The cost-effectiveness of clean cookstove carbon mitigation after adjusting for additionality and impact

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Abstract

More than 200 million people cook with charcoal daily. This has high climate costs: a Kenyan household using a charcoal stove emits as much CO_2e per year as an average U.S. household using a gasoline vehicle. However, concerns around additionality (do subsidies increase sales?) and impact (do sales reduce emissions?) undermine the clean cooking transition. We conduct a randomized trial with 955 households in Nairobi to quantify the additionality and impact of subsidies for an improved cookstove in use by millions of households. Incentivizing one additional stove sale requires US$32 in subsidy spending, of which 16% flows to non-additional participants. Three-and-a-half years later, 83% of buyers use the improved stove and 11% of non-buyers do. Factoring in control group adoption and breakage rates, each additional stove generates at least 2.8 additional years of working improved stove ownership. Despite widespread stacking, stove ownership on average abates 1.7 tCO_2e per year. Together, the subsidies abate CO_2e at US$7 per ton (estimates range between US$3.5 and US$8.1). Each dollar of cookstove subsidy abates 168-383 times more CO_2e than a dollar of electric vehicle subsidy.

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1 Introduction

More than 2.1 billion people use biomass stoves on a daily basis, with more than 200 million using charcoal as their primary cooking fuel (IEA et al., 2025). Biomass stoves generate a plethora of well-known negative impacts. The deforestation, production, transportation, and combustion of the charcoal production sector generate significant emissions of carbon dioxide-equivalent emissions (CO_2e).[1] But despite pressures to reduce biomass usage, improved cookstove projects often yield disappointing results (Gill-Wiehl, Kammen, and Haya, 2024; Gill-Wiehl et al., 2023; Mobarak et al., 2012; Pattanayak et al., 2019; Thompson, 2022; Hanna, Duflo, and Greenstone, 2016; Gill-Wiehl, Hogan, and Haya, 2026).

Concerns center around *additionality* (the fraction of buyers who would not have bought the improved stove absent the subsidy) and *impact* (the realized emissions reduction from buying a stove, which can be diminished through stacking, rebound, low usage, or poor durability). Articles investigating low-quality cookstoves projects (Civillini, 2023) and high-profile cases such as the Security and Exchange Commission's finding that C-Quest Capital violated federal securities law (U.S. Securities and Exchange Commission, 2024), have further damaged the sector's reputation. The lack of rigorous, standardized methodology for quantifying the causal impacts of improved cookstove subsidies has suppressed widespread cookstove subsidization.

Do high-quality, low-cost carbon mitigation opportunities exist? If so, how cost-effective are these opportunities when rigorously accounting for their realized additionality and impact? With no way of separating themselves from low-quality technologies, high-quality technologies are subject to the same reputational penalty (Akerlof, 1970). As a result, even high-quality technologies offering genuine low-cost abatement opportunities will struggle to attract climate financing. Identifying and financing low-cost abatement technologies is critical for maximizing abatement and slowing climate change.

This paper demonstrates how randomized trials can quantify the cost-effectiveness of abatement subsidies, factoring in realized rates of additionality and impact. In this context, *additionality* is the number of stoves sales generated by each dollar of subsidy expenditure, factoring in that some subsidy dollars will go to non-additional buyers. *Impact* is the average abatement in tons of CO_2e (tCO_2e) caused by the sale of one stove. This captures for example compliance (the rate at which buyers switch from the old technology to the new technology, stacking, and rebound responses), the abatement realized when buyers do switch, durability (the number of years the household owns a working energy efficient stove), and improved stove purchasing among non-buyers after the study's end. Aggregate cost-effectiveness can thus be defined in terms of tCO_2e abated per US\$1 of subsidy expenditure as follows:

$$\frac{\text{tCO}_2e\text{ abatement}}{\text{dollar expenditure}} = \underbrace{\frac{\text{tCO}_2e\text{ abatement}}{\text{stove purchase}}}_{\text{impact}} \cdot \underbrace{\frac{\text{stove purchases}}{\text{dollar expenditure}}}_{\text{additionality}} \tag{1}$$

We use data from a randomized trial with 955 households in Nairobi, Kenya who use tra-

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[1] This measure combines carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) over a specified time horizon in terms of global warming potential.

ditional charcoal stoves as their primary cooking technology. At baseline, households use on average 969 kilograms of charcoal per year. The Model of Fuelwood Savings Scenarios (MoFuSS), a global land use model that measures CO_2e emissions from reductions in woodfuel use, estimates that 38% of the biomass used to manufacture charcoal purchased in Nairobi, Kenya is non-renewable (fNRB). Floess et al. (2023) furthermore estimate an emissions factor of 38 tons of combustion CO_2e and 124 tons of non-combustion CO_2e (i.e. the production and processing of charcoal) per terajoule. Taken together, this corresponds to average annual emissions of 4.2 tCO_2e per household on average.[2] By comparison, an average U.S. gasoline passenger vehicle emits approximately 4.6 tCO_2e per year.[3]

In the experiment we both randomly assigned cookstove subsidies ranging between 25%–98% of the market price across study participants, and used an incentive-compatible, Becker, DeGroot, and Marschak (1964) mechanism to measure willingness-to-pay (WTP). This allows us to quantify how much of each subsidy US$1 goes to non-additional buyers versus additional purchases and estimate the causal impact of buying an improved charcoal cookstove.[4]

In this paper, we combine the detailed demand estimates from Berkouwer and Dean (2022a) with long-term follow-up data from Berkouwer and Dean (2026a). Charcoal usage was measured in four ways. First, we weigh the aggregate amount of ash produced through cooking activities over a one-month period. Second, we collect pollution measurements of PM2.5 using Purple Air (PA-II) devices deployed at each household. Third, we conduct surveys 1 month, 1 year, and 3.5 years after initial purchasing. Fourth, we conduct a high-frequency SMS survey for 2 months after purchasing and again between 12-14 months after purchasing.

We generate three key findings. First, carbon abatement through cookstove subsidies costs US$7 per ton of CO_2e in this context. This is well below the most recent Social Cost of Carbon (SCC) estimate of US$120 per ton even under a conservative 2.5% discount rate (EPA, 2023). For comparison, it costs US$1,356 in electric vehicle subsidies or US$237 in rooftop solar subsidies to abate one ton of CO_2e (Hahn et al., 2024).

Second, while the improved stoves are significantly cleaner than the incumbent stoves, compliance is imperfect, many stoves break, and households often stack fuel types: abatement would have been more cost-effective had usage and compliance rates been higher. 27% of households who bought an improved stove still own the traditional stove one year later. During a follow-up visit 3.5 years after the main study, 83% of original buyers still own the improved stoves in working condition, and 11% of non-buyers had purchased one by then. We estimate that the improved stoves last on average between 3.1 and 6 years. Factoring in observed control group adoption and breakage rates, each additional sale caused by a subsidy generates between 2.8 and 5.4 additional years of improved stove ownership depending on the assumptions about breakage

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[2] To offer intuition: Each carbon atom in charcoal combines with one O_2 molecule to form CO_2e; since CO_2e has molecular mass 44 and carbon atomic mass 12, burning 1 kg of pure carbon yields 3.67 kg of CO_2e.

[3] According to the EPA, a typical gasoline passenger vehicle is driven 11,500 miles per year, at an efficiency of 22.2 miles per gallon, and emitting 8.9 kilograms of CO_2e per gallon of gasoline (EPA, 2025).

[4] Berkouwer and Dean (2022a) previously estimated the short-run impact of buying an improved charcoal stove and compared this against the stove's US$40 store price. This type of naive abatement cost calculation fails to account for imperfect additionality, non-compliance, or durability. Berkouwer and Dean (2022a) also used an outdated charcoal-to-CO_2e conversion methodology and only one year of follow-up data.

rates after visits (to be conservative, our main estimates throughout the paper use 2.8 years). In terms of abatement, owning a working improved stove for one year reduces household charcoal usage by 379 kilograms of charcoal. Combining these realized rates, the causal impact of one additional stove sale on emissions is a reduction of 4.6 tCO_2e.

Third, 16% of total subsidy expenditures flows towards buyers who would have bought the stove even without the higher subsidy. The subsidies would thus have been more effective had additionality been higher. At the same time, the additional subsidy increases the purchasing rate by 41 percentage points. Taken together, incentivizing one additional stove sale requires US$32 in aggregate subsidy spending.

Global investment in climate mitigation now exceeds one trillion dollars per year (Buchner, 2024). The 2021 Paris Agreement established trillion-dollar financing goals for carbon mitigation in the coming decade (UNFCCC, 2024), and 2024's COP29 was dubbed the 'finance COP' (Buchner, 2024). Yet even though low- and middle-income countries are expected to generate two-thirds of global emissions by 2050 (IEA, 2024), 84% of global climate finance is currently spent in North America, Europe, and East Asia and the Pacific (CPI, 2023). The world could thus be missing credible mitigation opportunities. This paper demonstrates how rigorous methodologies can quantify the carbon abatement achieved through cookstove subsidies. Clean cooking has enormous potential for scale. Each of the 54 million charcoal stoves currently in use might therefore be able to offer the same abatement opportunity as an electric vehicle, at 195 times less cost.

A meaningful amount but a modest fraction of global mitigation financing is currently being spent on improved stove subsidies. The World Bank's Clean Cooking Fund is poised to invest more than US$500 million to boost the adoption of clean cooking technologies (ESMAP, 2023). Domestic government programs in, for example, Uganda and Kenya have dedicated enormous resources toward the adoption of clean cooking fuels (Kenya Power & MECS, 2024; MEMD Uganda, 2023). Carbon offset verification bodies have issued more than 433 million offsets credits for cookstoves projects, representing one (nominal) ton of CO_2e each and amounting to billions of dollars worth of investment (Ecosystem Marketplace, 2025). However, low-quality abatement projects have plagued the market for carbon credits and damaged its reputation (Pande, 2024a; Jones and Lewis, 2023; Lezak et al., 2025), with offset projects achieving on average only 7–11% of their claimed emissions reductions (Gill-Wiehl, Kammen, and Haya, 2024; Probst et al., 2024; West et al., 2023). Identifying high-quality energy efficient cookstove projects can therefore draw in additional financing from multilateral institutions, domestic governments, philanthropists, private investors, and businesses. Funding improved cookstove subsidies can be a highly cost-effective way to reduce global CO_2e emissions.

More broadly, our approach can be applied to other carbon financing projects. As long as it is possible to identify potential buyers, randomize price subsidies, and repeatedly survey a sample, the exact same tools can be applied. Using randomized trials can enable credible reduction opportunities to distinguish themselves and avoid the reputation issues currently plaguing the market.

2 A methodology for evaluating emissions reductions

What is the causal effect of one dollar of subsidy expenditure on aggregate CO_2e emissions? This calculation first requires estimating the additionality of the subsidy: how much of the subsidy goes to buyers who would have bought the energy efficient technology even without the subsidy, and how much does the subsidy actually increase purchasing? Second, it requires understanding the impact: how much does buying the improved technology reduce emissions when factoring in that many people continue using their old technologies to some degree, and some buyers may not switch at all?

Since observers have imperfect knowledge of the determinants of stove purchasing and usage, simply observing the difference in emissions between owners and non-owners does not reflect how much of the difference is caused by one dollar of subsidy. However, the causal impact of improved cookstove purchasing can be straightforwardly estimated using well-established randomized controlled trial methodologies. Randomized subsidies can provide unbiased estimates of additionality and impact by addressing many of the existing concerns transparently and without the need for additional assumptions. Projects can also be imperfectly additional—for example, some buyers might be fully inframarginal (and would have bought the technology even without the subsidy) and others could be only partially marginal (they required some subsidy, but a smaller subsidy would have sufficed). In principle, a technology could still abate CO_2e cost-effectively even if many buyers are non-additional, so long as the additional buyers have a sufficiently large impact.

Despite these benefits, the use of randomized trials remains limited in the cookstove sector. Project certification agencies generally rely on self-reported data with selection-on-observables designs rather than randomized assignments. While randomized trials have certain limitations, which we review in the discussion, this paper is designed to demonstrate how randomized trials can be used to rigorously quantify additionality and impact in these contexts.

2.1 Additionality

Randomizing subsidies for energy efficient cookstoves across households allows the observer to estimate additionality by measuring differences in uptake across different subsidy levels. Consider either a low (or no) or high subsidy, $0 \leq s_l < s_h$, lowering the price relative to the competitive market price. Denote n_l and n_h to be the number of individuals who buy the stove when its price is lowered by a low or a high subsidy, respectively. For any given subsidy increase from s_l to s_h, the cost per additional sale is the increase in aggregate expenditures relative to the increase in the number of buyers:

$$\text{Subsidy cost per additional sale} = \frac{n_h s_h - n_l s_l}{n_h - n_l} \tag{2}$$

The aggregate difference in cost between the low and high subsidy can be separated into subsidies spent on non-additional and additional buyers:

$$n_h s_h - n_l s_l = \underbrace{n_l(s_h - s_l)}_{\substack{\text{Increased payouts}\\ \text{to non-additional buyers}}} + \underbrace{s_h(n_h - n_l)}_{\substack{\text{Full payouts to}\\ \text{additional buyers}}} \tag{3}$$

In addition to the initial purchasing decision, estimating additionality requires estimating the duration of working ownership. Repeating the above process on, for example, an annual basis—as additional low-subsidy participants buy the technology or high-subsidy participants lose the technology—will identify the total additional number of years of ownership caused by each dollar of subsidy expenditure.

2.2 Impact

Low usage rates, high stacking rates, or high rebound rates can undermine the impact of an energy efficient stove relative to what is estimated in a lab setting (Gill-Wiehl, Kammen, and Haya, 2024). These concerns are widespread, applying not just to cookstoves but to the adoption of a wide range of energy efficient household appliances including for example refrigerators and air-conditioners (Gillingham, Rapson, and Wagner, 2016; Chan, Gillingham, and Karakaplan, 2023). Observers generally have imperfect insight into how often each individual uses different technologies, which is needed to calculate rebound and stacking rates.

Crucially, in the context of an RCT, impact calculations require only the aggregate difference in average emissions between the groups receiving different subsidies. Aggregate emissions are significantly more straightforward to estimate than usage patterns: for a household switching from one type of charcoal stove to another type of charcoal stove, an aggregate measure of monthly charcoal spending is sufficient. For a household that uses both charcoal and liquefied petroleum gas (LPG) stoves, measurements of monthly spending on charcoal and on LPG can be converted to tCO_2e using local prices and emissions factors. Measures of stacking and rebound are critical for understanding the causal chain and informing, for example, product development. However, they are not needed for impact calculations.

Comparing aggregate emissions across randomly assigned owners and non-owners is sufficient to establish the causal impact of the subsidies. The random assignment of subsidies can be used as an instrument for ownership in a standard instrumental variables regression (Angrist and Imbens, 1994; Imbens and Rubin, 2015). The causal impact can be estimated using standard two stage least squares methods, where y_i is the outcome of interest (such as tCO_2e), z_i is individual i's subsidy level, and d_i indicates whether they bought the cleaner technology:

$$\begin{aligned} d_i &= \theta_0 + \theta_1 z_i + u_i \\ y_i &= \beta_0 + \beta_1 \hat{d}_i + e_i \end{aligned}$$

Standard statistical tools can also be used to measure heterogeneous treatment effects in case these are of interest, although the average impact for the additional buyers (i.e. the local average treatment effect) is likely the policy-relevant estimand. In regressions with multiple observations per respondent we cluster standard errors by respondent. Regressions include standard socioeconomic and demographic controls. Berkouwer and Dean (2022a) present balance tables, attrition tables, recruitment and study methodologies, and additional robustness tests.

3 Empirical application

Many East African households use a Kenyan Ceramic Jiko (KCJ), developed in the 1970s as an improvement on the three-stone fire. Most households who use a KCJ to meet their daily cooking and heating needs buy charcoal at least once every other day from their local charcoal vendors. This paper studies the Jikokoa (Figure S1), a more energy efficient charcoal cookstove that is manufactured in Nairobi and was available in stores for US$40 at the time of the study. The manufacturer has sold more than 2 million Jikokoa stoves across East Africa in the past decade (ECOA, 2026). Across their portfolio, the company has issued more than 4.8 million carbon credits in Kenya for sales of their improved wood, charcoal, and electric stoves.[5]

The Jikokoa is nearly identical in usage to the KCJ, using the same type of charcoal and requiring effectively no learning to use, and there is little discernible difference in the taste and smell of food cooked. The primary difference is that the Jikokoa's engineering quality generates superior insulation. Its main combustion chamber is constructed using insulation materials, including a metal alloy that better withstands heat and a layer of ceramic wool that insulates the chamber to cut heat loss, and is designed for optimized fuel-air mixing. Individual components are designed with high precision to fit tightly to minimize air leakage and are manufactured to strict specifications. These features were designed and tested by laboratories in Nairobi and Berkeley, which estimated that they double the charcoal-to-heat conversion rate. Only half the charcoal should therefore be required to reach and maintain the cooking energy as the KCJ.

We implement a randomized field trial with 955 low-income households living in the Dandora, Kayole, Mathare, and Mukuru neighborhoods of Nairobi, Kenya Figure S5 shows approximate respondent locations across Nairobi).[6] Subsidy randomization and stove purchasing took place during baseline surveys in 2019 (Figure S2 presents a timeline of research activities). Participants were randomly assigned a subsidy for the stove of between US$10 and US$39 such that all study participants received a subsidy of at least US$10 (Figure S4 shows the randomized subsidy levels). In total, 570 of 955 participants (60%) purchased the improved stove.

Charcoal consumption was measured in four ways. First, expenditures were measured using a recurring SMS survey wherein households were asked about their charcoal expenditures once every three days, resulting in almost 8,000 data points collected over one month. Additionally, in the month after the main survey, users were asked to dispose of the ash generated from cooking with charcoal (on any stove) in a plastic bucket that was provided to them for this purpose. At the end of this month after the baseline survey, enumerators visited respondents for an in-person follow-up survey to ask about charcoal expenditures and to weigh the ash collected in the

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[5] The project is registered with Gold Standard Registry project IDs 5642, 10791, and 11432.

[6] A first companion paper uses this trial to evaluate the impacts of improved stove ownership on fuel spending and to evaluate the barriers to ownership by randomizing access to a loan and increasing attention to potential financial savings (Berkouwer and Dean, 2022a). A second companion paper uses this trial to evaluate the impacts of improved stove ownership on air pollution and health outcomes (Berkouwer and Dean, 2026a).

buckets. One year after the baseline survey, enumerators conducted phone surveys asking about recent charcoal expenditures (they were unable to make in-person contact due to COVID-19 related considerations). Finally, three-and-a-half years after the baseline survey, enumerators visited respondents for an in-person follow-up survey about charcoal expenditures and deployed Purple Air monitors to record PM2.5 levels for 48 hours.

3.1 Converting charcoal usage to CO_2e emissions

We use local charcoal prices to convert charcoal expenditures to charcoal usage in kilograms (KG) of charcoal. To convert kilograms of charcoal to CO_2e emissions, we use the following equation, where NR refers to combustion using non-renewable biomass, R refers to combustion using renewable biomass, and NC refers to non-combustion emissions (Gill-Wiehl, Kammen, and Haya, 2024; Floess et al., 2023; Whitman and Lehmann, 2011):

$$ERs = \frac{\substack{\text{tonnes of} \\ \text{charcoal reduced}}}{\text{hh-year}} * NCV\left(\frac{TJ \text{ of charc}}{\text{tonne of charc}}\right) * \left[\text{fNRB} \cdot NR + (1 - \text{fNRB}) \cdot R + NC\right]$$

These three types of calculations incorporate CO_2, CH_4 and N_2O equivalents and assume a 4-to-1 firewood-to-charcoal conversion ratio.[7] The net calorific value (NCV) of charcoal is 0.027 terajoules per tonne (Floess et al., 2023). We assume a fraction of non-renewable biomass (fNRB) of 38% reflecting the most recent Model of Fuelwood Savings Scenarios (MoFuSS) estimates for urban Kenya used in Ghilardi and Bailis (2024) and UNFCCC (2023) (Table 2 shows sensitivity of the results to a range of 10% to 100% fNRB).

These calculations result in an emissions factor of 162 per terajoule, consisting of 38 tons of combustion CO_2e and 124 tons of non-combustion CO_2e generated through the production and processing of charcoal. Together, each kilogram of charcoal burned in this context emits 4.4 kilograms of CO_2e.

4 Results: Additionality and impact of an improved cookstove

4.1 Additionality

Estimating additionality in this sample can use two approaches. The first approach focuses on the 86% of study participants who were randomly assigned a subsidy of between US$13-15 or between US$28-30. The advantage of this method is that it does not require the full distribution of willingness-to-pay (WTP) and is thus significantly more cost-effective to implement at larger

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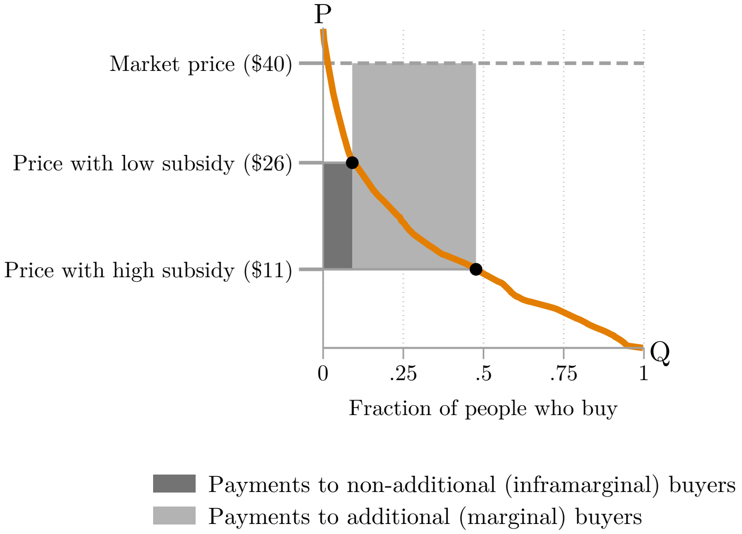
[7] Specifically, we calculate aggregate emissions as follows, with 0 downstream N_2O emissions:

$$\begin{aligned} R &= (EF_{CH_4 \text{ of charc}} \cdot GWP_{CH_4}) + (EF_{N_2O \text{ of charc}} \cdot GWP_{N_2O}) = (0.2 \cdot 27.2) + (0.008 \cdot 298) = 7.8 \\ NR &= EF_{CO_2 \text{ of charc}} + (EF_{CH_4 \text{ of charc}} \cdot GWP_{CH_4-NR}) + (EF_{N_2O \text{ of charc}} \cdot GWP_{N_2O}) \\ &= 78.5 + (0.2 \cdot 29.8) + (0.008 \cdot 298) = 86.8 \\ NC &= EF_{CO_2 \text{ of charc upstream}} + (EF_{CH_4 \text{ of charc upstream}} \cdot GWP_{CH_4}) + (EF_{N_2O \text{ of charc upstream}} \cdot GWP_{N_2O}) \\ &= 72 + (1.7 \cdot 29.8) + (0.005 \cdot 298) = 124.2 \end{aligned}$$

Figure 1: Additionality with additional and non-additional payments



Notes: Demand curve elicited through an incentive-compatible willingness-to-pay exercise (Berkouwer and Dean, 2022a). The market price was US$40 at the time of the study. A low or high subsidy of US$14 or US$29 reduces the price to US$26 or US$11, respectively. Non-additional buyers would buy the stove even with the low subsidy but still receive increased subsidy payments when the subsidy is increased. Additionality is the total number of purchases that arise for each additional US$1 of subsidy expenditure.

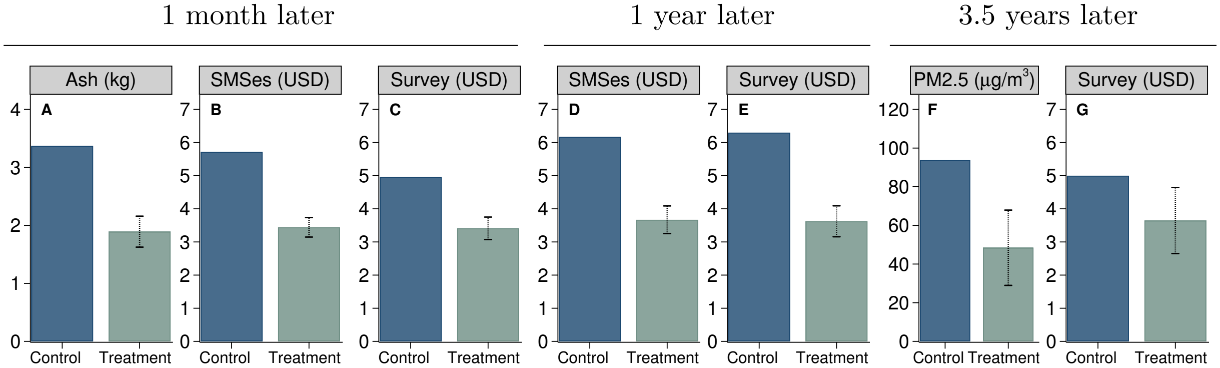
scale. We focus on participants who were not randomized to receive a loan in addition to the randomized subsidies (Berkouwer and Dean (2022a) discusses the impact of the loan).

Figure 1 displays non-additional and additional payments when moving from a low subsidy to a high subsidy. At a low-subsidy price of US$26, 7.6% of study participants are willing to buy the energy efficient stove. At a high-subsidy price of US$11, 48% of study participants are willing to do so. The higher subsidy increases the number of buyers by 41 percentage points, but the original 7.6% will also receive an increased subsidy, resulting in non-additionality. The higher subsidy is cost-effective in part because only 16% of buyers in the high subsidy group were non-additional, and would have bought the stove even with the lower subsidy. In other words, the subsidies were additional for the decision of the vast majority of households.

Using Equation 2, these numbers indicate that incentivizing one additional stove purchase requires an additional US$32 in subsidy expenditure, of which 16% flows to inframarginal buyers. Table 1 presents additional detail around this calculation.

A second approach to estimate additionality is to use the full willingness-to-pay (WTP) distribution shown in Figure 1. Specifically, having the full distribution allows us to estimate counterfactual demand for the full sample at the two subsidy levels. The comprehensive distribution of WTP—elicited through the BDM mechanism—reveals the fractions of each recipient's subsidy amount that was inframarginal relative to their WTP. Even marginal buyers often received some amount of inframarginal subsidy payment depending on their WTP. This yields very similar results: 9.3% of respondents have a WTP above the price with the low subsidy and 47% have a WTP above the price with the high subsidy group. Repeating the calculations

Figure 2: Impact of improved stove ownership on measures of charcoal usage



Notes: The left bar represents the mean among non-owners. The right bar represents the control mean plus the treatment effect (with standard error bars) from an instrumental variables regression (Table S1). a: weight of ash generated by one month of charcoal usage. b,d: charcoal expenditures reported in recurring 3-day SMSes collected over a 30 day period. c,g: charcoal expenditures as reported during in-person surveys. e: charcoal expenditures as reported during a phone survey one year after the baseline (due to COVID-19, no in-person surveys were conducted in 2020). f: pollution exposure collected by Purple Air devices during cooking hours.

above, this method results in a marginal subsidy cost of US$32 per additional sale. Still, the first method (using realized buying rates among those who received a subsidy of between US$13-15 or between US$28-30) better reflects most randomized trials and matches how the treatment effects are estimated. Table 1 thus presents numbers from the first method.

4.2 Impact

Figure 2 shows impact estimates from the randomized trial across seven independently-collected outcome variables (Table S1 presents the corresponding regression estimates): a weighing of the ash generated over one month of stove ownership; a recurring SMS survey wherein households were asked about their charcoal expenditures once every three days; socio-economic surveys conducted over the phone and in-person, and particulate matter under 2.5 micrometers in diameter (PM2.5) collected by Purple Air devices. The improved stoves cause a reduction of between 27-48% across all outcomes.

Using local charcoal prices to convert charcoal expenditures to kilograms of charcoal consumed, the median reduction of US$114 per year thus equates to an annual reduction of 379 kilograms of charcoal. We discount fuel savings at 10% but we do not discount CO_2e reductions. Using the methodology discussed in Subsection 3.1 to quantify charcoal emissions, this corresponds to a 1.7 tCO_2e emission reduction per year.

These estimates allow for stacking, rebound effects, or low usage rates, without needing to explicitly account for them. To the extent that households stack charcoal stoves, increase usage of their charcoal stove because cooking is now cheaper (a rebound effect), or under-use the energy efficient cookstove and instead continue using their old stove, this would be captured in the aggregate amount of charcoal they use. The primary outcome measure is simply aggregate charcoal used. Still, we observe some stacking: only 27% of households who bought an improved

Table 1: Subsidy cost per ton of CO_2e abated

	Low subsidy	High subsidy
(1) Subsidy	\$14	\$29
(2) Percentage households who buy	8%	48%
(3) Households who buy[a]	8	48
(4) Total cost	\$107	\$1,405
(5) Additional cost		\$1,298
(6) Additional stoves sold		41
(7) Subsidy cost per additional stove sold		\$32
(8) Abatement per additional stove sold (tCO_2e)		4.57
(9) Subsidy cost per additional ton of CO_2e abated		\$6.95

Note: [a] As an illustrative example, we perform calculations as if there are 100 households. Row (2) is derived from the demand curve in Figure 1 in Subsection 4.1. Row (3) is row (2) times 100. Row (4) is row (1) times row (3). Rows (5) and (6) are the difference between the high subsidy and low subsidy for rows (4) and (3), respectively. Row (7) is row (5) divided by row (6). Row (8) is derived from Figure 2 in Subsection 4.2 (each stove purchase increases stove ownership by on average 2.8 years and abates 1.7 tCO_2e per year). Row (9) is row (7) divided by row (8).

stove still had a KCJ in their home one year later, fewer than half of whom still used it at least once per month. Households could use the financial savings from the improved stove to increase their consumption of non-charcoal goods that emit greenhouse gases. However, the same concern is present when U.S. individuals purchase energy efficient appliances—this could therefore increase or decrease the relative efficiency of the estimates.

Among this study sample, buying an improved stove had no effect on liquefied petroleum gas (LPG) stove ownership. Still, even in a setting where improved charcoal stove ownership affected usage of other cooking technologies such as LPG or electric stoves, the same methodology could be used to estimate impact by simply aggregating fuel usage to a measure of CO_2e emissions.

After one year, 98% of buyers reported owning the stove (and 4.3% of non-buyers).[8] During the 3.5-year follow up visit, at which field officers visually inspected the stove, 83% of buyers still owned a working stove (and 11% of original non-buyers). Estimating total ownership requires interpolation, and possibly extrapolation, from these three data points. To offer bounds on durability we use two approaches. Under both methods we assume that the average stove adopted by the control group has the same durability as the average stove adopted by the treatment group.

The most conservative method assumes that immediately after the one year endline ownership changes to what was observed 3.5 years later, and that ownership drops to zero immediately after the 3.5 year endline survey (method 1 in Figure S3). In other words, this assumes zero usage beyond what was confirmed by field officers during surveys. While is almost certainly an

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[8] Since this survey was conducted in September 2020, due to COVID-19 related public health safety concerns this survey was conducted over the phone and field officers were therefore unable to inspect the stove visually.

underestimate, the main estimates below use the lower bound of the interval to be conservative. The alternative approach allows for a quadratic breakage rate (method 2 in Figure S3). This results in average stove durability of between 3.1 and 6 years, respectively. After netting out ownership increases in the control group, each original stove sale causes between 2.8 and 5.4 additional years of stove ownership.

Combining the more conservative estimate of 2.8 with the annual emissions reduction of 1.7 tCO_2e estimated above, this indicates that each stove sale abates an additional 4.6 tons of CO_2e over its expected lifetime.

4.3 Aggregate cost-effectiveness

Subsection 4.1 estimated that incentivizing the sale of one additional stove requires US$32 in subsidy expenditures (across both non-additional and additional buyers). Subsection 4.2 subsequently showed that the purchase of one stove reduces total CO_2e emissions by 4.6 tCO_2e over its expected lifetime. Combining these estimates following Equation 1, improved stove subsidies reduce emissions at a cost of US$7 per tCO_2e. Table 1 presents the corresponding calculations.

Table 2 expands the calculations under alternative assumptions. Scenario (1) allows for quadratic breakage (corresponding to method 2 in Figure S3). Scenarios (2) and (3) examine the sensitivity of the results to alternative assumptions around the fraction of biomass that is non-renewable. Assuming an fNRB of either 10% or 100% changes the estimated abatement cost to US$8.1 or US$5.3 per ton of CO_2e, respectively. Scenario (4) assumes a 6:1 conversion ratio of firewood to charcoal, which results in an abatement cost of US$5.1.

5 Discussion

5.1 Cost-effective CO_2e mitigation

This paper estimates a subsidy cost of abatement of US$7 per ton of CO_2e, with estimates ranging between US$3.5 and US$8.1 per ton depending on the exact assumptions. The most recent Social Cost of Carbon (SCC) estimates that each ton of CO_2e emitted generates between US$120 and US$340 in climate damages when using a 2.5% or 1.5% discount rate, respectively (EPA, 2023). Our entire range of abatement cost estimates thus falls well below even the most conservative SCC estimate. Net of the cost of manufacturing each stove, each US$1 of subsidy spending generates between US$17 and US$49 in avoided climate change damages.

It is worth emphasizing the cost-effectiveness of these estimates when compared with alternative clean technology subsidies that have received major public investment in the U.S. Subsidies for hybrid and electric vehicles, rooftop solar, weatherization, and energy efficient appliances credibly reduce emissions—but do so at high abatement costs. Electric vehicle subsidies cost US$1,356 in subsidy expenditure per tCO_2e abated (Hahn et al., 2024): in other words, each dollar of green subsidy towards improved cookstoves abates approximately 195 times more CO_2e than a dollar of electric vehicle subsidy (estimate range between 168 and 383 depending on the

Table 2: Results under alternative assumptions

Scenario	Description	Subsidy spending per ton of CO_2e abated
	Paper estimate *Sharp breakage assumptions; fNRB of 38%; firewood-to-charcoal ratio of 4:1*	US$7
(1)	Assuming quadratic breakage	US$3.5
(2)	Assuming an fNRB of 10%	US$8.1
(3)	Assuming an fNRB of 100%	US$5.3
(4)	Assuming a firewood-to-charcoal conversion ratio of 6-to-1	US$5.1

Note: Sensitivity of the estimated subsidy cost per ton of CO_2e abated to alternative assumptions about ownership duration, the fraction of non-renewable biomass (fNRB), and the upstream charcoal production process. The "Paper estimate" reproduces the headline result from Table 1. Scenario (1) replaces the sharp breakage step-function with a quadratic breakage function (Figure S3 shows these assumptions visually). Scenarios (2) and (3) bracket the fNRB assumption at 10% and 100%, respectively, holding all other assumptions at their baseline values. Scenario (4) revises the upstream emissions factor by assuming a firewood-to-charcoal mass conversion ratio of 6-to-1, near the upper end of the range reported in the kiln-efficiency literature, which raises the non-combustion emissions per kilogram of charcoal burned. Across all scenarios considered, the abatement cost remains below US$10 per tCO_2e—well under the EPA's most conservative Social Cost of Carbon estimate of US$120 (EPA, 2023).

assumptions). Subsidies for weatherization, appliance rebates, and residential rooftop solar cost US$779, US$474, and US$237, respectively, in subsidy expenditure per ton of CO_2e abated.

These results partly reflect the fact that, despite its significantly higher cost, one electric vehicle reduces about the same CO_2e emissions as an improved stove. The evidence indicates that improved stove ownership abates 1.7 tCO_2e annually. An electric vehicle abates between 0.1–1.5 tCO_2e per year depending on assumptions about grid emissions and electric vehicles manufacturing (Hahn et al., 2024; Muehlegger and Rapson, 2023). Under all assumptions, ownership of an improved cookstove reduces more CO_2e per year than ownership of an electric vehicle.

Improved cookstove subsidies look even more favorable when factoring in the US$284 total private fuel savings that stove buyers benefit from on average. Factoring in the fuel savings, the avoided climate change damages, and the subsidy transfer, and netting this against the cost of manufacturing each stove, each US$1 of subsidy expenditure generates between US$26 and US$58 in total societal welfare gain, using the Marginal Value of Public Funds (MVPF) framework (Hendren and Sprung-Keyser, 2020). We refrain from estimating local environmental benefits, but these could plausibly increase the MVPF further.

As was actively discussed during the Article 6 developments at the 2024 U.N. Conference of Parties, rigorously evaluating the impact and additionality of mitigation projects may require significant expenditures on monitoring and evaluation (M&E). Suppose every US$1 of subsidy requires an additional US$1 on M&E: for example, requiring carbon credits to be independently evaluated through a randomized trial prior to being eligible for issuance. Even in this scenario, improved cookstove subsidies continue to generate an order of magnitude more CO_2e abatement than alternative technologies. Such expenditures would thus easily pay for themselves in terms of larger carbon emissions reductions facilitated through a more efficient allocation of abatement financing.

General equilibrium effects in the charcoal market could moderate these reductions to the extent that supply is inelastic and demand is elastic. However, the fact that ownership does not increase cooking time suggests that demand is inelastic (Berkouwer and Dean, 2022a), and the fact that the barriers to entry in selling charcoal are low suggests that pass-through from demand reduction to equilibrium quantity reductions is likely close to full.

5.2 Evaluation and abatement at scale

Any study that evaluates a specific technology in a specific location, like ours, has shortcomings. The cost-effectiveness of one fuel type (charcoal), in one type of residential setting (informal urban areas), in one particular country (Kenya) may not translate to other settings. Our study does not make claims to the cost-effectiveness of cookstoves outside of this setting. Rather, we advocate for the independent evaluation of cookstove projects using rigorous methodologies to guide the optimal allocation of global abatement financing. Our results suggest that, when accompanied by rigorous evaluation, improved cookstoves may offer a large opportunity for cost-effective CO_2e abatement.

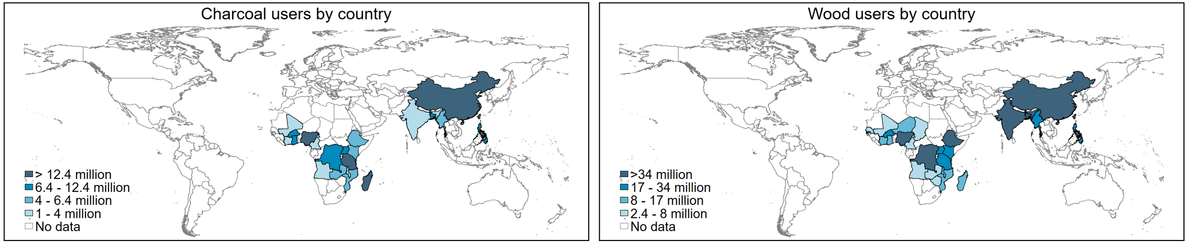
According to census data from across more than a dozen countries, more than 54 million households, or 200 million people, use charcoal as their primary cooking fuel (Figure S6 presents the global abatement supply curve for improved charcoal cookstoves under the assumption that the households in our study are representative). Figure 3 shows the pervasiveness of biomass cooking across the world (Table S2 presents the statistics and sources). If these households are similar to the households in our study, then widespread adoption of improved stoves can abate more than 90 million tCO_2e ($MtCO_2e$) per year. This is equivalent to the volume of the entire 2023 voluntary carbon offset market (Ecosystem Marketplace, 2024).

In addition, more than 1.1 billion people use wood as their primary fuel, suggesting the cooking sector as a whole could abate even more. Additional independent research in these areas using sophisticated econometric methodologies could help better allocate global financing towards the most effective CO_2e abatement opportunities. While much of the world is seeing rapid transitions towards cleaner cooking technologies like induction and liquefied petroleum gas (LPG) stoves, in 2030 more than 1.5 billion people are expected to still be cooking with wood, charcoal, or kerosene, including more than 1 billion in Africa (IEA et al., 2025).

Our aggregate abatement estimates align well with the company's carbon offset issuances. If each *additional* stove abates 4.6 tCO_2e in expectation, and 16% of stoves sold are not additional to the subsidy, then each stove sold abates 3.9 tCO_2e in expectation. This is in line with the company's issuance of approximately 1.5 credits (each valued at one ton of CO_2e) per year for 2-3 years.

The use of randomized trials has long been established practice in many policy domains,

Figure 3: Biomass stove users across the world



Notes: Number of charcoal and wood users in countries where census data indicate at least 1 million charcoal users or at least 1 million wood users. Table S2 provides additional details and data sources.

including for example in the development of medical interventions and in the evaluation of anti-poverty programs. It can straightforwardly be applied to evaluate carbon mitigation financing, even at large scales. Evaluators can follow standardized guidelines to ensure best practices during the initial evaluation of a potential opportunity (Glennerster and Takavarasha, 2013). Beyond an initial evaluation, evaluators can follow accepted best practices to maximize impact while continuing randomization and monitoring at scale (Muralidharan and Niehaus, 2017; Kasy and Sautmann, 2021). Crucially, these methods can be implemented independently of offset developers to ensure independence and avoid the moral hazard problem that arises when developers self-report.

These methods are already standard practice in evaluating other household energy durables. A recent randomized trial found promising results for subsidizing solar lamps to replace kerosene use (Rom, Günther, and Pomeranz, 2023). More than 25 million people use kerosene as their primary lighting source on a daily basis: replacing this with solar lanterns would abate approximately 9.9 $MtCO_2e$. There are between 400–500 million ceiling fans in India alone: Fowlie et al. (2022) find that energy efficient ceiling fans reduce electricity use by between 67–83%, which corresponds to a meaningful reduction in CO_2e emissions given India's coal-heavy grid. While there continues to be limited experimental evidence evaluating energy efficiency adoption in low- and middle-income countries, there has been substantial methodological progress on this topic (Fowlie and Meeks, 2021). In higher-income countries, randomized trials on energy efficiency subsidies have evaluated for example weatherization (Fowlie, Greenstone, and Wolfram, 2018), lightbulbs (Allcott and Taubinsky, 2015), and energy conservation (Ito, Ida, and Tanaka, 2018); see Gandhi et al. (2016) for a discussion of randomized trials to evaluate energy efficiency.

Randomized trials have also been used to evaluate land use subsidy programs such as payments for ecosystem services (Jayachandran et al., 2017; Jack, 2013). That said, they may be less likely to be effective in evaluating large, low-quantity projects, such as energy efficiency adoption among a small number of large firms, given the limited number of units available for randomization.

5.3 Impacts on poverty reduction

As shown in Figure 3, many charcoal and wood users reside in low- and middle-income countries. For many households residing here, even modest fuel reductions can generate significant quality-of-life improvements. The average household saves US$114 in charcoal expenditures in the first year and US$78 per year after that (Berkouwer and Dean, 2022a). The average improved stove buyer therefore saves US$284 over the average course of 3.1 years of ownership. In addition to abating 0.14 tCO_2e, each dollar of subsidy spending therefore also generates significant in fuel savings for low-income households. Respondents report spending these fuel savings on important household items like food, school fees, and medical expenses that generate large welfare improvements.

Put differently, abating CO_2e in this context reduces the use of economic resources and thus has a *negative* resource cost of abatement.

In rural areas, improved cookstoves can also reduce the time women spend collecting fuel which could advance women's empowerment (Krishnapriya et al., 2021). According to the World Health Organization, the indoor air pollution caused by inefficient stoves results in millions of premature deaths each year (WHO, 2024; Gill-Wiehl and Kammen, 2022). Ownership of improved cooking technologies has been shown to generate important health benefits (Berkouwer and Dean, 2026a). These co-benefits may make improved cookstove subsidies more appealing to funders who value co-benefits such as poverty reduction and climate justice (Pande, 2024b). Many households report that charcoal burning offers heating co-benefits during winter months, but buying an improved stove has no impacts on the rates of doing so or amount of time households burn charcoal just for heating purposes.

6 Conclusion

This study makes two contributions. First, we establish a methodology to assess the additionality and impact of subsidies for improved cookstoves using a randomized trial and other well-established quantitative research methods. The methodology is straightforward and transparent to implement by institutions concerned with reducing climate change and alleviating poverty, including multilateral institutions, domestic government organizations, philanthropic organizations, private donors, environmentally-minded firms, and individuals. These evaluations can be conducted by a number of independent agencies including for example carbon credit verification bodies such as Verra and Gold Standard, philanthropists and investors looking to maximize abatement efficacy, as well as regulators such as the SEC or the European Union looking to strengthen the climate finance sector. The policy findings in this paper are thus concrete and actionable.

Second, we apply the methodology to evaluate the subsidy efficiency of a novel energy efficient cookstove that is in widespread use across East Africa. The estimates account for imperfect additionality by measuring impacts of additional subsidies on additional purchases. By measuring aggregate energy consumption across owners and non-owners, the calculations do not need to explicitly adjust for stacking and rebound effects.

High-quality improved cookstove subsidies can abate greenhouse gas emissions at less than US$10 per tCO_2e, making them among the most effective abatement opportunities available in the world today. Every dollar of cookstove subsidy reduces 195 times more CO_2e than a dollar of electric vehicle subsidy. It is possible that other clean cooking technologies such as induction stoves (Berkouwer and Dean, 2026b) or liquefied petroleum gas could offer similarly efficient abatement opportunities: additional research in this area could help inform a more complete green transition path in the cooking sector. Yet, in regions without high-quality electricity connections or dependable LPG supply chains, subsidies for improved biomass stoves are likely to continue to be an optimal policy.

Optimally timing the global energy transition is crucial. The energy transition will eventually affect all sectors of the economy. However, the energy efficiency gains in cooking offer significant opportunities for cost-effective greenhouse gas abatement and poverty alleviation that can be implemented as soon as today.

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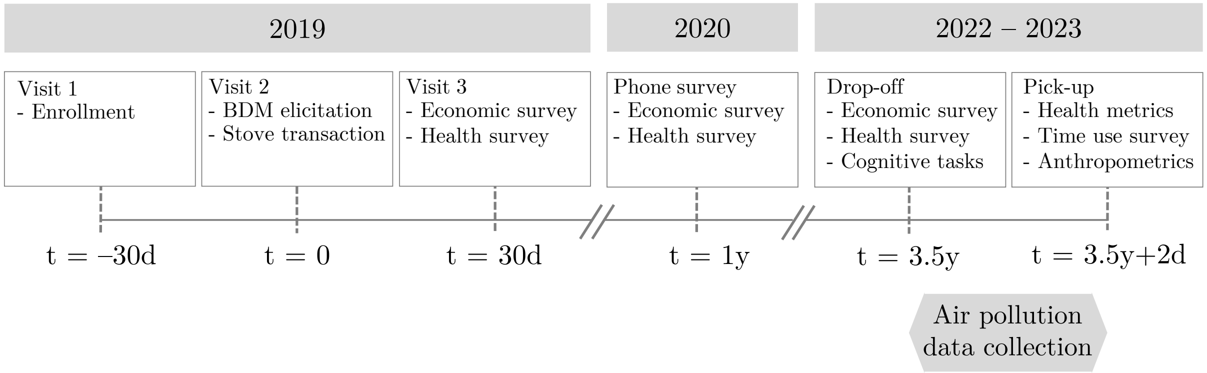
Supplemental Tables and Figures

Figure S1: Kenyan Ceramic Jiko and energy efficient stove

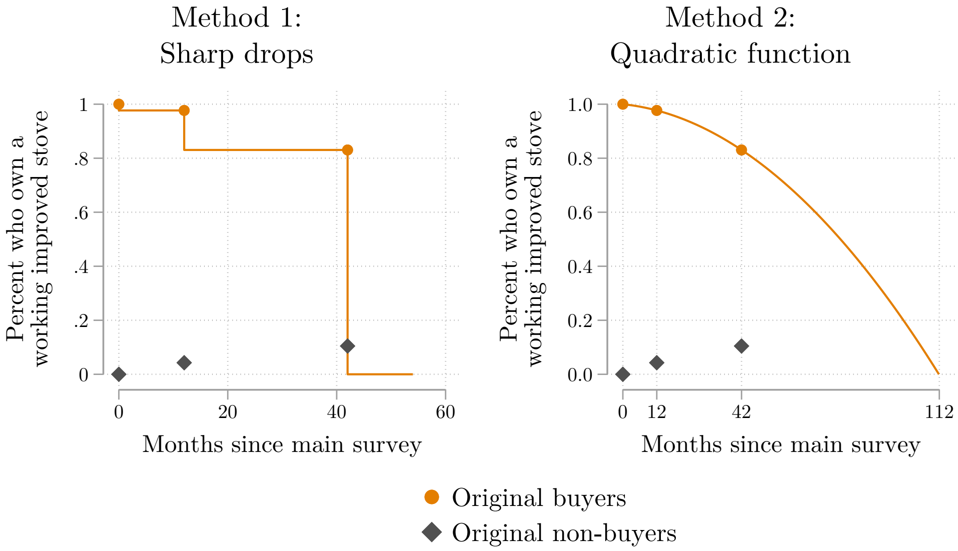
Notes: Reproduced from (Berkouwer and Dean, 2022a). On the left is the traditional *jiko*. On the right is the energy efficient stove. The two stoves use the same type of charcoal and the same process for cooking food, hence the energy efficient stove requires essentially no learning to use. After usage, 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.

Figure S2: Timeline of field activities



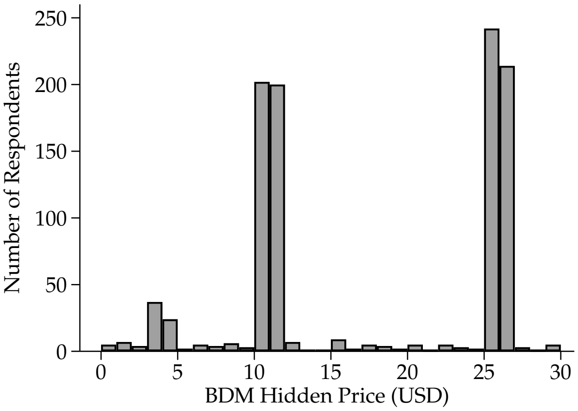
Notes: Participants who purchased the stove did so during the main visit ($t = 0$). For 89% of respondents the long-term endline was conducted 3.4–3.7 years after the main visit. Child anthropometrics were collected on either drop-off or pickup depending on presence. Due to health restrictions, the 2020 survey was conducted by phone.

Figure S3: Extrapolation between and after visits to estimate stove-year additionality



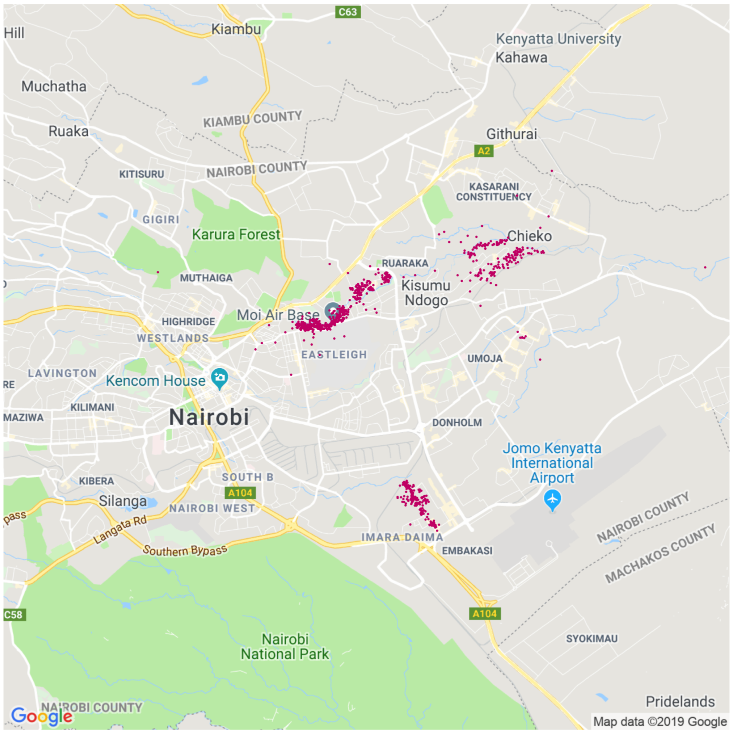
Notes: The dots show the observed improved stove ownership rates separated by those who bought the improved stove during the initial visit and those who did not. During the 42-month visit ownership of a working stove was established by visual inspection of the stove by an independent research staff member. The 12-month visit took place in September 2020; for public health reasons this survey was conducted by phone. The lines show interpolations across these points using two different methods. Method 1 assumes immediately after the one year endline ownership changes to what was observed 3.5 years later, and that ownership drops to zero immediately after the 3.5 year endline survey: this is the more conservative method, offering a lower bound on durability, and we therefore use it for the main calculations in the text. Method 2 assumes a quadratic fit. Method 1 generates an estimated 3.1 stove lifetime; method 2 yields 6 years. After netting out adoption in the control group, this results in an additional 2.8 or 5.4 years of working stove ownership, respectively.

Figure S4: BDM Hidden price distribution



Notes: Reproduced from (Berkouwer and Dean, 2022a). The distribution of prices P_i used in the BDM elicitation mechanism. 6% of participants are allocated a price drawn from $U[3.50, 4.50]$, 39% of participants are allocated a price drawn from $U[10, 12]$, and 44% of participants are allocated a price drawn from $U[25, 27]$. The remaining prices are drawn from a uniform distribution over the entire interval $U[0.01, 29.99]$. Respondents buy the stove if and only if $WTP_i \geq P_i$.

Figure S5: Approximate respondent locations across Nairobi



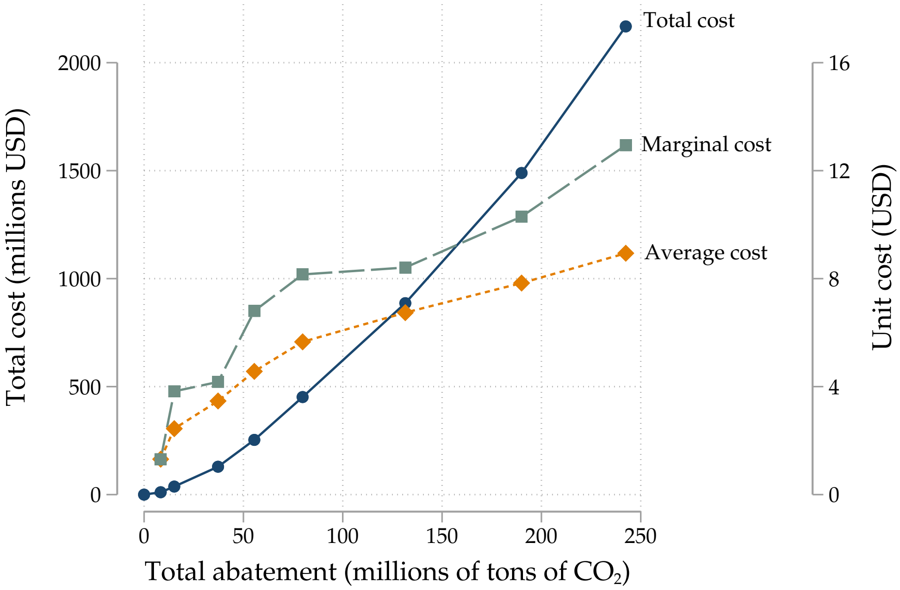
Notes: Approximate locations of study participants' home residences across Nairobi, Kenya. Reproduced from (Berkouwer and Dean, 2022a).

Table S1: Instrumental variables estimates of the effect of improved stove ownership on various independent measures of charcoal usage

	1 month later			1 year later		3.5 years later	
	(a) USD	(b) kg	(c) USD	(d) USD	(e) USD	(f) μg/m^3	(g) USD
Owns improved stove (=1)	-2.28 (0.29)	-1.48 (0.27)	-1.55 (0.34)	-2.50 (0.42)	-2.68 (0.47)	-45.30 (19.48)	-1.35 (1.00)
Observations	7853	796	911	6979	855	593	696
Control Mean	5.72	3.37	4.96	6.17	6.30	93.74	5.00
Treatment Effect	-0.40	-0.44	-0.31	-0.41	-0.42	-0.48	-0.27
SES Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Data Source	SMSes	Buckets	Survey	SMSes	Phone	PA-II	Survey

Notes: Results from instrumental variables regressions in which the randomly assigned subsidy is an instrument for whether the respondent owns the improved stove to estimate the impact of improved stove ownership on various outcomes. Columns (a) and (d) use self-reported weekly charcoal expenditures collected through a recurring SMS survey (standard errors clustered by respondent). Column (b) uses the weight of ash generated through charcoal stove usage. Columns (c) and (f) use self-reported weekly charcoal expenditures collected through in-person surveys. Columns (d) uses self-reported weekly charcoal expenditures collected through a phone survey (due to COVID-19, no in-person surveys were conducted in 2020). Column (e) uses PM2.5 data collected by Purple Air II sensors (in μg). The baseline survey was conducted in May-June 2019. The 1-month follow-up survey was conducted in June-July 2019. Regressions control for baseline charcoal spending, income, wealth, risk aversion, credit constrainedness, household size, and beliefs about stove benefits.

Figure S6: Supply curve of abatement at different subsidy levels



Notes: This graph plots the total abatement, total cost, average cost, and marginal cost for subsidies of {0, 5, 10, 15, 20, 25, 30, 35, 40} applied to a US$40 competitive market price. This graph assumes that the demand curves for the 54.3 million households that use charcoal as their primary cooking fuel are similar in demand and usage as our research sample. At all quantities, the average and marginal abatement costs are below the United States Environmental Protection Agency (US EPA)'s most conservative Social Cost of Carbon (SCC) estimate of US$120 (EPA, 2023).

Table S2: Households using charcoal and wood as primary fuels

Country	Households (millions)	Charcoal households (millions)	Wood households (millions)	Source
China	522.7	17.7	50.1	CNSB (2020)
Madagascar	6.9	4.5	2.2	MNIS (2022; 2022)
Tanzania	13.8	3.6	7.7	TNBS (2022)
Nigeria	40.8	3.2	23.4	NNBS (2024)
Burkina Faso	18.3	3.1	4.4	BFNISD (2021)
Dem. Rep. of the Congo	13.2	3.1	9.9	DMPH (2021)
Ghana	8.4	2.6	3	GSS (2022)
Philippines	23	2	8.5	PSA (2022)
Uganda	7.2	1.7	5.1	UBS (2020)
Bangladesh	41	1.7	28.2	BBS (2023; 2023)
Ethiopia	19.5	1.6	15.7	EPHI (2019)
Mozambique	6.2	1.4	4.3	MNIS (2023)
Kenya	12	1.4	6.4	KNBS (2022)
Zambia	2.8	1.2	1.4	ZSA (2018)
Myanmar	11.2	1.1	6.7	MMPF (2017)
India	291.7	1	95.1	INSO (2024)
Angola	5.8	.9	1.9	ANIS (2016)
Malawi	4.1	.8	3.3	MNSO (2020)
Mali	2.4	.5	1.8	INSTAT (2021)
Sierra Leone	1.3	.4	.8	SSL (2019)
Ivory Coast	6.6	.4	3.6	CINS (2021)
Cameroon	3.5	.3	1	CNIS (2022)
Senegal	1.6	.2	.6	ANSD (2023)
Chad	1.9	.1	1.6	INSEED (2019)
Pakistan	38	0	16.6	PBS (2020)
Other		.1	2.3	
Total		54.3	305.9	

Notes: Charcoal or wood households are those that use charcoal or wood as their primary cooking fuel, respectively. The table shows numbers of households in 17 countries where census data either lists at least 1 million households as using charcoal or at least 5 million households using either charcoal or wood as their primary daily cooking fuel. Only countries for which census data lists at least 1 million charcoal households are included. Some countries may be missing.

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