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Article

Reducing Emission of CO_2 from Africa's Tropical Forests: A Randomized Controlled Trial

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Abstract

This paper evaluates the impact of distributing high-cost LPG stoves to urban households through subsidy and on credit in a randomized controlled trial setup on charcoal consumption, CO_2 emission, and cooking time. The paper finds that the treatment group (credit and subsidy combined) reduced charcoal consumption by 28.7 percent 15 months after the intervention, corresponding to an average aversion of 3.78 MT of CO_2/household/year. The two treatments are not statistically significantly different. However, a social cost-benefit analysis suggests that the benefit of the stoves is 30-fold larger than their cost under credit and 18-fold larger under subsidy, which indicates that credit is the most socially effective instrument for supporting LPG interventions. The paper also documents that LPG stoves reduced cooking time by 68.5 percent 15 months after the interventions. The findings suggest that access to micro-finance is a promising avenue for promoting energy transition and addressing the adverse effects of biomass fuel use in developing countries.

JEL classification: G21, H31, O10, O13, Q23, Q51

Keywords: charcoal, deforestation, carbon dioxide, LPG stoves, liquidity constraint,

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1. Introduction

This paper uses a large-scale randomized controlled trial to identify the impact of switching from cooking with charcoal to liquified petroleum gas (LPG) on household welfare and the environment in a Sub-Saharan African (SSA) context. Charcoal is households' primary cooking energy source in many SSA countries' urban areas (Campbell et al. 2007; World Bank 2009, 2014). In the urban parts of Tanzania—the focus of this paper—the proportion of households that use charcoal to meet their primary cooking needs increased from 47 percent in 2001 to 71 percent in 2007 (World Bank 2009). The commercial capital, Dar es Salaam, alone consumes 500,000 tonnes of charcoal, half of the total annual charcoal consumption of the country (World Bank 2009). Unsustainable biomass fuel production and consumption have severe environmental and climatic implications. Biomass fuel use has been a prime cause of deforestation and forest degradation of forests and woodlands in SSA (Campbell et al. 2007; Ahrends et al. 2010; Mercer et al. 2011; Chidumayo and Gumbo 2013; Bailis et al. 2015), clearly resulting in the loss of irreplaceable biodiversity and degradation of local ecosystems (Allen and Barnes 1985; Geist and Lambin 2002; Hofstad, Köhlin, and Namaalwa 2009; Köhlin et al. 2011).[1] Land-use change, mainly driven by deforestation, is the second major contributor to global greenhouse gas emissions after fossil fuel combustion (Jayachandran et al. 2017). Moreover, biomass fuel, often burned in inefficient cookstoves, contributes further to climate change through its emission of other harmful greenhouse gases, such as black carbon and methane (Sagar and Kartha 2007; Kandlikar, Reynolds, and Grieshopdy 2009; Grieshop, Marshall, and Kandlikar 2011; Bailis et al. 2015). In a series of efforts to slow down deforestation and forest degradation in developing countries and to improve climate change adaption capacity, the international community has supported multi-million dollar climate-action initiatives in the past decade.[2]

At the household level, biomass fuelwood use results in indoor air pollution, which claims 3.3 percent of the global disease burden, especially that of women and children, and causes about 3.8 million premature deaths per year (WHO 2018). When households burn solid fuel, such as biomass fuels, indoors, mainly using inefficient cookstoves, harmful pollutants like PM2.5 are emitted. When inhaled deep into the lungs, these pollutants eventually lead to disability and death from serious diseases such as pneumonia, chronic obstructive pulmonary disease, stroke, ischemic heart disease, and lung cancer (WHO 2018; Díaz et al. 2007). Biomass fuel use also burdens women and children in many developing countries, where they are the primary household members responsible for collecting fuel (World Bank 2011; Blackden and Wodon 2006).

Therefore, transitioning to cleaner fuels is crucial to combat the adverse consequences of biomass fuel use. The complete transition of households in low- and middle-income countries from cooking with biomass fuel to LPG and/or electricity by 2040 will reduce the emission of nearly all pollutants that affect the environment and, possibly, health (Floess et al. 2023). However, the transition is conditional on adopting appropriate cooking appliances, which can have significant financial implications for poor households, who will have to forgo the consumption of other items to acquire them (Edwards and Langpap 2005; Mobarak et al. 2012; Lewis and Pattanayak 2012). Using randomized controlled trials, previous studies (Smith-Sivertsen et al. 2009; Miller and Mobarak 2014; Hanna, Duflo, and Greenstone 2016; Beyene et al. 2015; Bensch and Peters 2015; Pattanayak et al. 2019; Mobarak et al. 2012; Beltramo et al. 2015; Levine et al. 2018; Berkouwer and Dean 2022; Alem et al. 2023; Jeuland et al. 2023) have investigated the factors that promote adoption of cookstoves and their impact on fuelwood consumption and indoor air quality in developing countries. These studies identify affordability, social networks, availability of

1 The deforestation and forest degradation effect of charcoal production is particularly evident in Tanzania, where there was massive deforestation during 1991–2005 in areas 10 to 220 km from Dar es Salaam city (Ahrends et al. 2010).

2 For example, to support the programs known as Reducing Emissions from Deforestation and Forest Degradation (REDD) and REDD+ during 2006–2014 alone, the European Union and its member states spent over 3 billion euros (USD 3.21 billion) (EU 2015).

continuous technical support, cultural factors, proper technical designs, and empowerment of women as the key drivers of the adoption and continued use of cookstoves. Except Pattanayak et al. (2019), all these studies focus on improved biomass stoves. These authors distribute improved biomass and electric stoves in the Indian Himalayas in a large randomized controlled trial setup and show that subsidizing stoves improves uptake, but effective marketing campaigns and robust supply chains are key for continued diffusion. They also show that treatment households reduced fuel use by 15 percent and fuelwood collection time by 9 percent 15 months after the interventions.

The critical question we focus on is whether helping urban households relax liquidity constraints can induce them to switch to costly modern cookstoves or whether dependence on charcoal for cooking is driven by cultural factors that cannot be altered by public policy in the short run. This paper provides rigorous evidence on the causal effects of relaxing households' liquidity constraints to acquire high-cost cooking appliances (LPG stoves) on household outcomes and the environment. The high-cost nature of the stove we distribute is critical compared to all previous improved stove studies whose prices range from USD 5 to USD 40 (Alem 2021). The two-burner LPG stove we offer costs USD 111.11 at the time of the baseline (2015). The amount was equivalent to about five months' consumption expenditure of an average urban Tanzanian.[3] We collaborated with Tanzania's largest saving and credit cooperative (SACCO), Women Advancement Trust—WAT SACCOS Ltd.—and randomly distributed the LP gas stoves to households in Dar es Salaam through subsidy and on credit repayable in six months. The study quantifies the impact of the two policy instruments on charcoal consumption and the possible corresponding reduction in deforestation and emission of carbon dioxide (CO_2). The paper also documents a detailed social cost-benefit analysis of the two policy instruments and investigates the impact of LPG stoves on the cooking times of women, who are the default cooks of the household in the African context. The study is therefore significant because it draws on a large-scale randomized controlled trial to identify the impact of modern and costly cooking appliances on charcoal consumption, CO_2 emission, and cooking time.[4] Before fieldwork, the research project was evaluated and approved by the International Growth Center (IGC) at the London School of Economics (LSE), the Environment for Development Network (the University of Gothenburg), and the University of Dar es Salaam.

The paper's first outcome variable of interest is charcoal consumption and the corresponding aversion of CO_2. It draws on comprehensive baseline, midline (conducted 4 months after the interventions), and endline (conducted 15 months after the interventions) surveys. The results suggest that LPG stove distribution overall resulted in a significant reduction in charcoal use by the treatment group. Intent-to-treat (ITT) estimates indicate that households in treated communities consumed 28.7 percent less charcoal than the control group 15 months after the interventions. Using the random assignment of treatment as an instrument for adoption in an instrumental variables regression, the paper also shows that adopting LPG stoves reduces charcoal consumption by 39.5 percent 15 months later. The paper documents large ITT effects in charcoal consumption (32.3 percent) by the subsidy treatment group compared to the credit group (25.3 percent). However, the coefficients of the two treatments are not statistically significantly different.

Almost all charcoal production in Sub-Saharan Africa, and most importantly in Tanzania, occurs through cutting down and burning trees from the natural forest and woodlands in a traditional and highly inefficient process, with a conversion efficiency of 8–12 percent (World Bank 2009). Reducing charcoal consumption due to the transition to LPG stoves can be translated into a possible reduction in deforestation and net carbon dioxide (CO_2) averted in metric tonnes (MT), significantly benefiting society. Liquified petroleum (LP) gas, which LPG stoves use, is a highly efficient cooking fuel whose vapor is

3 The "Design" section describes the intervention and the stove in detail.

4 See Cesur, Tekin, and Ulker (2015) and Cesur, Tekin, and Ulker (2018) for observational-data-based results on the impact of shifting from coal to natural gas on infant mortality in Turkey, and Alem (2021) for a review of the experimental literature on stove interventions in developing countries.

removed from the atmosphere by natural oxidation in the presence of sunlight or by precipitation; thus, it does not have an impact on the global climate when emitted in gas form (WAPGA 2020). However, when burned, LP gas emits equivalent to 34 percent of the CO_2 emitted from cooking the same meal with charcoal (Johnson 2009). Thus, accounting for the CO_2 emitted from LPG stoves, the reduction in charcoal consumption by treatment households is equivalent to 0.04 ha of forest and 3.78 MT of net CO_2/household/year.[5] The study uses these figures to conduct a social cost-benefit analysis using the Social Cost of Carbon (SCC), which quantifies the monetary value of the benefits of stored CO_2. The results suggest that supporting the distribution of LPG stoves offers a net benefit of USD 84.93 per LPG stove to society in the first year and USD 147.43 per LPG stove per year for the remaining stove life. Thus, the total net benefit accruing to society during the lifetime of the stove (10 years) sums to USD 1,412 per LPG stove, which is 23 times larger than the average cost of the stove. The paper's findings have significant implications for policies that aim to promote the transition of households to cleaner energy sources and save the remaining tropical forests of Africa, which have significant carbon sequestration capacity.

The paper also identifies the treatment effects of the LPG stoves on cooking time. Households in developing countries spend significant time collecting biomass fuels for cooking. Both women and children carry a larger share of the burden of collecting fuelwood. Almost exclusively, women do all household cooking while doing other household work, such as looking after children. Consequently, women and children are the primary victims of health hazards from indoor air pollution due to biomass fuel use (World Bank 2011). While many studies show improved cookstoves reduce cooking time in controlled laboratory cooking tests (Beyene et al. 2015), the empirical findings from the few studies that use randomized controlled trials are mixed. Bensch and Peters (2015) show that improved cookstoves facilitate cooking and allow for temperature regulation, which reduces cooking time in rural Senegal by about 75 minutes per day. Hanna, Duflo, and Greenstone (2016) on the contrary, document no significant effect on cooking time in rural India because households had to spend more time repairing their improved stoves. The study offers helpful insights on the time-saving impact of owning modern cooking appliances.

The results suggest that treatment households reduced the time spent on cooking by about 68.5 percent 15 months after the interventions. Decomposition of the ITT effect by treatment type shows that subsidy households used the stoves more often and reduced cooking time by 77.1 percent. In contrast, credit households reduced cooking time by 60.2 percent per day. The reduction in cooking time is consistent with the efficiency of LPG stoves, which, unlike charcoal stoves, are quick to light up and generate the heat required to cook food much more quickly. The benefits from the reduction in cooking time (and possibly from exposure to flame and indoor air pollution), including the reduction in time spent purchasing charcoal daily, primarily accrue to women. The saved time can be used for income-generating job opportunities and other productive household activities such as childcare or even leisure, which either way improves the welfare of women. A four-month sample-controlled cooking test also shows that cooking exclusively with LP gas is almost 50 percent cheaper than cooking with charcoal.

The paper describes the experimental design, including the context, sample selection, and treatments followed by a discussion of descriptive statistics and randomization checks. Next, the paper presents the treatment effects of the LPG stove interventions on charcoal consumption, CO_2 emission, and cooking time and a cost-benefit analysis of the two policy instruments. The paper also points out the caveats of the study and avenues for future research. Finally, the paper concludes by presenting a summary of the key findings.

5 To produce 1 tonne of charcoal, 0.13 ha of forest and woodlands must be burned (World Bank 2009), and the average carbon stored in a hectare of forest in a setup similar to Tanzania is 153.5 MT (Hansen et al. 2013).

2. Experimental Design

2.1. Context

The study was conducted in Kinondoni and Temeke, two of the three districts of Dar es Salaam, the largest city in Tanzania. These two districts are located at the two extreme ends of the city, separated by Ilala, the third district. Ilala, which was used for the pilot, is the smallest district in terms of geographical size and population.[6] Dar es Salaam is the most populous region in Tanzania (with nearly 5 million people), and over 70 percent of its population uses charcoal as its primary source of cooking fuel (NBS 2015). The heavy reliance on charcoal is evident in the open charcoal markets throughout the city. Tanzania consumes approximately 1 million tonnes of charcoal for cooking annually, and Dar es Salaam alone consumes half of this amount (World Bank 2009). From a comprehensive fact-finding survey, we noted that many households in Dar es Salaam cook in either naturally ventilated kitchens or outdoors because of the hot climate of the city and that we did not expect to detect significant health effects documented by previous studies (e.g., Smith-Sivertsen et al. 2009; Hanna, Duflo, and Greenstone 2016). In this context, the first-order impact of the transition to cleaner cookstoves like LPG is on charcoal consumption and, consequently, deforestation and CO_2 emission.

Tanzania has recently discovered vast reserves of natural gas, which is expected to play a significant role in the country's economy by transforming the energy sector and boosting the gross domestic product (World Bank 2017). Since 2010, the BG Group has made several offshore natural gas discoveries in partnership with Ophir Energy, Statoil, and Exxon Mobil, reaching around 30 trillion cubic feet of recoverable natural gas reserves. With more discoveries envisaged, a pipeline has been constructed to transport natural gas from Mnazi Bay (the central point of discovery) to Dar es Salaam. These discoveries are expected to significantly reduce the cost of gas and electric energy costs and incentivize households to switch from charcoal to meet cooking energy needs. However, this transition could be substantially constrained by the relatively high startup cost of modern cooking appliances, especially for poor households. Findings from the baseline survey presented in the descriptive statistics support this skepticism. Almost all the sample households (99 percent) reported a high awareness of LPG stoves and their benefits but felt constrained not to adopt them, mainly because of the high initial cost.[7]

The study was conducted at a critical time to provide valuable and policy-relevant evidence on the constraints that households face in adopting modern cookstoves and switching away from charcoal, as well as the roles public policy can play in tackling these constraints. Furthermore, given the similarities of many Sub-Saharan African countries to Tanzania regarding access to energy and living conditions, the findings from this study will also have significant relevance to these countries.

2.2. Sample Selection

To conduct our experiment, we chose 2 wards from the Temeke and Kinondoni districts, from 34 and 30 wards, respectively.[8] We randomly chose Sandali and Azimio wards from the Temeke district and Manzese and Mwananyamala wards from Kinondoni. We then approached ward secretaries—government officials responsible for administrating wards under districts—to provide us with a list of all streets (also called subwards), the lowest administrative units in urban Tanzania, ranked by the average economic status (consumption expenditure) of resident households using the national budget survey. We then selected the upper four streets by their rankings in terms of economic status from each ward to participate in our

6 See supplementary online appendix S1 for a map of Dar es Salaam city.

7 Currently, less than 4 percent of households in urban Tanzania own modern cooking stoves such as electric or gas stoves (NBS 2015).

8 The randomized controlled trial was reviewed and approved by the energy research program group of the International Growth Center (IGC) based at the London School of Economics (LSE). The project was registered and posted on IGC's website before implementation. See https://www.theigc.org/project/liquidity-constraint-lpg-stoves-charcoal-consumption-evidence-randomised-controlled-trial-tanzania.

study, which gave us a total of 16 streets.[9] The key argument for selecting households this way is the fact that refilling LP gas once the startup gas runs out requires a bulk purchase (as opposed to a low-cost daily purchase for charcoal, which is common in the city) and, thus, the targeted population should be able to afford such costs. Finally, we asked the 16 street leaders to prepare a roster of eligible households in their streets, from which we randomly selected 722 households in proportion to the population of the streets to participate in the baseline survey.[10] Eligibility criteria required that the selected households had never owned/used an LPG stove and used charcoal (but not kerosene) as their primary source of cooking energy.[11] From an external validity point of view, in the "Caveats" section, we discuss and show that the socioeconomic characteristics of our sample of households are not that different from the randomly selected Dar es Salaam sample of the Tanzanian National Panel Survey (NPS). We assigned treatments at the street level to minimize contamination (spillover effects) from the treatment groups to the control group. The sampled streets are scattered across the districts and are reasonably large by geographical size and demographics. Street-level randomization also makes implementation of the program relatively easier as it seems fair from the households' point of view and is politically acceptable to the street and ward leaders.

We are interested in answering three key research questions: First, we want to identify the impact of LPG stoves (regardless of their mode of acquisition) on charcoal consumption and the corresponding reduction in CO_2 emission. Second, we are interested in exploring whether the impact on charcoal consumption differs depending on the mode of acquisition (subsidy or credit). Third, we want to assess the effect of LPG stoves on the cooking time of women, who take the sole responsibility for cooking, including purchasing charcoal from the market. We randomly assigned five streets (30 percent or 216 households) to the credit treatment. We assigned four streets (29 percent or 209 households) to the subsidy treatment. We kept the remaining seven streets (41 percent or 297 households) as the control group. Given we have only 16 streets (clusters) in the sample, we check the robustness of our estimated treatment effects using the wild cluster bootstrap-*t* procedure proposed by Cameron, Gelbach, and Miller (2008).

2.3. Treatments and Timeline of the Experiment

We obtained a research permit for this project from the office of Dar es Salaam Regional and Districts Administrative Secretaries. Then we implemented a fact-finding survey of 40 urban households in October–November 2014. This survey aimed at documenting qualitative and quantitative background information about knowledge, adoption, and usage (and non-usage) of LPG and charcoal stoves in all districts, important information that we later used to design our interventions. We developed a short questionnaire and conducted a few focus group discussion sessions that allowed us to obtain informative responses. We also included questions on households' maximum willingness to pay for an LPG stove package at this stage. We found encouraging household responses regarding knowledge and desire to adopt LPG stoves. However, we also found that the high start-up cost of LPG stoves was the main factor that hindered households from acquiring the stove.

We conducted a comprehensive baseline survey from March to April 2015, covering all 722 sampled households in the 16 streets. In the baseline, we included questions on demographic and other socioeconomic characteristics, cooking habits, charcoal consumption, stove use, and awareness and willingness to pay for LPG stoves. This was important information given that the cost of acquiring the stove package is reasonably high, and, naturally, some households may not be willing to buy it either on credit or through

9 A ward, on average, constitutes about 50 streets.

10 We specifically divided the total number of households in each street by the proposed sample size of households in the street to get a number, say x. Then we picked every xth household from the roster. The minimum number of households recruited from a street was 30, while the maximum was 61.

11 The proportion of households that use kerosene gas in Dar es Salaam is only about 7.8 percent (NBS 2015).

a subsidy. In addition to household-level information, we collected community-level information such as distance to the nearest charcoal market and road access.

In early May 2015, we conducted a pre-intervention survey to check whether the households we assigned to the treatment group were available. During this time, we informed the treatment group that their household was one of the households randomly selected to receive an LPG stove through a subsidy or credit and that the stoves were planned to be delivered approximately 1–2 weeks after the pre-intervention survey. The households were then asked whether they would like to participate in the program. Out of the 426 households who we randomly assigned to the treatment groups, 293 (69 percent) agreed to purchase the stoves, and the remaining 133 households (31 percent) decided not to (72 or 17 percent in the credit treatment group, and 61 or 14 percent in the subsidy treatment group). In the "Results" section, we estimate the treatments' intent-to-treat (ITT) effects that account for the households who declined to take the stoves.

We implemented the credit side of the LPG stove program in collaboration with WAT SACCOS Ltd., which helped us handle the stoves' delivery and collection of repayment installments for the credit treatment households. WAT SACCOS is one of the fast-growing saving and credit cooperatives working to provide access to micro-finance for low-income urban families. It has gained a good reputation and credibility in the disbursement and handling of different types of loans, including micro-credit, to finance the purchase of household durables.[12] Households were not required to be a member of WAT SACCOS to be eligible for the credit treatment, and membership is open to any household that fulfils the requirements of WAT SACCOS Ltd. To make the loan credible and minimize the default rate, we followed all procedures for getting such loans as per the rules of WAT SACCOS, but with a few modifications to suit the objectives of this study. For example, we did not require households to present any physical asset besides the stove as collateral. They were also required to provide a letter of guarantee from their street offices, which offers a credible commitment device in a Tanzanian context. No household was denied the letter of guarantee as long as it was a street resident.

We rolled out the interventions in late May 2015. We purchased the full LPG package from Oryx Energies, the largest distributor of fuels, LPG, and lubricants in Tanzania and other East African countries.[13] All households who agreed to take up the stove were invited for an information and training meeting by Oryx Energies before they were handed the LPG stove in its full package. The training included instructions on how to safely use, clean, maintain, and refill the LPG stoves once the start-up gas runs out.[14] Households in the subsidy treatment received the stove at 75 percent, i.e., they paid only 25 percent of the total cost. At the time of delivery, the total cost of a two-burner LPG stove (including a 15-liter cylinder filled with gas) was TZS 200,000 (USD 111). We decided to subsidize 75 percent of the cost of the LPG stoves because the average reported willingness-to-pay for the stoves during the baseline was about TZS 65,000 (USD 36), which was only a third of the market price of the stoves.[15]

All credit treatment households were required to pay TZS 20,000 (USD 11), which is 10 percent of the total loan, up front as their initial repayment on the day of stove delivery. They were also provided additional instructions regarding how to fill in the application forms, how the repayments would be

12 See http://www.watsaccos.or.tz/ for more information about WAT SACCOS Ltd.

13 We purchased the LPG stoves through the University of Dar es Salaam following its complete purchasing regulations. Sealed bids were collected from several suppliers, and Oryx Energies won by offering the same quality LPG stoves and cylinders as offered by other suppliers at the lowest price.

14 See supplementary online appendix S2 for pictures taken during training sessions and home visits.

15 A more informative approach would have been to implement different levels of subsidy arms and determine the optimal level of subsidy based on uptake data. Unfortunately, we could not do so due to the high-cost nature of the interventions. In the Results section, we conduct a cost-benefit analysis of the two policy instruments. We argue that subsidizing LPG stoves at a 75 percent subsidy rate will still offer net benefits to society in terms of saving forest resources and averting the emission of CO_2.

collected, etc. All participants were allowed to ask as many questions as they wished, and the survey team gave answers. To minimize the associated transaction costs and inconvenience, we required credit households to transfer the repayment installments to a given mobile phone account managed by WAT SACCOS using the mobile phone banking system known in the region as M-Pesa. The complete loan repayment period was set to be six months after the delivery of the stove. We did not charge any interest on the loans but required beneficiary households to cover minor transaction fees charged by M-Pesa operators during loan repayment. The transfer fee can be considered an implicit interest rate on the loan. Finally, the control group was offered the complete LPG package to buy at the total market price.

We then conducted a midline follow-up survey at the end of September 2015—approximately four months after we distributed the stoves—to collect information on key outcome variables of interest, including charcoal consumption, LPG stove use, compliance with treatment, and satisfaction with the stoves.[16]

Finally, to assess our interventions' longer-term impact, we conducted a comprehensive endline follow-up survey in August 2016, i.e., 15 months after the interventions. We documented detailed information on household and community characteristics, cookstove use, energy use and consumption, cooking habits, and LPG stove use and satisfaction.

3. Descriptives, Randomization Checks, and Attrition

Table 1 presents descriptive statistics of crucial household socioeconomic characteristics, cooking patterns, charcoal use, reported demand for LPG stoves at the baseline, and statistical tests of the balance of covariates. Column (1) shows that the average age of the household head is about 48 years, the majority of whom (70 percent) are male, and the average education is 7.5 years of schooling, which is slightly higher than the standard primary school level in Tanzania (7 years). About half of the sample households live in privately owned homes. Still, only 41 percent have access to a private kitchen, the remainder either cooking in their corridors or sharing a kitchen with other households. The average reported mean annual income of the sample households is only TZS 329,000 (USD 182). However, we note that the reported average daily expenditure on essential consumption items is TZS 9,500 (USD 5.27), which, on an annual basis, is nearly 11 times larger than the reported income. This overwhelming difference provides evidence that, compared to consumption expenditure, income in developing countries is significantly underreported (Deaton 1997; Deaton and Grosh 2000). In our subsequent analysis, we rely on consumption expenditure to control the economic status of households in regressions.

Urban Tanzanian households primarily depend on charcoal to meet cooking energy needs (panel B). The average family cooked using charcoal for about 23 years and consumed approximately 19.18 kg of charcoal per week, which costs about TZS 11,200 (USD 6.22). Thus, our sample of households consumes 13,848 kg or approximately 13.85 tonnes of charcoal per week. This translates to about 59.5 tonnes per month. We use insights from World Bank (2009) to shed light on the devastating consequences of charcoal use. To produce 1 tonne of charcoal in Tanzania, one burns 0.125 ha of woodland forest. Therefore, our sample of 722 households depletes approximately 7.44 ha of forest monthly. Regarding the intra-household decision on the choice of cookstoves, only 44 percent reported that the head is the leading decision-maker about the type of stoves used by the household. This suggests that, on average, spouses (wives) have relatively strong decision-making power when acquiring kitchen appliances. The type of meals cooked by the household could influence the amount and type of fuel used due to the cooking time and taste of the food. During the fact-finding survey, a few respondents argued that rice tastes better when

16 We initially planned to conduct the midline survey six months after distributing the stoves. However, the 2015 Tanzania National Election was scheduled for October 2015. To avoid interference in our study due to election-related activities, we conducted the midline survey in September 2015, four months after the intervention.

Table 1. Baseline Summary Statistics and Test of Balance for Covariates

	(1) All	(2) Cont.	(3) Cred.	(4) Sub.	(5) Cont.- Cred.	(6) Cont.- Sub.	(7) Cred.- Sub.
Panel A: Socioeconomic char.							
Head's age	47.46	47.53	47.92	46.90	−0.388	0.636	1.023
	(12.54)	(12.71)	(12.88)	(11.98)	(1.149)	(1.114)	(1.209)
Male head	0.695	0.712	0.706	0.660	0.00621	0.0520	0.0458
	(0.461)	(0.453)	(0.457)	(0.475)	(0.0409)	(0.0415)	(0.0453)
Household size	5.834	6.020	5.611	5.792	0.409*	0.228	−0.181
	(2.190)	(2.246)	(2.045)	(2.236)	(0.195)	(0.201)	(0.208)
Annual income (TZS)	329,181	328,040	336,876	323,132	−8,836	4,908	13,744
	(279,851)	(222,902)	(280,698)	(344,854)	(22,336)	(25,138)	(30,582)
Head's years of schooling	7.510	7.455	7.531	7.566	−0.0760	−0.111	−0.0352
	(2.972)	(2.725)	(3.268)	(3.009)	(0.266)	(0.256)	(0.305)
Average daily expenditure	9,479	9,142	8,831	10,601	310	−1,459	−1,769*
	(9,154)	(6,376)	(6,057)	(13,804)	(561)	(910)	(1,037)
Separate kitchen	0.406	0.415	0.417	0.382	−0.00235	0.0326	0.0350
	(0.491)	(0.493)	(0.494)	(0.487)	(0.0444)	(0.0441)	(0.0477)
House privately owned	0.493	0.515	0.474	0.481	0.0411	0.0339	−0.00720
	(0.500)	(0.501)	(0.501)	(0.501)	(0.0450)	(0.0450)	(0.0487)
Panel B: Cooking & charcoal							
Years using charcoal stove	23.14	23.13	23.62	22.67	−0.486	0.456	0.942
	(10.93)	(10.73)	(11.08)	(11.09)	(0.978)	(0.977)	(1.078)
Head decides on stove	0.440	0.428	0.464	0.434	−0.0364	−0.00587	0.0305
	(0.497)	(0.496)	(0.500)	(0.497)	(0.0447)	(0.0445)	(0.0485)
Distance to charcoal market (min.)	4.452	4.249	4.429	4.759	−0.180	−0.510	−0.331
	(4.333)	(4.709)	(4.142)	(3.951)	(0.403)	(0.396)	(0.394)
Number of meals cooked/week	19.22	19.13	19.19	19.39	−0.0625	−0.260	−0.197
	(3.334)	(3.496)	(3.111)	(3.326)	(0.300)	(0.308)	(0.313)
Rice, main staple	0.507	0.485	0.536	0.509	−0.0506	−0.0245	0.0261
	(0.500)	(0.501)	(0.500)	(0.501)	(0.0450)	(0.0450)	(0.0487)
Charcoal used/week (in kg)	19.18	19.92	18.97	18.33	0.953	1.589*	0.636
	(10.20)	(11.82)	(8.854)	(8.893)	(0.961)	(0.961)	(0.863)
Charcoal exp/week (in TZS)	11,189	11,574	11,102	10,734	471	840	368
	(6,168)	(7,514)	(5,193)	(4,794)	(598)	(585)	(486)
Cooking time of a meal (min.)	101.8	102.7	99.48	102.7	3.199	−0.0158	−3.215
	(39.08)	(38.25)	(38.58)	(40.78)	(3.452)	(3.530)	(3.860)
Panel C: Demand for LPG stove							
Knows about LPG stoves	0.985	0.983	0.981	0.991	0.00223	−0.00729	−0.00952
	(0.123)	(0.128)	(0.137)	(0.0969)	(0.0119)	(0.0105)	(0.0115)
Knows LPG stove user	0.803	0.793	0.820	0.802	−0.0273	−0.00924	0.0180
	(0.398)	(0.406)	(0.385)	(0.400)	(0.0357)	(0.0362)	(0.0382)
LPG—High start up cost	0.934	0.933	0.953	0.915	−0.0195	0.0180	0.0375
	(0.249)	(0.250)	(0.213)	(0.279)	(0.0212)	(0.0236)	(0.0242)
Food tastes different with LPG	0.0235	0.0167	0.0427	0.0142	−0.0259	0.00257	0.0285*
	(0.152)	(0.128)	(0.203)	(0.118)	(0.0147)	(0.0112)	(0.0161)
Wishes to own LPG stove	0.961	0.940	0.981	0.972	−0.0412**	−0.0319*	0.00934
	(0.193)	(0.238)	(0.137)	(0.166)	(0.0182)	(0.0190)	(0.0148)
Max. willingness to pay for LPG stove (TZS)	63,419	60,732	62,758	67,867	−2,025	−7,135**	−5,109
	(38,548)	(40,812)	(36,683)	(36,816)	(3,520)	(3,520)	(3,573)
Affords gas refilling cost	0.882	0.863	0.891	0.901	−0.0281	−0.0381	−0.00995
	(0.323)	(0.345)	(0.312)	(0.299)	(0.0298)	(0.0293)	(0.0298)
Observations	722	299	211	212			

Source: Authors' calculations from baseline data.

Note: This table presents summary statistics of variables at baseline for the pooled sample, control group, credit treatment group, and subsidy treatment group, and the corresponding statistical *t*-test results on mean differences. ∗∗∗, ∗∗, and ∗ denote significance at the 1, 5, and 10% levels, respectively.

cooked on a charcoal stove. However, it takes significantly longer to boil beans (the main ingredient for the complementary sauce) on a charcoal stove than on an LPG stove. The baseline data suggest that nearly half of the sample cook rice very often, with about 19 meals per week.

The low adoption of LPG stoves in Dar es Salaam seems mainly driven by liquidity constraints. Panel C of table 1 reports that 99 percent of the sample households knew about LPG stoves, and 80 percent knew someone within their nearby network using the stove. However, 93 percent of the sample households reported the high startup cost of the stove package as the primary constraint to their adoption. The difference in the taste of food cooked using LPG stoves is not a fundamental reason for not owning LPG stoves for almost the entire sample. Only 2 percent reported it as the main reason for not owning an LPG stove. This could be partly because none of the households in our sample used an LPG stove previously, so they did not experience the taste of food cooked using the stove. Later, in the Results section, we show that adopter households are highly satisfied with all features of the LPG stove, including stove quality, stove functioning, food taste, and stove convenience. We also asked whether they would wish to have an LPG stove in the future if their economic status were to improve. A staggering 96 percent of our sample households replied yes, but their reported average willingness-to-pay for the stove package is only TZS 63,420 (USD 35.23), which is only 32 percent of the market price (TZS 200,000) of the stove package in Dar es Salaam.

Randomization of treatment should ensure that, on average, treatment and control groups have similar baseline characteristics. To check this, in columns (2)–(7) of table 1, we present means of several key characteristics of households in both groups, as well as test results for the null hypothesis that the difference in means is statistically significantly not different from zero. The mean difference is not statistically different from zero for nearly all the variables presented. The exceptions are that there is a marginally statistically significant difference in the consumption expenditure between the credit and subsidy groups (at 10 percent); in the variable "charcoal consumption" between the control and subsidy treatment groups (at 10 percent); "food tastes different" between the credit and subsidy groups (at 10 percent), "wishes to own LPG stoves," between the credit and control groups (at 5 percent), and "max WTP for LPG stoves" between control and subsidy groups. Although these differences are unfortunate, they are unlikely to bias our results because the magnitudes of the differences are not large, and we will re-estimate our treatment effects after controlling for the variables in the regressions.

Moreover, as described in "Design" section, around 31 percent of households we assigned to the treatments (72 households in the credit treatment group and 61 households in the subsidy treatment group) declined to take up the stove. We ran a simple OLS regression on the uptake as a function of the treatments and baseline covariates and report the results in table 2. The regression results suggest that households did not self-select themselves based on the type of treatment, i.e., uptake did not vary by treatment. However, given the small number of clusters, the statistical insignificance of the treatments on uptake should be taken with caution. We discuss sampling issues in the "Caveats" section. In table 2, we also note that male-headed families and those whose main food staple is rice are less likely to take up the stove, suggesting that female-headed households understand the stove's benefits more and that cooking patterns influence uptake decisions. On the other hand, households with better economic status (consumption expenditure), households headed by more educated individuals, households that have used charcoal for longer, and those who live further away from the nearest charcoal market are more likely to take it up. No household in the control group acquired the LPG stove at the market price. This is expected because the descriptive statistics reported in column (1) indicate that 99 percent of the households know about LPG stoves, and the high market price of the appliances is the critical reason for not owning one.

During the midline survey, which we conducted about four months after the intervention, the proportion of households who changed their residence and we could not track was only 3 percent. However, the proportion increased to about 25 percent (182 households) during the endline survey, which we conducted 15 months after the intervention. Of those who attrited, 112 households (62 percent) belonged to

Table 2. Correlates of LPG Uptake

	(1)	(2)
Credit	−0.053	−0.039
	(0.080)	(0.072)
Head's age	–	−0.000
		(0.002)
Male head	–	−0.099*
		(0.052)
Household size	–	−0.005
		(0.008)
Head's years of schooling	–	0.019*
		(0.010)
Log of household expenditure	–	0.115**
		(0.050)
Separate kitchen	–	0.003
		(0.033)
House privately owned	–	−0.059
		(0.037)
Number of years using charcoal stove	–	0.005**
		(0.002)
Head decides on acquisition of stove	–	−0.063
		(0.060)
Walking distance to the nearest charcoal market (in min.)	–	0.013*
		(0.007)
Number of meals cooked last week	–	−0.001
		(0.008)
Rice, main staple for the household	–	−0.076**
		(0.031)
Knows someone using LPG stove	–	0.034
		(0.045)
Controls	No	Yes
R-squared	0.003	0.069
Observations	426	426

Source: Authors' calculations from baseline survey.
Note: This table reports OLS regression results on correlates of LPG stove uptake. Column (1) controls for the treatment type. Column (2) controls for the treatment type and baseline covariates. Standard errors reported in parentheses are clustered at the street level. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

the treatment group, and 70 (39 percent) to the control group. It is common to encounter a more significant attrition rate in urban areas than in rural areas of developing countries (Bandiera et al. 2015). As shown in column (1) of table 1, about half of our sample of households lived in rented residential places during baseline. By the endline survey, several families had moved to rented apartments in other parts of the city. While the survey team managed to track some of them using their cell phone numbers and survey them at their new residence, we could not track others, and, thus, we could not document endline information for these households.

To check whether attrition in our sample has been systematic, we ran an OLS regression for the correlates of attrition and report the results in table 3. The dependent variable is a dummy equal to 1 if the household could not be tracked by endline. Column (1) controls for being treated (LPG acquisition either on credit or through subsidy). Column (2) differentiates the correlates of attrition by treatment type. Column (3) controls for baseline covariates in addition to the type of treatment. Results in all columns suggest that the interventions are not statistically significant in predicting attrition. Column (3), however, shows households living in their residential property are less likely to attrite, and the correlation is statistically

Table 3. Correlates of Attrition, Baseline–Endline: OLS Regression Results

	(1)	(2)	(3)
Treated	0.042	–	–
	(0.041)		
Credit	–	0.024	0.026
		(0.052)	(0.047)
Subsidy	–	0.060	0.060
		(0.050)	(0.052)
Head's age	–	–	−0.000
			(0.001)
Male head	–	–	0.004
			(0.040)
Household size	–	–	0.003
			(0.009)
Head's years of schooling	–	–	−0.009
			(0.007)
Log of household expenditure	–	–	0.036
			(0.044)
Separate kitchen	–	–	−0.009
			(0.037)
House privately owned	–	–	−0.101***
			(0.033)
Number of years using charcoal stove	–	–	−0.002
			(0.002)
Head decides on acquisition of stove	–	–	−0.021
			(0.050)
Walking distance to the nearest charcoal market (in min.)	–	–	−0.006**
			(0.003)
Number of meals cooked last week	–	–	−0.000
			(0.005)
Rice, main staple for the household	–	–	−0.003
			(0.032)
Knows someone using LPG stove	–	–	−0.012
			(0.046)
Observations	722	722	722
R-squared	0.002	0.003	0.030

Source: Authors' calculations from baseline and endline surveys.
Note: This table reports OLS regressions for the correlates of attrition. The dependent variable is a dummy equal to 1 if the household is lost to attrition by endline. Column (1) controls for being treated (LPG acquisition either on credit or through subsidy). Column (2) differentiates the correlates of attrition by treatment type. Column (3) controls for the type of treatment and baseline covariates. Standard errors reported in parentheses are clustered at the street level. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

significant at the 1 percent level. We also note that those closer to a charcoal market are less likely to attrite. In the Results section, we compute treatment effects, which account for attrition and report Lee (2009) bounds to check the robustness of the estimated treatment effects to non-random attrition.

4. Results

4.1. Specification

Given the randomized nature of our design, we can identify the effects of the LPG stoves on charcoal consumption and cooking time from the single mean differences between treatment and control groups in an OLS regression. Participation in our interventions (credit and subsidy) was voluntary, so not all households assigned to the interventions took up the stove. Consequently, we focus on intent-to-treat

(ITT) impacts. Given the random assignment of streets to treatment, we can estimate the ITT impact of the LPG credit and subsidy programs using the following OLS specifications:

$$y_{ijt} = \alpha + \gamma \text{treat}_j + \beta X_{ij0} + \varepsilon_{ijt}$$

and

$$y_{ijt} = \alpha + \eta \text{credit}_j + \theta \text{subsidy}_j + \beta X_{ij0} + \varepsilon_{ijt},$$

where y_{ijt} represent our key outcome variables of interest, charcoal consumption and cooking time by household i in street j at four months ($t = 1$) and 15 months ($t = 2$), treat is a binary indicator for either credit or subsidy treatment, credit and subsidy refer to binary indicators of treatment type, X_{ij0} are control variables at the baseline, and ε_{ijt} is a random error term that we allow to be clustered by street. The terms γ, η, and θ are the coefficients of interest, which measure the ITT impact of our credit and subsidy interventions, and β is the vector of the coefficient of control variables.

To minimize measurement error in one of the key outcome variables of interest—charcoal used for cooking—during all three surveys, we asked households to record the quantity of charcoal used during the most recent week using the local measurement units. We visited four charcoal markets in each ward and constructed average conversion factors to standard units by measuring each available local unit using a digital scale. Using these conversion factors, we converted all local units reported by households into standard units.

4.2. Charcoal Consumption

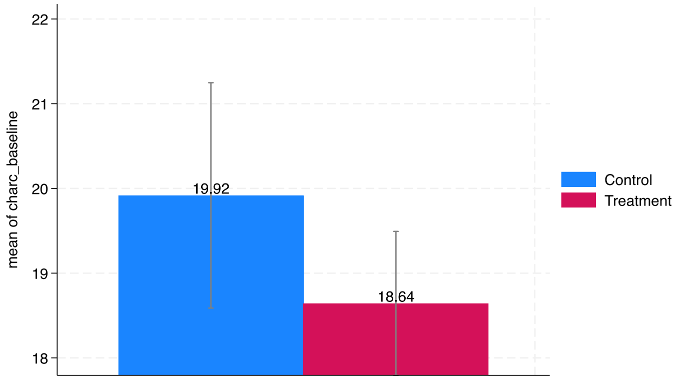
We begin with results from the simple mean comparison of charcoal consumption between the treatment and control groups during the baseline, midline (4 months after the interventions), and endline (15 months after the interventions). Figure 1 reports weekly charcoal consumption by treatment and control groups. While the control and treatment groups reported almost similar amounts of charcoal consumption per week during the baseline (19.92 kg and 18.64 kg, respectively), treated households consumed 4.06 kg less (19.91–15.85 kg) compared to the control households during the midline, and 4.38 kg less (19.96–15.58 kg) during the endline. Both these effects translate into a considerable reduction in charcoal use, which is statistically significant at the 1 percent level. When we look at the charcoal consumption data of the treatment group in detail, we find that 4.6 percent of the treated households at baseline, and 3.83 percent at endline, completely shifted away from charcoal.

Table 4 provides a formal empirical estimation of intent-to-treat (ITT) effects. Columns (1) and (2) present ITT effects regardless of the treatment type at the midline. In columns (3) and (4), we extend the analysis by controlling for the type of treatment (subsidy and credit) and key covariates. This is very important from a public policy point of view, given the ongoing debate that people tend to value and use goods less when they receive them at a lower price (Hoffmann 2009; Hoffmann, Barrett, and Just 2009; Cohen and Dupas 2010). Standard errors in all specifications are clustered at the street level.

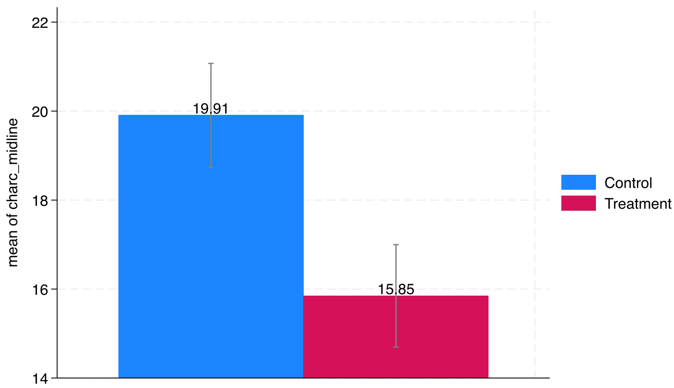
Consistent with the observation in the mean comparison presented in the previous table, column (1) of table 4 suggests that, compared to the control group, the treatment group reduced charcoal consumption by about 34.4 percent per week four months after the interventions. Controlling for baseline covariates slightly reduces the impact to 32 percent. When we assess the treatment type's impact, column (3) suggests a somewhat higher impact (34.9 percent) for the credit treatment group compared to the control group than the subsidy treatment group (33.8 percent). Again, controlling for baseline covariates (column 4) reduces the treatment effects slightly. However, we note that the coefficients of the two treatment arms are not statistically significantly different.

In columns (5)–(8), we investigate the impact of the treatments at endline—15 months after we distributed the stoves. This is important given the recent finding on improved stoves that households might not continue using them after adoption for several reasons (Hanna, Duflo, and Greenstone 2016). Results

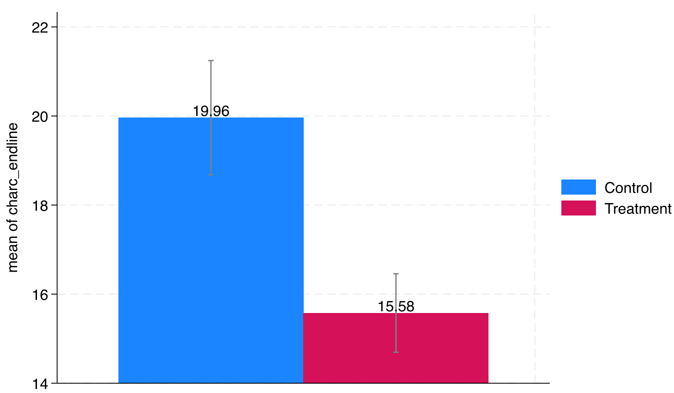
Figure 1. Weekly Charcoal Consumption: Baseline, Midline, and Endline



(a) Baseline



(b) Midline



(c) Endline

Source: Authors' calculations from baseline, midline and endline data.
Note: This figure presents mean weekly charcoal consumption (in kg) for the control and treatment groups at baseline, midline, and endline, and the corresponding mean comparison test results.

Table 4. Intent-to-Treat Effect of the LPG Interventions on Charcoal Consumption

	Midline				Endline			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treated	−0.344***	−0.320***	–	–	−0.287***	−0.253***	–	–
	(0.070)	(0.059)			(0.085)	(0.079)		
WC *P*-value	[0.000]	[0.000]	–	–	[0.006]	[0.008]	–	–
RI *P*-value	[0.000]	[0.000]	–	–	[0.000]	[0.009]	–	–
Lee (2009) bounds								
Lower bound	−0.361***	–	–	–	−0.375***	–	–	–
	(0.059)				(0.065)			
Upper bound	−0.316***	–	–	–	−0.250***	–	–	–
	(0.067)				(0.065)			
Credit	–	–	−0.349***	−0.329***	–	–	−0.253**	−0.208**
			(0.083)	(0.063)			(0.086)	(0.071)
Subsidy	–	–	−0.338***	−0.311**	–	–	−0.323**	−0.299**
			(0.098)	(0.093)			(0.127)	(0.119)
Cr. vs. sub. (*p*-value)	–	–	(0.925)	(0.862)	–	–	(0.610)	(0.460)
Control group mean	19.906	19.906	19.906	19.906	19.962	19.962	19.962	19.962
	(10.109)	(10.109)	(10.109)	(10.109)	(9.963)	(9.963)	(9.963)	(9.963)
Controls	No	Yes	No	Yes	No	Yes	No	Yes
R-squared	0.048	0.080	0.048	0.080	0.042	0.125	0.044	0.127
Observations	695	695	695	695	540	540	540	540

Source: Authors' calculations from baseline, midline, and endline data.
Note: This table reports intent-to-treat (ITT) effects of participating in the LPG stove programs on charcoal consumption at midline and endline. Columns (1) and (2) present ITT effects at midline controlling for treatment only and treatment with baseline covariates respectively. Columns (3) and (4) present ITT effects at midline by treatment controlling for treatments only and treatments with baseline covariates respectively. Columns (5) and (6) present ITT effects at endline controlling for treatment only and treatment with baseline covariates respectively. Columns (7) and (8) present ITT effects at endline by treatment controlling for treatments only and treatments with baseline covariates respectively. "Control group mean" refers to the average weekly charcoal consumption of the control group in kilograms. Standard errors reported in parentheses are clustered at the street level. Wild cluster bootstrap-*t* *p*-values (WC *P*-values) of treatment effects estimated with 100,000 replications are reported in square brackets. Randomization inference *p*-values (RI *P*-values) reported in square brackets. The Lee (2009) bounds show the treatment effect bounds for samples with non-random sample attrition. ∗∗∗, ∗∗, and ∗ denote significance at the 1, 5, and 10 percent levels, respectively.

remain quite robust 15 months after the intervention, although the magnitude of the treatment effects declined compared to the midline. On average, the treatment group reduced charcoal consumption by 28.7 percent (column 5), the subsidy treatment group reduced by 32.3 percent, and the credit group reduced by 25.3 percent (column 7). The results remained consistent after controlling for baseline covariates in column (8). Standard errors are clustered at the street level in all regressions. The coefficients of the two treatment arms are not statistically significantly different at the endline as well.

It is evident from column (3) of table 4 that, during the midline, credit households reduced charcoal consumption by a slightly larger magnitude (1.1 percentage points more) than the subsidy treatment group. During the endline, however (column 7), subsidy households reduced charcoal consumption by 7 percentage points more than credit households. The difference in charcoal consumption at endline is consistent with the difference in stove use and gas refill behavior between subsidy and credit households, which we discuss in in the "LPG Stove Use and Satisfaction" section in detail. Households in the subsidy treatment group used the stove and refilled LP gas more often than the credit treatment group, consequently reducing charcoal consumption by a larger magnitude. The main reason for such a difference in LPG stove use is likely an income effect. Households in the subsidy group acquired the stove at a much cheaper cost (with only 25 percent of the total cost) than credit households who had to pay the total price of the stove, albeit in about six months. Thus, it is plausible that subsidy households could better afford to pay for the LP gas than credit households, consequently using it more often and reducing charcoal consumption to a larger magnitude. However, as noted above, the difference in the credit and subsidy treatments is not statistically significant in all ITT regressions that estimate the impact based on treatment types.

We conduct three key robustness checks to investigate the robustness of the treatment effects. First, we estimate the wild cluster bootstrap-*t* *p*-values of the treatment effects proposed by Cameron, Gelbach, and Miller (2008). This procedure is proposed to address the issues arising from making inferences based on clustered standard errors when the number of clusters is small. The procedure is effective even when the number of clusters is as small as 6. In our case, the number of clusters (streets) is 16.[17] Second, we conducted a randomization inference (RI)[18] which tests whether the key results still hold when one considers all possible random assignments.[19]

We implemented the wild cluster bootstrap-*t* procedure with 100,000 replications and the randomization inference with 1,000 replications for the main results at midline and endline and reported the respective *p*-values (WC *P*-values and RI *P*-values) in square brackets under the coefficient for "treated". The null hypothesis in both cases is that the coefficient of "treated" is zero, i.e., the treatment does not impact the outcome variable (charcoal). In both regressions (baseline and endline), the wild cluster bootstrap-*t* and randomization inference *p*-values match the statistical significance levels of the treatment coefficient, indicating the robustness of the main results.

Third, to check for the possible impact of non-random attrition, we estimated Lee (2009) bounds both at midline and endline. This method makes a monotonicity assumption and then adjusts for differential attrition between the treatment and control groups. Since the response rates are lower for the treated group than the control group, the assumption here is that there are households who would attrite if they were to end up in the treatment group but not if they were to end up in the control group, but not vice versa. Given the attrition rate we encountered and discussed in "Randomization Check" section, this appears plausible in our case. Table 4 shows that the upper and lower bounds at midline and endline are statistically significant at 1 percent. Moreover, the treatment effects lie between the lower and upper bounds, although the gap between the lower and upper bounds widens at the endline. This is expected given the higher attrition rate at endline (25 percent) compared to the midline (3 percent).

When only a subsample of the treatment group takes up new technologies from a public policy point of view, it is crucial to understand the impact of adoption (actual uptake) on household outcomes and the environment using local average treatment effects (LATE). We estimate the impact of adopting LPG stoves on charcoal consumption using the random assignment of the treatment as an instrument for adoption in an instrumental variables setup and report the results in table 5. OLS results in column (1) suggest that households who took up the stove reduced charcoal consumption by almost 50.9 percent at midline. However, the impact of adoption increases to 51.3 percent in the instrumental variables regression results reported in column (3). Although the coefficients on adoption slightly decline during the endline, as shown in columns (5)–(8) of table 5, they remain significantly large in magnitude. instrumental variables (IV) regression results reported in column (7), for example, suggest that the adoption of an LPG stove led to a 39.5 percent reduction in charcoal consumption 15 months after the interventions.

17 Bootstrap methods compute statistical significance levels by creating many pseudo-samples. They estimate the parameters for each pseudo-sample and then examine the distribution of the parameters across the different pseudo-samples. The wild cluster bootstrap-*t* creates pseudo-samples by holding the regressors constant while re-sampling with replacement group-specific residuals to create new dependent variables. Using Monte Carlo simulations, Cameron, Gelbach, and Miller (2008) demonstrate that statistical tests based on the wild cluster bootstrap-*t* procedure have the appropriate size and offer valid inferences. See their paper for a detailed description of the procedure.

18 We thank an anonymous reviewer for suggesting the RI robustness test.

19 RI is an alternative (and more appealing) method of conducting hypothesis tests than the standard *t*- or *F*-tests in randomized experiments. It examines whether the probability (*p*-value) of a particular null hypothesis for a treatment coefficient is robust over all possible randomizations that could have occurred according to the design. See Gerber and Green (2012) for details and HeB (2017) for a discussion on implementing RI in Stata.

Table 5. The Impact of LPG Adoption on Charcoal Consumption

	(Midline)				(Endline)			
	(1) OLS-1	(2) OLS-2	(3) IV-1	(4) IV-2	(5) OLS-3	(6) OLS-4	(7) IV-3	(8) IV-4
LPG adopter	−0.509***	−0.487***	−0.513***	−0.483***	−0.296***	−0.286***	−0.395***	−0.349***
	(0.086)	(0.071)	(0.105)	(0.092)	(0.078)	(0.075)	(0.114)	(0.103)
Control group mean	19.906	19.906	19.906	19.906	19.962	19.962	19.962	19.962
	(10.109)	(10.003)	(10.003)	(10.003)	(9.963)	(9.963)	(9.963)	(9.963)
Controls	No	Yes	No	Yes	No	Yes	No	Yes
R-squared	0.106	0.133	0.106	0.133	0.045	0.134	0.041	0.132
Observations	695	695	695	695	540	540	540	540

Source: Authors' calculations from baseline, midline and endline data.

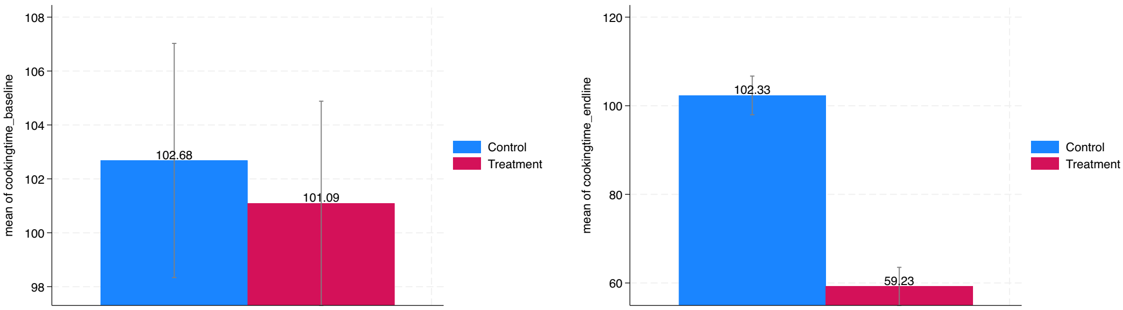
Note: This table reports regression results on the impact of LPG adoption (uptake) on charcoal consumption at midline and endline. Columns (1) and (2) present OLS results at midline controlling for adoption only and adoption with baseline covariates respectively. Columns (3) and (4) present instrumental variables regression results at midline controlling for adoption only and adoption with baseline covariates respectively. Columns (5) and (6) present OLS results at endline controlling for adoption only and adoption with baseline covariates respectively. Columns (7) and (8) present instrumental variable regression results at endline controlling for adoption only and adoption with baseline covariates respectively. "Control group mean" refers to the average weekly charcoal consumption of the control group in kilograms. Standard errors reported in parentheses are clustered at the street level. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

The considerable reduction in charcoal consumption due to the LPG stove intervention can be translated to a possible reduction in deforestation and emitted carbon dioxide (CO_2). According to World Bank (2009), all charcoal consumed in Tanzania is harvested unsustainably from dry woodlands up to 200 km away from urban areas. Charcoal production uses a traditional and highly inefficient process with an 8–12 percent conversion efficiency. To produce the 1 million tonnes of charcoal consumed annually in the country, nearly 125,000 ha of forest are destroyed. This is equivalent to 0.13 ha of forest to produce 1 tonne of charcoal. The average household in our sample consumed 19.18 kg of charcoal/week, 82.2 kg/month, or 986 kg (approximately 1 tonne) per year at baseline, translating to 0.13 ha of forest per year. Multiplying by the number of households in the sample, i.e., 722, yields charcoal consumption of 13,848 kg/week, 59,348 kg/month, or 711,892 kg (approx. 712 tonnes) per year, which translates to 92.6 ha of forest. On average, the introduction of LPG stoves reduced charcoal consumption by 28.7 percent 15 months after the intervention. This implies possibly saving 0.04 ha of forest per household or about 28.9 ha of forest for the entire sample of households per year. The average carbon stored per hectare of forest cover in a similar setup to Tanzania is 153.5 metric tonnes (MT) (Hansen et al. 2013). Therefore, the introduction of LPG stoves averts the emission of approximately 5.91 MT of CO_2 per household per year from forests. Decomposing the treatment effects by treatment type implies preventing the destruction of 0.03 ha (5.05 MT of CO_2) and 0.04 ha (6.56 MT of CO_2) of forest per household per year through the credit and subsidy treatments, respectively.

Despite being highly efficient and relatively clean, LP gas is still a fossil fuel, and when burned, it emits CO_2. Thus, some of the averted CO_2 through saving deforestation and charcoal burning will be compensated (emitted) by cooking with LPG stoves. Research shows that cooking with LPG emits CO_2 equivalent to only 34 percent of the CO_2 emitted when cooking with charcoal (Johnson 2009).[20] It is, therefore, reasonable to assume that the net averted CO_2 is 3.90 MT/household/year for the treatment group in general and 4.33 MT and 3.33 MT/household/year for the subsidy and credit treatment groups,

20 Johnson (2009) uses emission data from 300 grilling sessions using charcoal and LPG grill systems (150 sessions for each system) and shows that grilling with charcoal emits 6.7 kg CO_2e (CO_2 equivalent) per grilling session while grilling with LPG emits only 2.3 kg CO_2e.

Figure 2. Cooking Time per Week: Baseline and Endline



Source: Authors' calculations from baseline and endline data.
Note: This figure presents daily mean cooking time (in minutes) for the control and treatment groups at baseline and endline, and the corresponding mean comparison test results.

respectively. Later, we conduct a cost-benefit analysis of the interventions in terms of the monetary value of the forest saved and the corresponding averted CO_2 and compare it with the cost of the interventions.[21]

4.3. Cooking Time

Figure 2 presents a simple mean comparison of daily cooking time between treatment and control groups during the baseline and endline.[22] Panel A shows that, at baseline, there is no statistically significant difference between treatment and control groups, with the former spending about 102 minutes and the latter about 101 minutes/day on cooking. However, 15 months after the LPG stoves had been distributed, treatment households spent only 59 minutes per day on cooking, compared to control households, who spent about 102 minutes, comparable to the baseline amount. This implies around a 43-minute reduction in cooking time/day, a significant impact of owning a modern and efficient cookstove, which makes it convenient and quick to heat up and cooks on two burners simultaneously.

We present intent-to-treat estimates of the impact of adopting LPG stoves on cooking time in table 6. Columns (1) and (2) report ITT effects of LPG adoption on the log of cooking time regardless of the type of treatment at the endline. Columns (3) and (4) extend the analysis by controlling for the type of treatment (subsidy and credit) and baseline controls, respectively. Consistent with the mean comparison results presented in fig. 2, column (2) of table 6 suggests that compared to the control group, the treatment group reduced cooking time by about 68.5 percent per day 15 months after the interventions. Assessing the impact of LPG stove ownership by treatment type (columns 3 and 4) again reveals relatively larger impacts (77.1 percent reduction) for the subsidy treatment group than for the credit treatment group (60.2 percent reduction). We also note that the coefficients of the two treatments are statistically significantly different at conventional levels. The wild cluster bootstrap-*t* and randomization inference (RI) *p*-values and Lee (2009) bounds indicate that the treatment effect is robust to the small number of clusters and non-random attrition.

We also estimate the local average treatment of adopting LPG stoves on cooking time using the random assignment of the treatment as an instrument for adoption in an instrumental variables setup and report

21 World Bank (2009) , the most comprehensive report that documents the state of charcoal production in Tanzania to date, shows that the country loses 125,000 ha of forest to charcoal production each year. However, it also documents that the figure should be taken cautiously because a non-negligible part of the charcoal produced each year is a by-product of agricultural land clearance. Supplementary online appendix S3 considers alternative scenarios and investigates the sensitivity of the results from the cost-benefit analysis.

22 Unfortunately, we did not collect information on the cooking time at the midline.

Table 6. Intent-to-Treat Effect of the LPG Interventions on Cooking Time

	(1)	(2)	(3)	(4)
Treated	−0.685***	−0.686***	–	–
	(0.064)	(0.057)		
WC *P*-value	[0.000]	[0.000]	–	–
RI *P*-value	[0.000]	[0.010]	–	–
Lee (2009) bounds				
Lower bound	−0.741***	–	–	–
	(0.053)			
Upper bound	−0.650 ***	–	–	–
	(0.053)			
Credit	–	–	−0.602***	−0.602***
			(0.078)	(0.064)
Subsidy	–	–	−0.771***	−0.773**
			(0.058)	(0.050)
Credit vs. subsidy (*P*-value)	–	–	(0.050)	(0.013)
Control group mean	(102.662)	(102.662)	(103.666)	(103.666)
	(38.515)	(38.515)	(33.324)	(33.324)
Controls	No	Yes	No	Yes
R-squared	0.241	0.283	0.250	0.292
Observations	540	540	540	540

Source: Authors' calculations from baseline and endline data.
Note: This table reports intent-to-treat (ITT) effects of participating in the LPG stove programs on cooking time at endline. Columns (1) and (2) present ITT effects controlling for treatment only and treatment with baseline covariates respectively. Columns (3) and (4) present ITT effects by treatment controlling for treatments only and treatments with baseline covariates respectively. "Control group mean" refers to the average daily cooking time of the control group in minutes. Standard errors reported in parentheses are clustered at the street level. Wild cluster bootstrap-*t* *p*-values (WC *P*-values) of treatment effects estimated with 100,000 replications are reported in square brackets. Randomization inference *p*-values (RI *P*-values) reported in square brackets. The Lee (2009) bounds show the treatment effect bounds for samples with non-random sample attrition. ∗∗∗, ∗∗, and ∗ denote significance at the 1, 5, and 10 percent levels, respectively.

Table 7. The Impact of LPG Stove Adoption on Cooking Time

	(1) OLS-1	(2) OLS-2	(3) IV-1	(4) IV-2
LPG adopter	−0.836***	−0.829***	−0.942***	−0.948***
	(0.057)	(0.061)	(0.072)	(0.068)
Control group mean	(102.662)	(102.662)	(103.666)	(103.666)
	(38.515)	(38.515)	(33.324)	(33.324)
Controls	No	Yes	No	Yes
R-squared	0.364	0.389	0.361	0.382
Observations	540	540	540	540

Source: Authors' calculations from baseline and endline data.
Note: This table reports regression results on the impact of LPG adoption (uptake) on cooking time at endline. Columns (1) and (2) present OLS results at endline controlling for adoption only and adoption with baseline covariates respectively. Columns (3) and (4) present instrumental variable regression results at endline controlling for adoption only and adoption with baseline covariates respectively. ∗∗∗, ∗∗, and ∗ denote significance at the 1, 5, and 10 percent levels, respectively.

the results in table 7. OLS results in column (1) suggest that at the endline, LPG adopter households reduced cooking time by 83.6 percent. The impact of adoption on cooking time increases to 94.2 percent in the instrumental variables regression results reported in column (3).

The overall reduction in cooking time will likely significantly affect household production and female and children's empowerment. Most of the fuelwood fetching and household cooking in developing countries (almost 100 percent in our sample) is done by women, who also endure the hazards of cooking and are often multi-tasking, e.g., looking after children while cooking (World Bank 2011; WHO 2018). In addition to its adverse environmental, climatic, and health impacts, charcoal takes time to light up and prepare for cooking. At baseline, 99 percent of the sample households used charcoal stoves as the primary cookstoves, and only 10 percent reported using two stoves for cooking simultaneously. Households also reported spending an average of 1.45 hours cooking a complete meal (lunch or dinner) for the household using their charcoal stove. These data suggest that the mechanisms that explain the time reductions due to the LPG stoves are likely faster cooking times and the convenience of having two burners in the LPG stoves. Although we did not collect detailed information on the time use of mothers due to the limited scope of our study, it is plausible to expect that the extra time saved is often used to engage in additional income-earning activities, childcare, and leisure, all of which have significant welfare-enhancing impacts on household members in general and women in particular. In fact, Alem and Hassen (2020), who distributed improved cookstoves in Northern Ethiopia in a randomized controlled setup, show that women in the treatment households allocated the time saved from cooking and fuelwood collection to poultry and livestock keeping.

4.4. LPG Stove Use and Satisfaction

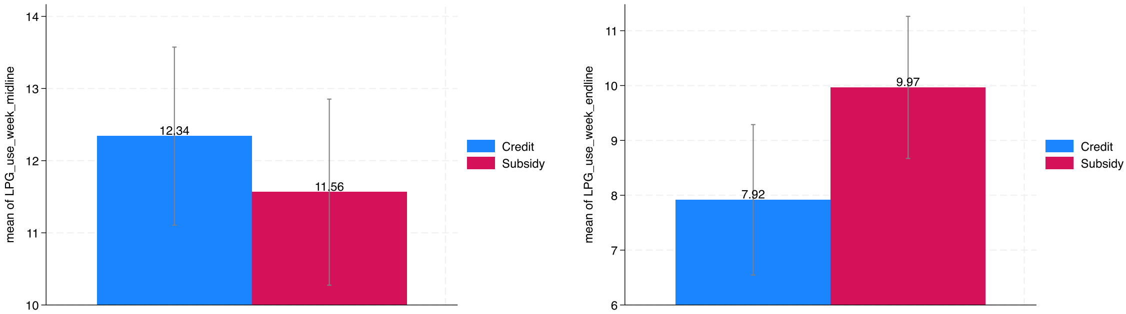
In addition to identifying the impact of LPG stove adoption on charcoal use and cooking time, it would be insightful to investigate how often adopter households use the stoves and whether the intensity of use differs across treatments. Providing LPG stoves would encourage households to switch from charcoal to LPG. However, existing empirical evidence (Masera, Saatkamp, and Kammen 2000; Heltberg 2005) suggests that households may continue to use the charcoal stove in combination with the LPG stove, a phenomenon known as "fuel stacking." To shed light on this, we collected information on weekly stove use at the midline and endline for the two treatment groups. We report the descriptive results in panel (a) of fig. 3. The results suggest that credit and subsidy households used the stove 12.34 and 11.56 times per week, respectively, during midline, with no statistically significant difference in use. At the endline, however, credit households used the stoves 7.92 times per week, while subsidy households used them 9.97 times per week, and the difference is statistically significant at 5 percent (p-value 0.033).

In panel A of table 8, we use regressions to explore whether stove use and intensity correlate with the type of treatment assigned to households at midline and endline. The results reported in columns (1)–(2) suggest that the number of times the stove is used at midline is not correlated with the treatment type. These results are robust to controlling for other covariates. During endline, however, consistent with the mean comparison results presented in fig. 3, the credit treatment group used the stove 2.6 times less than the subsidy treatment group, and the effect is statistically significant at 10 percent (column 4). Among the control variables we included in the regressions, education and the log of household consumption expenditure are both positively correlated with using the stove more often. Most likely indicating habit formation, households who used charcoal stoves for a longer period used LPG stoves less frequently at the endline, and the coefficient is statistically significant at the 1 percent level.

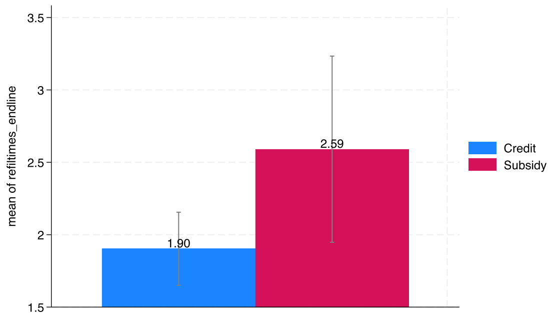
An important question related to stove use, which sheds light on the sustained utilization and reduction of charcoal, is whether and how frequently treatment households refilled their LPG stoves. Overall, treatment households refilled LP gas 2.25 times on average during the 15 months after receiving the stove.[23] Panel (b) of fig. 3 decomposes the frequency of refill by treatment type. We note that the credit treatment group refilled LP gas 1.90 times, while the subsidy group refilled 2.59 times during the 15 months after the intervention. The difference in the frequency of LPG refill between the two groups is statistically significant at the 10 percent level. We further explore LP gas refill behavior using regressions and report the results in panel B of table 8. Column (6) suggests that the credit treatment group refilled

23 The LPG stoves distributed to both treatment groups were filled with 15 kg (33 pounds) of gas at the time of delivery. Thus, households refill when the original gas delivered with the stove runs out after a few weeks.

Figure 3. LPG Stove Use and Refill: Baseline, Midline, and Endline



(a) LPG Use: Midline and Endline



(b) LPG Gas Refill: Endline

Source: Authors' calculations from midline and endline data.
Note: Panel A of this figure presents the average number of stove uses and refills by the credit and subsidy treatment groups at midline and endline, and the corresponding mean comparison test results. Panel B reports the average number of stove refills by the credit and subsidy groups at endline and the corresponding mean comparison test result.

gas about 0.68 times less than subsidy households, and the effect is statistically significant at 10 percent. The finding that the subsidy group reduced charcoal more than the credit group, which we documented in the preceding section, is consistent with the fact that the subsidy group refilled the gas and used the stove more often. The key reason is likely an income effect. The credit treatment group was required to pay the total cost of the stove in 6 months. In contrast, the subsidy group acquired the stoves at 75 percent subsidy, which enabled them to refill the gas and use the stove more often than the credit treatment group.

Given the LPG stoves reduce charcoal, cooking time, and very likely the cost of cooking energy (see the Cost-Benefit Analysis section), two important related questions are worth investigating here: Why did the treatment households not completely shift to LPG and why did they not refill LP gas more often? We leverage the rich baseline and follow-up data and attempt to shed light on these questions.

We showed that by endline, only 4 percent of the treatment households completely shifted away from cooking with charcoal to LPG, and the remaining treatment households continued using both fuels. We also showed that credit households used and refilled the LPG stoves less often than subsidy households at the endline. Before the interventions (at baseline), 74 percent of households purchased charcoal daily in small quantities, each daily purchase costing an average of USD 1.1. At the endline (15 months after

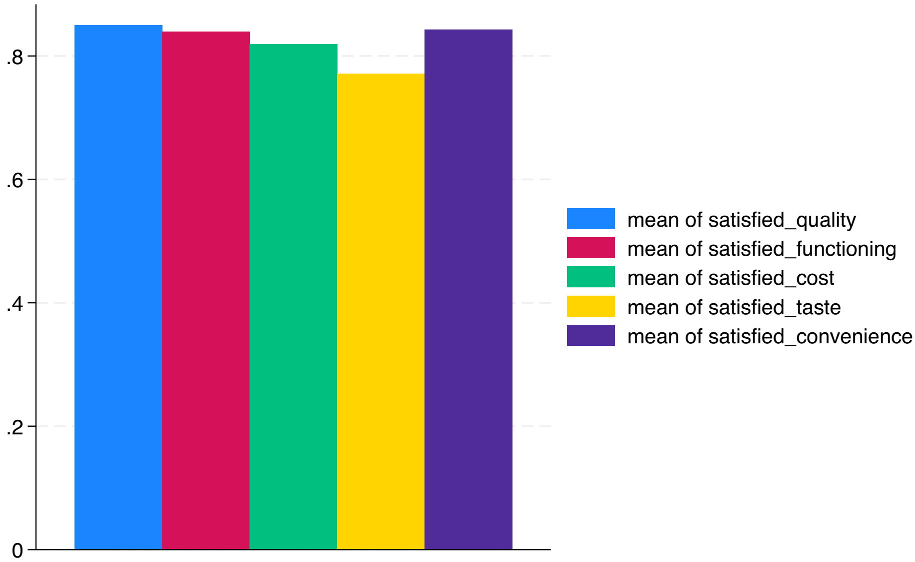
Table 8. Correlates of LPG Stove Use and Refill

	Panel A—LPG use				Panel B—Gas refill	
	Midline		Endline		Endline	
	(1)	(2)	(3)	(4)	(5)	(6)
Credit	0.198	0.105	−2.296	−2.626*	−0.677**	−0.681*
	(1.065)	(1.165)	(1.456)	(1.376)	(0.338)	(0.359)
WC *P*-value	[0.859]	[0.929]	[0.203]	[0.111]	[0.013]	[0.021]
Head's age	–	0.073	–	0.006	–	−0.003
		(0.043)		(0.038)		(0.009)
Male head	–	−0.478	–	1.725	–	−0.079
		(0.928)		(1.302)		(0.327)
Household size	–	0.101	–	−0.043	–	−0.001
		(0.292)		(0.237)		(0.103)
Head's years of schooling	–	0.291	–	0.257**	–	0.022
		(0.203)		(0.112)		(0.026)
Log household expenditure	–	1.951**	–	2.440**	–	0.449**
		(0.742)		(1.092)		(0.183)
Separate kitchen	–	−1.207*	–	−0.958	–	0.007
		(0.650)		(0.936)		(0.303)
House privately owned	–	−1.231	–	0.958	–	−0.211
		(1.108)		(0.921)		(0.320)
Number of years using charcoal stove	–	−0.082	–	−0.132***	–	−0.020**
		(0.056)		(0.035)		(0.010)
Head decides on acquisition of stove	–	1.810	–	2.015	–	−0.186
		(1.319)		(1.314)		(0.271)
Walking distance to the nearest charcoal market (in min.)	–	0.081	–	0.115	–	−0.005
		(0.134)		(0.065)		(0.053)
Number of meals cooked last week	–	−0.023	–	−0.281*	–	−0.028
		(0.136)		(0.132)		(0.037)
Rice, main staple for the household	–	−0.836	–	−1.041	–	0.036
		(0.838)		(0.646)		(0.445)
Knows someone using LPG stove	–	0.745	–	0.945	–	0.224
		(1.160)		(0.822)		(0.256)
R-squared	0.000	0.058	0.024	0.127	0.012	0.028
Observations	293	293	241	241	293	293

Source: Authors' calculations from baseline, midline and endline data.
Note: This table reports OLS regression results on the correlates of LPG use at midline and endline, and LP gas refill at endline. The dependent variable in panel A is the number of times the LPG stove has been put to use in the past week. The dependent variable in panel B is the number of times the household refilled LP gas since the intervention, i.e., in the past 15 months. Columns (1) and (3) report regressions for LPG use at midline and endlines respectively, controlling for the treatment type only. Columns (2) and (4) report the same regressions controlling for key baseline covariates. Column (5) reports OLS regression for LP gas refill at endline controlling for the type of treatment only. Column (6) reports the same regression controlling for key baseline covariates. Standard errors reported in parentheses are clustered at the street level. Wild cluster bootstrap-*t p*-values (WC *P*-values) of treatment effects estimated at 100,000 replications are reported in square brackets. ∗∗∗, ∗∗, and ∗ denote significance at the 1, 5, and 10 percent levels, respectively.

the interventions), refilling the 15 kg LPG costs USD 25 throughout Dar. Furthermore, refilling requires carrying the LPG cylinders to the nearest refill station. However, purchasing a small bag of charcoal from the nearest charcoal market is easy, and households have done it for decades. This likely increases the total cost of refilling LPG. Consequently, in addition to credit households facing higher costs of LPG

Figure 4. Satisfaction with Different Attributes of LPG Stoves



Source: Authors' calculations from midline data.
Note: This figure presents descriptive statistics on satsiscation on the different attributes of LPG stoves.

stove purchase, the treatment households, in general, are likely inattentive to the possible reduction in the cost of cooking energy from refilling the LPG stove sold in bulk compared to charcoal, and this keeps them in energy stacking.[24]

We finally explore the extent to which treatment households are satisfied with the different attributes of the LPG stoves. Figure 4 shows the distribution of responses to the questions on satisfaction with the stoves. More than 80 percent of the households who received the LPG stoves seem to be satisfied with all features of the stove, including stove quality, stove functioning, gas cost, and cooking convenience, and about 75 percent are satisfied with the taste of food cooked with the LPG stoves. These results indicate that the LPG stoves we distributed have a reasonably high level of acceptance by households in urban Tanzania.

To explore the correlates of reported satisfaction levels with the different attributes of LPG stoves, we run simple OLS regressions of satisfaction and report the results in table 9. Three variables appear to be consistently important correlates of satisfaction with LPG stoves: economic status measured by the log of consumption expenditure and the household head's age and years of schooling. Households with better economic status tend to be satisfied by the taste of food, the affordability of LP gas, and the convenience of the stoves. In contrast, those headed by educated individuals are satisfied with the stoves' functioning and food taste. Those headed by older individuals are satisfied by the cost of gas and the convenience of the stoves. We do not find evidence suggesting that satisfaction with stove attributes is correlated with the type of treatment—the coefficient of the credit treatment variable is statistically insignificant.

24 Very likely, observing households' charcoal purchase behavior, LP gas dealer companies in recent years began offering LPG on a pay-as-you-go basis, where households could get the gas that is remotely controlled by the gas company using smart meters. Households can buy as much gas as they can afford and use it pay-as-you-go. See https://acumen.org/companies/kopagas/.

Table 9. Correlates of Satisfaction with Different LPG Stove Attributes

	(1) Quality	(2) Functioning	(3) Food taste	(4) Gas cost	(5) Convenience
Credit	0.040	0.032	0.048	0.029	0.057
	(0.029)	(0.038)	(0.037)	(0.033)	(0.040)
Head's age	0.001	0.003	0.003	0.004**	0.003*
	(0.001)	(0.002)	(0.003)	(0.002)	(0.001)
Male head	−0.025	−0.053	−0.061	−0.077	−0.073
	(0.056)	(0.070)	(0.073)	(0.076)	(0.068)
Household size	0.006	0.002	0.016	−0.000	0.008
	(0.006)	(0.007)	(0.014)	(0.007)	(0.006)
Head's years of schooling	0.009	0.014*	0.023***	0.012	0.012
	(0.007)	(0.007)	(0.007)	(0.009)	(0.007)
Log household expenditure	−0.002	0.046	0.076**	0.084**	0.060*
	(0.034)	(0.041)	(0.031)	(0.031)	(0.032)
Separate kitchen	0.014	0.012	0.029	0.031	0.013
	(0.049)	(0.054)	(0.049)	(0.063)	(0.043)
House privately owned	−0.006	−0.041	−0.038	−0.060	−0.039
	(0.029)	(0.059)	(0.060)	(0.058)	(0.054)
Number of years using charcoal stove	−0.001	−0.002	−0.004	−0.002	−0.003
	(0.002)	(0.003)	(0.003)	(0.003)	(0.003)
Head decides on acquisition of stove	0.047	0.025	0.071	0.013	0.037
	(0.085)	(0.089)	(0.078)	(0.094)	(0.085)
Walking distance to the nearest charcoal market (in min.)	0.005	0.001	−0.000	0.006	0.003
	(0.005)	(0.006)	(0.007)	(0.006)	(0.006)
Number of meals cooked last week	−0.002	−0.004	−0.004	−0.001	0.003
	(0.007)	(0.005)	(0.006)	(0.007)	(0.007)
Rice, main staple for the household	−0.016	−0.008	−0.022	−0.026	0.009
	(0.045)	(0.052)	(0.045)	(0.038)	(0.041)
Knows someone using LPG stove	0.001	0.035	0.097	0.001	0.023
	(0.064)	(0.044)	(0.073)	(0.045)	(0.054)
R-squared	0.023	0.033	0.073	0.049	0.044
Observations	293	293	293	293	293

Source: Authors' calculations from baseline ane midline data.
Note: This table reports OLS regression results on the correlates of satisfaction with the different attributes of the LPG stove. The dependent variable is a binary variable coding 1 if the household reported satisfaction with the respective attribute of the stove, and 0 otherwise. Standard errors reported in parentheses are clustered at the street level. ***, **, and * denote significance at the 1, 5, and 10 percent levels, respectively.

4.5. Cost–Benefit Analysis

This subsection presents a simple cost-benefit analysis of the two policy instruments we considered in our study—subsidy and credit. Since we did not find a statistically significant difference in the impact of the two policy instruments on charcoal consumption, policymakers' choice to encourage urban households to switch to LPG will depend on the net social benefit of the policy instruments. At the time of the baseline survey (April 2015), a complete two-burner LPG stove, including the cylinder, costs TZS 200,000 (USD 111.11). If the government aims to implement a 75 percent subsidy initiative to encourage adoption, the per-unit cost of an LPG stove to the government would be TZS 150,000 or USD 83.33. Consider offering LPG stoves on credit: three months after the end of the credit period or nine months after the stove distribution (i.e., on March 31, 2016), credit households on average paid back around 90 percent of the total amount of the loan. This results in a 10 percent default rate (TZS 20,000) per LPG stove. In addition, it costs TZS 55,000/LPG stove to process and collect back credit from treatment households through WAT SACCOS. Therefore, the total per LPG stove cost of the credit treatment to the government

Table 10. Cost-Benefit Analysis of Policy Instruments, Year 1

	(1) Subsidy	(2) Credit	(3) All
Baseline charcoal consumption/hh/year in tonnes	0.964	0.995	1.000
Baseline deforestation/hh/year in ha	0.125	0.129	0.130
Baseline CO_2 emission/hh/year in MT	19.229	19.863	19.957
Reduction in charcoal consumption per LPG stove at endline (%)	0.323	0.253	0.287
Reduction in deforestation per LPG stove/year in ha	0.040	0.033	0.037
Gross CO_2 averted in MT (153.5 MT per ha)	6.211	5.025	5.728
CO_2 emitted from cooking with LPG in MT (eq. to 34%)	2.112	1.709	1.947
Net CO_2 averted	4.099	3.317	3.780
Social cost of carbon (SCC) in saved forest (USD 39/MT CO_2)	159.867	129.355	147.430
Average cost of program per unit of LPG in USD	83.330	41.670	62.500
Average cost of program per MT of CO_2 averted	20.329	12.563	16.533
Average net benefit per LPG	76.537	87.685	84.930

Source: Authors' calculations from endline data.

Note: This table reports a social cost-benefit analysis of the subsidy and credit treatments in year 1 in 2012 USD. Column (1) presents baseline charcoal consumption, deforestation, CO_2 emission, reduction in charcoal consumption and deforestation, the amount of CO_2 averted including its cost and benefit to society due to subsidizing 75 percent of the cost of LPG stoves. Columns (2) and (3) report the same information for the credit treatment group and both treatment groups combined respectively. The average cost of the subsidy program per LPG stove (USD 83.33) is 75 percent of the market price of the stove. The average cost of the credit per LPG stove (USD 41.67) is the sum of the loan processing fee per LPG (USD 30.55) and the average defaulted loan per LPG (USD 11.12).

is TZS 75,000 or USD 41.67 maximum. The unit cost will likely decline significantly when the number of adopters increases.

Suppose the lifetime of the two-burner LPG stove is 10 years.[25] Then we can calculate the monetary value of the averted CO_2 due to reduced charcoal consumption and trees cut down following our interventions and compare the benefit to the cost. Tables 10 and 11 present the details of the cost-benefit analysis in year 1 and years 2–10, respectively.[26] We showed that, after accounting for emission of CO_2 through cooking with LP gas, LPG stoves at the endline possibly reduced 0.037 ha of forest (3.78 MT of net CO_2)/household/year on average, subsidy possibly reduced 0.040 ha of forest (4.10 MT of CO_2)/household/year, and credit reduced 0.033 ha of forest (3.32 MT of CO_2)/household/year.[27] Given the average per LPG stove cost of the subsidy and credit interventions calculated above, i.e., USD 83.33 and USD 41.67, respectively, it is straightforward to show that the programs cost USD 20.33 and USD 12.56, respectively, to avert the emission of 1 MT of CO_2. This shows that in terms of cost per MT of CO_2 averted, offering LPG stoves through the type of microcredit we implemented is about 38 percent cheaper than subsidizing.

One can compare the cost of implementing the subsidy and credit interventions with the benefits of averting the emission of CO_2 using the social cost of carbon (SCC). The United States Environmental Protection Agency (US EPA) estimates the SCC of 1 MT of averted CO_2 to be USD 39 in 2012 USD (Jayachandran et al. 2017). The total SCC value of averted CO_2 in year one because of an LPG stove is USD 147.43, USD 159.87 under subsidy, and USD 129.36 under credit. Thus, supporting the distribution of LPG stoves offers a net benefit of USD 84.93, USD 76.54 under subsidy, and USD 87.69 under credit in the first year alone. During years 2–10, the cost of the LPG stoves to the government is zero. The LPG

25 Oryx Energies, the supplier of the LPG stoves, indicated that with proper use, the stoves could last 25 years. Thus, our assumption of a 10-year lifespan is very conservative.

26 We assume that the endline treatment effects remain constant throughout the remaining lifetime of the LPG stoves. However, one could argue that the effects may increase as households learn more about the stoves.

27 Note that without accounting for CO_2 emitted by cooking with LPG stoves, the amount of CO_2 averted due to reduction in deforestation following the reduction in charcoal consumption is 5.73 MT for the whole treatment group, 6.21 MT for the subsidy treatment group and 5.03 MT for the credit treatment group.

Table 11. Cost-Benefit Analysis of Policy Instruments, Years 2–10

	(1) Subsidy	(2) Credit	(3) All
Baseline charcoal consumption/hh/year in tonnes	0.964	0.995	1.000
Baseline deforestation/hh/year in ha	0.125	0.129	0.130
Baseline CO_2 emission/hh/year in MT	19.229	19.863	19.957
Reduction in charcoal consumption per LPG stove at endline (%)	0.323	0.253	0.287
Reduction in deforestation per LPG stove/year in ha	0.040	0.033	0.037
Gross CO_2 averted in MT (153.5 MT per ha)	6.211	5.025	5.728
CO_2 emitted from cooking with LPG in MT (eq. to 34%)	2.112	1.709	1.947
Net CO_2 averted	4.099	3.317	3.780
Social cost of carbon (SCC) in saved forest (USD 39/MT CO_2)/year	159.867	129.355	147.430
Average cost of program per unit of LPG in USD	0.000	0,000	0.000
Average cost of program per MT of CO_2 averted	0.000	0,000	0.000
Average net benefit per LPG/year	159.867	129.355	147.430
Average net benefit per LPG in 10 years	1,515.343	1,251.875	1,411.799
Net benefit to cost ratio	18	30	23

Source: Authors' calculations from endline data.
Note: This table reports a social cost-benefit analysis of the subsidy and credit treatments during years 2–10 in 2012 USD. Column (1) presents baseline charcoal consumption, deforestation, CO_2 emission, reduction in charcoal consumption and deforestation, the amount of CO_2 averted including its cost and benefit to society due to subsidizing 75 percent of the cost of LPG stoves. Columns (2) and (3) report the same information for the credit treatment group and both treatment groups combined respectively. The average cost of the subsidy and credit programs per LPG stove is zero from year 2 onwards.

stove's net yearly benefit would be USD 147.43, USD 159.87 under subsidy, and USD 129.36 under credit (table 11). Thus, during its lifetime, an LPG stove will offer an accumulated net benefit of USD 1,411.78, USD 1,515.34 under subsidy, and USD 1,251.88 under credit.[28] The net benefit originating from the use of LPG stoves is, therefore, 23 times larger than its cost regardless of the type of intervention, 18 and 30 times larger under subsidy and credit, respectively.

The social benefit of both interventions is much higher than the monetary cost of implementing them. However, on a per MT of CO_2 averted basis, the 75 percent subsidy scheme is about 35 percent more costly than the credit scheme in the first year, i.e., USD 20.33 vs. USD 12.56. Moreover, despite that previous studies (e.g., Cohen and Dupas 2010; Dupas 2014; Kremer and Miguel 2007) point out subsidies as the most effective way to boost inefficiently low adoption rates of new technologies in developing countries and that subsidies could be easy to implement, from a public policy point of view, such a high rate of subsidy is likely to be unpopular among government decision-makers who often have to allocate limited resources among competing needs.[29] Some studies (e.g., Kar et al. 2019) also show that subsidies could be mis-targeted, i.e., captured by well-to-do households who could afford to buy the stoves without the subsidies. Equivalent levels of reduction in deforestation and aversion of CO_2 can be achieved using micro-finance credit schemes, which is one of the key messages of our analysis.[30] Given most SSA

28 The average accumulated net benefit in 10 years per LPG stove reported in the last row, last column of 11 is computed as follows: USD 1,411.79 = USD 84.93 in year 1 + USD 147.43/year for years 2–10. The average accumulated net benefits for subsidy and credit reported in the last row of table 11 are computed similarly.

29 In the context of LPG stoves, subsidies have also been found effective even in promoting gas refills by households. Jeuland et al. (2023) offer different levels of LP gas subsidies to low-income rural households in the Tamil Nadu state of India and find that the refill of LPG cylinders increased significantly with the size of the discounts.

30 Supplementary online appendix S3 presents sensitivity analysis of the cost-benefit results under three scenarios: (a) reduced cost of credit for the government through the introduction of market interest rate on the LPG loans, (b) reduced rate of uncollected credit through better credit repayment management, and (c) reduced effect of the LPG stoves on deforestation. The section shows that under all the three scenarios, credit is the most preferred policy instrument to encourage the uptake of LPG stoves.

governments are resource constrained and prioritize financing other activities, such as education and health, over charcoal-saving LPG stoves, there is significant room for the international community to play a role by financing the stove programs through initiatives like the REDD+.[31]

The unsustainable production of charcoal in Africa and its consumption to meet the cooking needs of households have other significant adverse impacts. Charcoal production is one of the critical causes of deforestation and forest degradation, which directly results in permanent loss of biodiversity and disturbance of local ecosystems (Campbell et al. 2007; Mercer et al. 2011; Allen and Barnes 1985; Geist and Lambin 2002; Hofstad, Köhlin, and Namaalwa 2009; Köhlin et al. 2011). Burning of charcoal also emits other harmful greenhouse gases, such as methane—the second major greenhouse gas next to CO_2 in terms of volume emitted, which contributes to global warming 21 times more by trapping heat in the atmosphere (van Dam 2017; USEPA 2012)—and black carbon emitted when burned in inefficient cookstoves (Sagar and Kartha 2007; Kandlikar, Reynolds, and Grieshopdy 2009; Grieshop, Marshall, and Kandlikar 2011), which absorbs light and reduces the reflectivity of snow and ice (van Dam 2017). Charcoal and other solid biomass fuels often burned in inefficient cookstoves result in the premature death of 3.8 million people in developing countries due to indoor air pollution (IEA 2017; WHO 2018). These are significant additional negative aspects of charcoal consumption in Africa, which we did not incorporate in the cost-benefit analysis we conducted above because they are difficult to quantify and beyond the scope of the paper. Thus, the social benefit of reducing charcoal use through acquiring modern cooking appliances, such as the LPG stove we offered to households in urban Tanzania, extends far beyond reducing the emission of CO_2.

Finally, an important finding we document in our study is the possible household-level welfare effects of cooking with LPG rather than charcoal. Our sample of households at baseline, which on average had 5.83 household members, consumed 19.18 kg of charcoal per week, which cost TZS 11,189 (USD 6.23). The reported median price paid by households to refill the 15 kg LPG cylinder was about TZS 45,000 (USD 25). To clearly understand how long a household can use the 15 kg gas if they cooked exclusively with LPG, we conducted a controlled cooking test with the household of one of the coauthors. The household (comprising three adults and three children) resides in a newly constructed apartment where cooking with biomass fuel is prohibited. All members' three meals of the day were cooked exclusively using LPG for four months. The household could cook with the 15 kg LPG for six weeks on average. The comparable six-week cost of charcoal would be TZS 67,134 (USD 37.30). Charcoal is almost 50 percent more expensive for the household than LPG, and households could save significantly by switching to LPG once they get access to the stove. While this finding is highly insightful, we acknowledge its limitation that it is based on a controlled cooking test conducted in one household only and that we cannot shed light on how these cost reductions vary by household size.

Given we document high uptake of the LPG stoves by both groups of the treatment group, but more importantly the credit group, and that the stoves reduce charcoal consumption, cooking time, and very likely the per unit cost of cooking energy, an important question is why are households not able to save for it? In table 1, we showed that 99 percent of the sample of households know about LPG stoves, but 93 percent of them stated that they could not buy them due to their high upfront cost. Furthermore, we showed that both groups (more importantly, the credit group) did not refill gas more often and continued buying charcoal in small portions daily and continued cooking with it. Although we cannot pinpoint

31 Berkouwer and Dean (2022) , a recent experimental study that investigates the willingness-to-pay for and the impact of an improved charcoal stove called "Jikokoa" by households in urban Kenya also finds positive net social benefits from adopting the stoves. These authors show that the return from the stove in terms of reduction in charcoal is three times the market price of the stove. However, the average WTP for the stove is significantly lower than the market value. They also show that the stoves reduced charcoal consumption by 39 percent and cooking time by 31 percent two years after the stoves were adopted. The reduction in charcoal consumption is equivalent to 5.4 MT of CO_2e (CO_2 equivalent) in averted emission, with a social value of USD 225 and a unit value of CO_2e USD 7.45 per tonne.

the exact behavioral reasons (e.g., present-biased preferences) that may also contribute to the zero uptake of the stoves before the interventions, we have ample indicative evidence suggesting that liquidity constraints in both the purchase of the LPG stoves and the refill are critical factors that the government should address.[32] Previous studies conducted in different contexts (e.g., Mobarak et al. 2012; Levine et al. 2018; Pattanayak et al. 2019; Berkouwer and Dean 2022) document that liquidity constraint is the key reason for the low adoption and diffusion of fuel-saving improved cookstoves, and that access to credit is critical.

5. Caveats: Livelihoods from Charcoal, Design, and External Validity

We find large treatment effects from the distribution of LPG stoves on charcoal consumption in urban Tanzania 15 months after distributing the stoves. We also investigated the possible impact of reducing charcoal consumption on deforestation and carbon dioxide emissions. We showed that promoting the switch to LPG stoves would offer significant social net benefits. Nevertheless, the study has some limitations related to charcoal production's role in providing livelihood, experimental design, and experimental validity that should be considered while discussing the results. We discuss these caveats and the scope for future research as follows.

The first crucial social justice issue that we could not incorporate in the cost-benefit analysis is the significant role of charcoal production and distribution in the livelihoods of hundreds of thousands of people. Charcoal production is the major source of deforestation and forest degradation in many parts of Africa (Campbell et al. 2007; World Bank 2009; Mercer et al. 2011; Chidumayo and Gumbo 2013). However, in many of these contexts, the charcoal sector serves as a source of livelihood to rural communities who engage in charcoal production, transportation, distribution, and retail (Khundi et al. 2011; Schure, Levang, and Wiersum 2014; Vollmer et al. 2017). This is particularly true for Tanzania, where hundreds of thousands depend on the sector and generate tax revenue for the government (Mabele 2020). Our paper focuses on the reduced form effect of transition away from charcoal by using LPG stoves. While integrating the contributions of the charcoal sector to the livelihoods and the economy in the cost-benefit analysis is beyond the scope of the study, from a social justice point of view, policymakers should seriously consider the issue while planning and implementing energy transition initiatives.

The second issue, which is still related to charcoal consumption, is the effects of the treatments in the context of sustainable production of charcoal. We acknowledge that quantifying the exact impact of the reduction in deforestation (or forest degradation) following a reduction in charcoal consumption requires high-resolution before-and-after forest coverage data measured over a longer time horizon, which we do not have. The effect of charcoal production on deforestation depends on the fraction of non-renewable biomass (NRB), which is the wood harvested more than the incremental growth rate of the woody biomass stock to meet demand (Bailis et al. 2015). Based on this definition, Bailis et al. (2015) shows that in most developing regions of Sub-Saharan Africa, South Asia, and Latin America, the predicted fraction of the non-renewable biomass used exceeds 50 percent. As a result, they are considered fuelwood "hotspots," and their fuelwood consumption is unsustainable. In the context of Tanzania, World Bank (2009) shows that all charcoal consumed is harvested unsustainably and produced using traditional and highly inefficient processes—about 125,000 hectares of forest are lost to produce the 1 million tonnes of charcoal

32 We communicated the key findings of our study in a non-technical version to stakeholders in Tanzania, including the Ministry of Environment. One of the coauthors presented the findings and played a key role in shaping Tanzania's National Clean Cooking Strategy 2024–2034 at the 2022 Clean Cooking Conference, which the president of the country attended. The strategy aims at moving 70 percent of the Tanzania population to clean cooking. As part of this initiative, the government of Tanzania is distributing 100,000 LP gas cylinders free of charge to rural and peri-urban households. See https://www.nishati.go.tz/ for Tanzania's "Clean Cooking Strategy." There has also been a recent news piece based on our study: https://dailynews.co.tz/tanzania-pushes-for-microfinance-support-in-clean-cooking-initiative/.

consumed annually. However, the same document also shows that this figure should be taken with caution because a non-negligible part of charcoal is a by-product of agricultural land expansion. Thus, it will be reasonable to assume that reducing charcoal consumption translates to reducing deforestation and forest degradation, but one cannot be certain of the exact magnitude.

Third, we acknowledge design and sampling issues that affect the study's external validity in other contexts. The sampling is only from 16 clusters. Although we verified the robustness of our results and the study is unlikely to be underpowered, we acknowledge that one would need a larger number of clusters to draw definite conclusions on the impact of a transition to modern cooking fuels. Moreover, we selected wards randomly in the first stage of our sampling but opted for the relatively well-off streets or subwards based on socioeconomic indicators. To investigate how our sample of households differs from the rest of Dar es Salaam, we compared the socioeconomic variables of the Dar es Salaam part of the Tanzania National Panel Survey collected in 2014–2015 ($N = 544$), precisely during the time we collected the baseline data. Out of the variables measured similarly (household size, age and gender of the head, and housing ownership), we find similar mean values except in household size. In the NPS data, 66 percent of household heads are male, their average age is 43 years, and 43 percent of them live in privately owned houses.[33] These figures are similar to the descriptive statistics in table 1. Thus, our sample of households is unlikely to differ significantly from the rest of Dar es Salaam.

Finally, our study focused on the effects of LPG stoves on charcoal consumption, and previous research linked charcoal production with deforestation and forest degradation in Africa. We show that an LPG stove offers a net benefit of USD 1,412 in its lifetime through reduced charcoal consumption. However, some of the effects of deforestation could be mediated by market forces. For example, micro-, small, and medium enterprises, such as restaurants and food-processing firms, consume almost 40 percent of the biomass fuel produced in Sub-Saharan Africa (Alem 2021). The switch to LPG stoves by households may reduce the price of charcoal and, as a result, increase charcoal consumption by firms. The cost-benefit analysis does not consider such types of general equilibrium effects. Therefore, one should view our treatment effects as the upper-bound effects of LPG stoves on deforestation and CO_2 emission.

6. Conclusions

Charcoal production to meet households' cooking energy needs in Sub-Saharan Africa's urban areas is one of the region's leading causes of deforestation and forest degradation. Clearing the natural forest for charcoal production using unsustainable production methods results in the loss of invaluable biodiversity, destruction of local ecosystems, and emission of harmful greenhouse gases that exacerbate the problem of climate change. One crucial factor hindering households' transition from biomass energy to clean energy sources is the high start-up cost of modern cooking appliances. To test this hypothesis, we collaborated with one of Tanzania's largest micro-finance institutions and offered a durable and high-quality two-burner LPG stove package through subsidy and on credit. We conduct a midline survey 4 months after the interventions and an endline survey 15 months after. We measure the impact of the LPG stoves on charcoal consumption and the corresponding possible reduction in deforestation and averting of carbon dioxide (CO_2). We then conduct a social cost-benefit analysis, which compares the cost of the two policy instruments to the social cost of carbon, which is the monetary value of the benefits of sequestered CO_2. Our design also allows us to investigate the impact of LPG stoves on women's cooking time. We, therefore, offer rigorous evidence about the causal effects of relaxing households' financial constraints through

33 The average number of household members in the NPS sample for Dar is 4 persons, but it is 5.8 persons in our sample. The NPS data are publicly available at https://www.nbs.go.tz.

alternative policy instruments on charcoal consumption and the resulting significant benefits that accrue to households and society at large.

The LPG stoves we offered had a high uptake rate (69 percent) by the treatment group. The adoption rate in the control group, where we provided the stoves at the market price, is zero. These findings suggest that the critical reason that hinders households' transition to cleaner energy sources is liquidity constraint. Intent-to-treat results indicate that the treatment group reduced charcoal consumption by 28.7 percent per week compared to the control group 15 months after treatment. The reduction is equivalent to saving 0.037 ha of forest, which translates to an aversion of 3.78 MT of CO_2/household/year after accounting for the CO_2 emitted from cooking with LP gas. A social cost-benefit analysis conducted using the social cost (benefit) of carbon estimated by the US EPA (USD 39/MT CO_2 in 2012 prices) shows that the distribution of LPG stoves, in general, offers a net benefit of USD 84.93/LPG stove in the first year and USD 147.43/LPG stove/year for the remaining life of the stove, which sums to USD 1,412/LPG stove. Instrumental-variable regressions that use the random assignment of the treatment as an instrument for the adoption of LPG stoves show that adopter households reduced charcoal consumption by 39.5 percent 15 months after treatment. Using a carefully conducted 4-month-long controlled cooking test, we show that cooking with LP gas is 50 percent cheaper than cooking with charcoal. This finding, together with the 69 percent reduction in cooking time by treatment households, shows that the transition to cooking with LPG is highly beneficial even to households.

Millions of hectares of Africa's forests are destroyed for the production of charcoal and firewood each year. Given the documented high carbon sequestration potential of Tanzania's forests, targeting the reduction of charcoal production will likely provide substantial external benefits to society. Our findings provide insights into reducing charcoal consumption in urban areas of Africa. Both the descriptive statistics and results from our randomized controlled trial demonstrate that the high start-up cost of modern cooking appliances such as LPG stoves is the main factor prohibiting households from switching to modern and relatively environmentally friendly energy sources. Because of this, simple policy interventions, such as reducing the import duty on LPG stoves, could increase the adoption and use of LPG stoves and consequently reduce charcoal consumption. Currently, the Tanzanian government levies a 25 percent import duty on LPG stoves and 10 percent on the cylinders. Reducing these duties and making LPG stoves affordable would likely result in a more significant uptake rate. This is the key message of our study, which should be picked up by policymakers, donors, and other stakeholders interested in saving the remaining forest resources of Africa and tackling the emission of harmful greenhouse gases that exacerbate the problem of climate change.

We acknowledged the possible caveats of our study. These caveats relate to charcoal's role in rural communities' livelihoods, the external validity implications of our sampling and design, and the possible general equilibrium effects of reducing charcoal consumption by households on demand by other economic agents, such as micro-, small, and medium enterprises. We believe that these limitations open up great opportunities for future research, specifically experimental studies using larger sample sizes, energy use behavior of enterprises, and whole-rounded analysis on the general equilibrium effects of interventions on the charcoal sector.

Conflict of Interest Statement

The authors of this paper declare that they have no competing interests to disclose.

Data Availability Statement

Data and codes to replicate the analysis and results reported in the paper have been deposited at the OPENICPSR Wbsite: https://doi.org/10.3886/E221102V1.

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