.

However, our findings still support heavily subsidizing cookstove adoption. The high additionality of the subsidies makes them an extremely cost effective way of reducing carbon emissions. Building on earlier work, which found that stove adoption reduces annual emissions emissions by 3.5 tons of CO_2-equivalent per year, a policy of subsidizing stoves would likely abate emissions at a cost of approximately $5 per ton. This is significantly cheaper than most alternatives available today. In addition, the stoves continue to generate large co-benefits: urban households continue to save on average $1.65 (44%) in weekly energy expenditures, or $86 per year. Despite the modest impacts on health, stove subsidies to spur widespread adoption would generate large environmental and social benefits.

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