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RESEARCH ARTICLE

# Improved biomass cookstove use in the longer run: results from a field experiment in rural Ethiopia[1]

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**Abstract**
This study examines longer-run usage frequency of Mirt improved biomass cookstoves (ICS), one of the most important ICS promoted in Ethiopia. Mirt has been shown to improve childhood health, and reduce fuelwood consumption and greenhouse gas emissions, but to generate those benefits, households must regularly use it over extended periods. Thus, this paper focuses on longer-run use using stove surface temperature data over five time intervals. We find that, close to its estimated lifespan, 63 per cent of households had their stoves in place after more than 3.5 years. Of those who abandoned their stoves, over 80 per cent did so due to breakage, indicating little abandonment of functional stoves. Among those who retained their stoves, despite the relatively long time frame, we observe no decline in regular usage, suggesting the ICS deliver long-term benefits. We find no correlation of dis-adoption with three randomly assigned monetary treatments and no effect of treatments on long-run usage frequency.

**Keywords:** abandonment and usage; biomass; Ethiopia; improved stove; Mirt

**JEL classification:** Q23; Q42; Q55

## 1. Introduction

Despite considerable progress, as we move through the third decade of the 21st century, almost two in five people on the planet still cook with highly polluting, mainly solid fuels (e.g., biomass, coal), burned in their main homes or nearby buildings (Jeulandand

[1]Authorship is equally shared.

Pattanayak, 2012; Jeuland *et al.*, 2015*b*; Stoner *et al.*, 2021). This reliance, particularly on biomass fuels like fuelwood, agricultural waste and animal dung, is primarily concentrated in low-income developing countries (Jeuland *et al.*, 2015*a*; Stoner *et al.*, 2021), contributing to indoor and outdoor air pollution (Smith *et al.*, 2013; WHO, 2022), forest degradation (Gebreegziabher and van Kooten, 2013) and climate change (Bailis *et al.*, 2015).

Though across the world the percentage of people depending on biomass fuels has declined dramatically in the past decades and will continue to decline, the absolute number of people who depend on biomass fuels is expected to fall only slightly through 2030, to 2.4–2.7 billion people (IEA, 2020; Stoner *et al.*, 2021). Biomass cooking fuel use is also expected to remain very significant in Ethiopia, which is the focus of this paper, because over 1 billion people in sub-Saharan Africa are projected to use solid fuels in 2025 (Stoner *et al.*, 2021). In 2021, Ethiopia depended on biofuels and waste for about 88 per cent of its energy demand (IEA, 2024), most of which is used for cooking, though use of commercial fuels is expected to increase in the coming decades (Mondal *et al.*, 2018).

Burning biomass cooking fuels causes indoor and outdoor air pollution (e.g., Lim *et al.*, 2013; Smith *et al.*, 2013), forest degradation (e.g., Arnold *et al.*, 2006; Boucher *et al.*, 2011; Gebreegziabher and van Kooten, 2013), which can create serious labor demands due to the need to collect fuelwood (e.g., see Cooke *et al.*, 2008) and climate change (e.g., Bailis *et al.*, 2015). Traditional biomass cookstoves, such as the three-stone tripod typically used in Ethiopia, are only 5–15 per cent efficient (Mobarak *et al.*, 2012), implying they use more biomass than needed to cook meals and emit high levels of air pollution. To mitigate some of the problems associated with biomass fuels, improved biomass cookstoves (ICS) have been introduced around the world. These stoves seek to provide efficiencies by cooking meals with less fuel, resulting in less fuelwood consumption (Mondal *et al.*, 2018) and potentially offering improved performance in other ways, such as reduced cooking time and improved indoor air quality compared with traditional technologies.[2] These technologies are typically not sophisticated, are often cheap (e.g., Hanna *et al.*, 2016), and in some cases require only minor changes in cooking habits (Jeuland and Pattanayak, 2012).

Many ICS were introduced in the 1980s, but often it was found that cooks did not regularly use those stoves (e.g., Gil, 1987; Barnes *et al.*, 1993), suggesting that benefits observed in labs either did not materialize in the field or were outweighed by additional costs to users. It soon came to be recognized that ICS adoption really has two parts. The first is willingness to try stoves, which implies distribution to households. The second and more important aspect of adoption is regular use over an extended period, which has come to be seen as the main litmus test of true adoption (Johnson *et al.*, 2009; Bensch and Peters, 2015; Hanna *et al.*, 2016). Because of the critical role of longer-run regular use in determining whether potential benefits of ICS technologies are generated in households, in this paper we focus on regular use over an extended time period.

[2] A particularly interesting policy development is the use of carbon finance to fund both private sector and nonprofit pay-for-performance ICS programs (Lewis and Pattanayak, 2012), with the goal to reduce greenhouse gas emissions and improve human health and livelihoods. For example, the for-profit firm DelAgua Health has distributed more than 1.5 million EcoZoom stoves in Rwanda and claims to have reduced greenhouse gas emissions by 8.6 million tons per year, which they note is equivalent to the annual automobile emissions of London and New York. (http://www.delagua.org/projects/rwanda). See www.projectsurya.org for an interesting example of a nonprofit project relying on carbon finance.

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We examine adoption of the Mirt ICS, which is a low-cost (approximately $12), chimneyless manufactured stove made of six pieces of concrete joined together with mud.[3] It has been promoted in Ethiopia since 1998 and is used primarily to cook *injera*. *Injera* is a type of pancake that is eaten in most parts of Ethiopia, and it requires hot, even energy delivery to be properly baked. The average household uses about 20 kg of fuelwood per week to make *injera*, and *injera* baking has been estimated to use about half of the primary energy of the country (Tesfay *et al*., 2014).

Mirt has been estimated to use 50 per cent less wood in laboratory tests (GIZ, 2011), 40 to 50 per cent relying on self-reports in surveys (Megen Power Ltd., 2008; Dresen *et al*., 2014) and 20 to 30 per cent in field-based controlled cooking tests (Gebreegziabher *et al*., 2018). Use of ICS in rural Ethiopia is limited (Mondal *et al*., 2018), with most households relying exclusively on three-stone tripods that waste approximately 90 per cent of the energy input (Alem *et al*., 2014).

Wassie and Adaramola (2021) estimate a significant reduction in fuelwood consumption and the potential emissions reductions associated with use of improved cookstoves in Ethiopia. Gebreegziabher *et al*. (2017) also find a significant reduction in fuelwood and dung consumption from use of improved cookstoves. They also note the associated positive externalities in the form of reduced pressure on the forest as well as increased soil productivity from reduced dung use as fuel.

We extend our previous field experiment-based work on this topic, which examined regular use of Mirt over a period of about a year (Bluffstone *et al*., 2021), in light of three monetary treatments, which were randomly applied at baseline. *Injera* is not cooked every day, but regular baking would occur at least twice per week in areas such as our study regions, which lack refrigeration. Regular usage of the Mirt *injera* stove therefore means using it at least twice per week (Tesfay *et al*., 2014).

The three monetary treatments applied at baseline are providing the stoves: (1) free of charge; (2) at a monetary cost, and (3) with a one-off incentive to regularly use the Mirt ICS during the first approximately six-week monitoring period after distribution. In all cases, randomization was at the site level. As will be discussed in section 2 of this paper, monetary incentives have been very important as part of policy packages to promote new technologies in the Global South. For example, Hassen and Kohlin (2017) examined the role of sunk cost and screening effects on Mirt stoves in rural Ethiopia.

In our previous paper (Bluffstone *et al*., 2021), which examined behaviors that occurred within the first year, we found that households in general regularly used the Mirt stove. We also found that average usage – and average regular usage defined as use at least twice per week – increased over time; and free distribution promoted both sustained high levels of regular use and increases in average usage over time. Paying for the Mirt ICS was found to promote increased usage mainly because average use in the beginning was very low compared to the other two monetary treatments. We therefore concluded after one year of evidence that the Mirt stove was on average regularly used and free distribution is the preferred treatment for maximizing uptake (Bluffstone *et al*., 2021).

In this paper, we test whether these results hold up in the longer run, meaning approximately three-and-a-half years after initial distribution of the Mirt stove. This period is about 70 per cent of the estimated lifespan of Mirt and allows us to examine common ICS program outcomes that were not observed during the first year. These outcomes

[3]See online appendix figure A1 for Mirt stove images.

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include dis-adoption and abandonment due to breakage or poor fit with family cooking styles, which were not observed during our shorter-run analysis. We also evaluate if use behavior has changed during the approximately 2.5 years since the Mirt stoves were last monitored, and if there are any lingering effects on stove use from the monetary treatments applied in 2013.

A theory of change we consider in this paper is that the stove is expected to be more useful and the benefits for households would be larger if it is used over an extended period. The benefits of the improved stove for households include time and money saved due to reduced use of fuelwood, and reduced exposure to indoor smoke. Thus, extended use of the stove would have significant private benefits, especially because the cooking fuel is so important in terms of total energy consumption in Ethiopia. Moreover, for the benefits to be realized it may be necessary to incentivize use and it is important to examine the extent to which the stove is being used regularly. There are also benefits from reduced outdoor air pollution locally as well as global benefits from reduced GHG emissions. Thus, ascertaining how regularly the stove is used in the long run and whether incentives matter has important implications for policy.

We find that about 63 per cent of households still have their Mirt stoves in place after about 3.5 years, and over 80 per cent of those who no longer have them report that they were abandoned due to breakage. In our previous shorter-run analysis, no stoves were abandoned. In the longer run we find that, among those who retained their functioning stoves, Mirt stove use is high and on average in line with regular use (roughly twice per week). If anything, average usage frequency increased over time. We therefore conclude that in the longer run the Mirt stove continues on average to be regularly used.

We also find that usage intensity 3.5 years after introduction is not driven by the monetary incentives given at the time of the introduction. In contrast to our previous shorter-run analysis, while free distribution does no worse at promoting persistent longer-run regular usage, it is generally not more effective than the other treatments.[4] Persistent regular usage of the stove that we find in this study, combined with the reduction in fuelwood consumption and carbon emissions reported in Mekonnen *et al.* (2022), is likely to imply that ICS policies should be continued or even expanded in Ethiopia because of the sustained benefits to households, as well as society at large through climate change mitigation benefits.

Our study contributes to the limited literature on adoption of improved stoves in the longer run, with Bensch and Peters (2015) and Hanna *et al.* (2016) being the major studies. Bensch and Peters (2015) randomly distributed an improved stove with expected

[4]Bluffstone *et al.* (2021) refined the initial work in Beyene *et al.* (2015); also see Mekonnen *et al.* (2020) for a precursor to the current paper. Related work and data investigate research questions that are unrelated to regular use and abandonment. Gebreegziabher *et al.* (2018) use two rounds of field-based controlled cooking tests and find that the Mirt stove reduces the fuelwood needed to cook standardized batches of *injera* by 20–30 per cent and is on average well-liked by users. Bluffstone *et al.* (2022) evaluate the role of learning and experience within the context of three controlled cooking tests and find that learning and experience reduce the time required to cook standardized batches of *injera*. Mekonnen *et al.* (2022) estimate fuelwood savings and reduced $CO_2$ emissions of the Mirt stove. They combine controlled cooking test data with electronic stove use monitoring data, which are also used in the current paper, and estimate that the average stove reduces fuelwood consumption by about half of previous estimates and sequesters 0.65 tons of $CO_2$ per year. LaFave *et al.* (2021) focus on indoor air pollution reductions and health effects for children as a result of Mirt stove adoption and use. They find that adoption and use of the Mirt stove reduces indoor air pollution, which improves development of very young children.

lifespan between one year and three-and-a-half years free of charge and analyzed behavior more than one year after distribution. Hanna *et al.* (2016), in contrast, found that the usage rate and performance of the stove they studied declined over the four years examined, mainly due to limited or no maintenance investments by households. Section 2 discusses the key literature that is germane to our research topic. Section 3 discusses the methods and section 4 presents results. Section 5 discusses the findings and section 6 concludes.

## 2. Literature review

In this section, we briefly review previous literature on long-run adoption of new technologies, with a special emphasis on the monetary terms under which those technologies were provided. Of the two parts of ICS adoption – distribution and regular use – the second part is more ambitious and important. Financial incentives such as subsidies and rewards are often used to promote distribution, but sometimes concerns are raised that promoting distribution by offering stoves free or at low cost may waste resources and even reduce usage. Other instruments to induce behavioral changes and enhance adoption in diverse spheres of life, including energy conservation, smoking cessation, and adherence to medication, include social comparisons (e.g., Schultz *et al.*, 2007; Nolan *et al.*, 2008), and provision of nudges (Allcott and Rogers, 2012, 2014). Abrahamse *et al.* (2005), Delmas *et al.* (2013), Karlin *et al.* (2015), and Andor and Fels (2018) provide useful analyses and reviews of the literature on behavioral interventions centered around energy conservation. For example, Abrahamse *et al.* (2005) conclude that information does not necessarily result in behavioral changes or energy savings. They also find that payments for adoption of energy efficiency technologies encourage short-run adoption, but effects dissipate in the long-run.

With regard to monetary treatments, free or low-cost distribution of technologies may promote uptake (e.g., Cohen and Dupas, 2010; Bensch *et al.*, 2015), but could also potentially mean that technologies go to those who will not use them (e.g., Ashraf *et al.*, 2010; Chassang *et al.*, 2012). Payments could also potentially generate psychological sunk costs that promote use, but little evidence appears to exist of such effects (Ashraf *et al.*, 2010; Cohen and Dupas, 2010).

Some of the most significant work on long-run adoption has been on insecticide-treated bed nets in Sub-Saharan Africa. The WHO analyzed free distribution of bed nets versus charging nominal prices. They find that free distribution is most effective (The Economist, 2008). Dupas (2014) also shows that a one-time subsidy can boost the purchase of mosquito-repellent bed nets and those who received the bed nets under concessionary terms do not anchor their valuations on those prices.[5] Cohen and Dupas (2010) do not find a significant difference in the use of bed nets between households who paid, compared with those who received their bed nets for free. In a field experiment in Zambia, Ashraf *et al.* (2010) investigated the intensity with which chlorine to treat drinking water was used. They find that higher prices of chlorine increase the average probability that people use it by screening out low-value users. They find little evidence, however, that high sunk costs promote use.

A second potential monetary treatment is payment for performance. Cahill and Perera (2011) review the effectiveness of incentives for smoking cessation. They argue that, though there seems to be some evidence that incentives work in the short run, generally

[5] Bensch and Peters (2020) find no evidence of anchoring in their study of ICS adoption in Senegal.

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the effects dissipate and there is no clear evidence that initial behavioral changes translate into routine practice. Kane *et al.* (2004) categorize behavioral changes into 'simple' (single actions at a point in time), such as taking a medication, and 'complex' (requiring effort over a sustained period of time) such as smoking cessation and weight loss to reduce obesity.

According to Giuffrida and Torgerson (1997) and Aveyard and Bauld (2011), incentives are effective for simple, but not for complex, behavior change. They argue that complex behavior change requires multiple interventions. Moreover, the effectiveness of interventions for complex behavioral change often declines when the incentive is withdrawn (Paul-Ebhohimhen and Avenell, 2007). Adoption of a new cooking technology can potentially require significant adjustments by cooks, which could qualify it as a complex behavioral change. The literature therefore suggests that a one-shot monetary incentive which, along with free distribution and requiring payment is one of the treatments analyzed in this paper, would be no more effective at incentivizing longer-run adoption than other treatments.

## 3. Field experiment

### 3.1 Design

The field experiment involved distributing the Mirt stove under randomly-assigned monetary treatments to a sample of rural Ethiopian households in 2013. In our study area and throughout much of Ethiopia, households with no refrigeration typically bake *injera* at least twice per week (Tesfay *et al.*, 2014). We therefore use baking *injera* at least twice per week as our definition of regular usage.

We identified cooking events by measuring the surface temperature of the Mirt stoves using electronic Stove Use Monitors (SUMs).[6] The SUMs we used are approximately the size of a watch battery. We set the SUM device to record surface temperature every ten minutes and the memory can record for approximately 60 days and tolerate temperatures up to 120° Celsius (C). Temperature, time and date data were then downloaded after the monitoring period was completed. Respondents were informed that the purpose of the SUM device was to record surface temperature of the stove and that enumerators would come back periodically to download the data and reinstall the SUM devices.

We have three randomly-assigned monetary treatments: (1) users received the stove for free; (2) users paid 25 Birr for the Mirt stove (about 13 per cent of the market price), and (3) users paid nothing for their stoves and received a 50 Birr,[7] one-time incentive payment if the SUMs that were affixed to their stoves indicated that Mirt stoves were used at least twice per week (i.e., were regularly used) during the first monitoring period.

Using signal processing and analysis (O'Haver, 1997), we measured frequency of stove use for a monitoring period by simply counting the number of times the stove

[6]The Mirt stoves were monitored over five periods of up to about 8 weeks per period over approximately three-and-a-half years. A subset of 108 households also participated in three controlled cooking tests that are not part of this study but are discussed in Gebreegziabher *et al.* (2018). In our regression models we control for participation in this activity, but do not find effects on regular usage.

[7]The exchange rate in June 2013 when the Mirt stoves were distributed was approximately ETB19/US$1 and the daily unskilled wage rate was approximately ETB40. Half the sample was randomized into village-level groups that received one-time group training focusing on stove features and usage methods. These instructions were in addition to individualized training. These groups, which were composed of households in the same village sites who received the Mirt stove, were found to have no effect on usage and are treated as a control in all models.

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surface temperature exceeded a critical value. The average stove use in a period is calculated as the number of cooking events divided by total days temperature was measured. Because *injera* is not baked daily, we express this value per week and define regular use of the stove as average use of at least twice per week.

Based on readings from the SUMs, we identify a cooking event as having taken place if the recorded temperature exceeded 40°C. We chose 40°C as our cutoff, because it is considerably higher than the maximum in-home ambient temperature measured using thermometers, which was 35°C. We therefore reduce the possibility of counting normal temperature variations as cooking events by using the 40°C cutoff. We also conduct robustness checks with 45°C and 60°C cutoff points and find that results do not change.

The three-stone tripod is the traditional *injera* baking technology in rural Ethiopia and in our study sites. It is difficult to reliably monitor three-stone tripod cooking using SUMs, because the stones are often moved, fires are less controlled than with an enclosed stove, and SUMs may be destroyed. We therefore only analyze use of the ICS, which is the objective of this paper, implying that we are unable to observe effects on overall cooking behavior, including use of three-stone tripods. Images of the Mirt stove are included in online appendix figure A1.[8]

### 3.2 Sampling and fieldwork

Our sampling frame is based on a random sample of 110 villages in local jurisdictions called *kebeles*.[9] We eliminated 29 of the 110 villages because they were part of our pilot survey, *injera* was not typically baked in villages or the normal three-stone tripod technology was not used. We then selected 36 villages using stratified proportional random sampling from the 81 villages that were left. Stratification was by regional state (Amhara, Oromia, and Southern Nations, Nationalities and Peoples (SNNP)), with forest area used as the state weight. Forest area was used because most fuelwood comes from forests and it also proxies well for total regional state population and land area. In total, 20 per cent of villages were from Amhara, 50 per cent from Oromia and 30 per cent from SNNP regional states. From the 36 village/site clusters, 360 households were randomly selected to receive the Mirt stove. A total of 10 households received the Mirt stove in each village.[10]

Respondents were informed about the nature of the survey and experiment and formal oral consent was received from all respondents. Full information was provided individually to respondents on stove features, usage methods, the SUMs, and details about the monetary treatment randomly applied to them. Though all households were

[8]Households in any case need to use three-stone tripods to cook most non-*injera* foods. The Mirt *injera* stove has a 50 cm burner which cannot accommodate normal pots. The way the stove is designed makes it difficult to shift to other uses.

[9]Kebele translates as peasant association and is made up of several villages. It is the smallest official jurisdiction in Ethiopia. We have only one village per research site and *kebele*. We, therefore, use the terms site, village and *kebele* interchangeably.

[10]Another 144 households (4 from each site) did not receive the stove and serve as controls for other analyses using the field experiment. The total number of households involved in the field experiment is therefore 504. In this paper we are concerned only with households that received the Mirt stove. The experiment was designed in 2012, which was before ex ante power calculations became the standard. There were also few randomized stove use experiments from which to estimate standard deviations. Post-hoc power calculations are not recommended for assessing sample sizes but are primarily useful for developing future experiments (see, e.g., Hoenig and Heisey, 2001; O'Keefe, 2007).

monitored using the SUMs, we acknowledge that knowing they were being monitored could itself potentially increase Mirt stove usage.

Respondents were also informed that stove use was not required to receive a stove, that the stove was anticipated to reduce fuelwood consumption and respondents were encouraged to use their Mirt stoves. While the strategy to address refusals was to replace refusing households by randomly choosing from remaining households in each site, there were no refusals during the random distribution of the stoves or abandonment until after the first year of data collection. There was very low attrition for the long-term study, with the end-line (2016) data collection including approximately 95 per cent of the 2013 households.

The baseline survey and user training, which were conducted during June–August 2013, were done concurrently with stove distribution, and included household characteristics and socioeconomic variables. In 2016, when the final monitoring period occurred, a second survey was conducted. This survey updated baseline household characteristics, but particularly focused on kitchen characteristics and use/disuse and abandonment of the Mirt stove. Field workers were experienced and were trained directly by investigators, with approximately four enumerators working under each of the five field supervisors. All of the supervisors and many of the enumerators who conducted the follow-up field work in 2016 also participated in the baseline research in 2013.

In addition to installing the stoves in the *injera* baking area at baseline (the first period of the study), the fieldworkers installed the SUMs on the stoves and initiated them in each of the five periods the study was conducted. The five monitoring periods were: June–August 2013 (period 1); August–October 2013 (period 2); March–May 2014 (period 3); May–July 2014 (period 4) and November–December 2016 (period 5). The use of multiple follow-up periods (four in this study) rather than just one, is expected to increase the power of the analysis (McKenzie, 2012).

Randomization in the selection of Mirt stove recipients within each village was at the household level. Randomization of the monetary treatments was at the village level to ensure that all those in a village received their Mirt stoves on the same terms, with 12 villages receiving each treatment, for a total of 120 observations within each treatment and period.[11] Households in Ethiopian villages were likely to know the terms under which their neighbors received the improved stoves. Allocation of stoves using different treatments within a village would have likely created resentment, which would have been unethical and potentially biased usage intensity. This village-level distribution approach also reflected typical implementation of improved stove programs, where all individuals in villages would generally receive stoves under the same conditions.

In sum, therefore, three equally weighted monetary treatments were distributed randomly across villages using the stratification procedure noted above, and 10 households were randomly selected to receive Mirt stoves within each village, for a total of 360 observations in each period. As previously noted, there was very low attrition in this long-term study, but to analyze a consistent sample of households in all rounds, the sample is restricted to those households that could be reached and provided valid data in 2016,

[11] As noted in Bluffstone *et al.* (2021), using 11 key characteristics of our research sites across our treatments, we tested for site-level imbalances across our three monetary treatments. These variables at the site level include average altitude and rainfall, measures of population size, participation in forest user groups, existence of forest regulations and changes in forest biomass over time. We find that only one of the community variables was significant at the 5 per cent level using Kruskal-Wallis tests (table A6, online appendix).

**Table 1.** Descriptive statistics of outcome variables

| | Mean | Std. dev. |
|---|---|---|
| Stove is in place in period 5 (1 if yes, 0 otherwise) (period 5 sample, $N = 315$) | 0.63 | 0.48 |
| **Stove use by households who did not abandon the stove in period 5 (period 5 only, $N = 193$)** | | |
| Uses stove twice or more per week (1 if yes, 0 otherwise) | 0.52 | 0.5 |
| Average frequency of stove use per week (times/week) | 2.50 | 2.04 |
| **Stove use by households with valid data in period 5 (pooled sample, $n = 1{,}295$)**[a] | | |
| Uses stove twice or more per week (1 if yes, 0 otherwise) | 0.47 | 0.5 |
| Average frequency of stove use per week (times/week) | 2.36 | 2.26 |

[a]This total does not include observations for period 5 in which the household abandoned the Mirt stove.

which was the end line. In the analysis of regular stove use and frequency of stove use, we include only period 5 observations from households who had not abandoned the stove.[12]

## 4. Results

Our analysis starts with evaluating whether our randomly-assigned monetary treatments and controls may have contributed to households abandoning their stoves between July 2013 and November/December 2016 (up to 3.5 years after the initial distribution of the stoves). These results are then followed by analysis of longer-run usage frequency, including effects of treatments on use of stoves at least twice per week, both considering and ignoring dis-use. Our main findings are that almost 2/3 of stoves were still used after 3.5 years, those that were in place in 2016 were on average regularly used and our monetary treatments did not appear to affect longer-run regular usage.

Descriptive statistics for our outcome variables are given in table 1 for the pooled sample, and for households for which the stove was in place in 2016 (i.e., period 5). For the pooled sample, we find that average usage is 2.4 times per week and 47 per cent of households used the stove an average of two or more times per week. The corresponding figures for households in period 5 who had not abandoned the stove were slightly higher (2.5 times/week and 52 per cent regular usage).

Indicator variables for the three monetary treatments (approximately 1/3 of sample each), which are our variables of interest, as well as one-time village-level group training (half of households) and controls are included in all models. Table 2 presents descriptive statistics for the controls, which were collected at baseline and are potential drivers of the decision to keep stoves in place in the long run, the frequency of use and also regular use of the Mirt stove. These variables include socioeconomic characteristics, such as gender, education and age of the respondent, indicators of economic status and cooking-related characteristics. As shown in table 2, about 87 per cent of respondents were men, a majority of whom were illiterate. The mean family size was five adult equivalents.

[12]As mentioned above and discussed in detail below, no stoves were abandoned in periods 1 to 4 of the study, and the vast majority of those who abandoned their stove in period 5 did so because of breakage that made the stove unusable.

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**Table 2.** Descriptive statistics of baseline controls

| Variable description | Mean | Std. dev. |
|---|---|---|
| Incentive treatment (1 if yes, 0 otherwise) | 0.33 | 0.47 |
| Pay treatment (1 if yes, 0 otherwise) | 0.35 | 0.47 |
| Free treatment (1 if yes, 0 otherwise) | 0.32 | 0.47 |
| One-time group training (1 if yes, 0 otherwise) | 0.49 | 0.50 |
| *Socioeconomic controls* | | |
| Age of respondent in years | 41.95 | 12.63 |
| Male household head (1 if yes, 0 if female) | 0.87 | 0.34 |
| Education (1 if literate, 0 otherwise) | 0.40 | 0.49 |
| Family size in adult equivalent | 4.95 | 1.82 |
| Number of livestock in tropical livestock units (TLU)[a] | 4.97 | 3.54 |
| Estimated coefficient of risk aversion[b] | 3.82 | 1.18 |
| Corrugated roof (1 if yes, 0 otherwise) | 0.71 | 0.45 |
| Distance to all weather road in hours (two ways) | 0.97 | 1.48 |
| Randomly selected to participate in controlled cooking test (1 if yes, 0 otherwise)[c] | 0.31 | 0.46 |
| *Cooking characteristic controls* | | |
| Uses stove for purposes other than baking (1 if yes, 0 otherwise) | 0.35 | 0.48 |
| Average number of *injera* baked at a time | 19.96 | 10.26 |
| Uses pure teff flour (1 if yes, 0 otherwise) | 0.16 | 0.37 |
| The stove is installed inside the house (1 if yes, 0 otherwise) | 0.36 | 0.48 |

*Notes:* Households with valid data in 2016 are included. Number of observations varies by variable.
[a]TLU is a standard method developed by the Food and Agriculture Organization (FAO) for combining different livestock types into one metric based on weight, with a cow = 1.
[b]Please see Vieider *et al.* (2018) for a discussion of the estimation method.
[c]As part of the study, households were randomly selected to participate in a controlled cooking test to compare the traditional tripod stove with the Mirt stove. This variable is included as a control variable to see if it had effects on use of the Mirt stove.

Tropical livestock units based on cow-equivalents (mean of about 5) and whether the house has a corrugated roof ($>70$ per cent) are potential indicators of economic status, as is whether the household uses pure teff flour. Teff flour is more expensive than other grains used to bake *injera* and, as shown in table 2, a minority of households use it. Distance to all weather roads measures market access and integration and we find that, on average, households live within an hour of walking time of roads.

We control for participation in controlled cooking tests to adjust for potential Hawthorne effects that could affect the dependent variables.[13] Whether the household uses the stove for purposes other than baking attempts to capture whether households are making full use of the Mirt stove, which can cook coffee and to some extent stews while simultaneously baking *injera*. Most respondents report only using their Mirt stoves for cooking *injera*. The number of *injera* baked during a session captures how intensively the stove is used at each baking, which can affect usage and abandonment, and we find

[13]Controlled cooking tests are intensive, experimental methods for estimating differences in fuel use and cooking time. These were done three times in 108 households. This variable is included in models to control for potential effects that could arise from these additional interactions with respondents.

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a mean of 20 *injera*. Whether the stove was installed inside the house (as opposed to in a separate kitchen) also may be correlated with use and dis-adoption of the stove, because of undesirable smoke in the home and potentially higher chance for breakage. Almost 2/3 of households placed their Mirt stoves in separate kitchens rather than in the main house.[14]

### 4.1 Dis-adoption of stoves prior to November/December 2016

At the end of 2016 (about three-and-a-half years after baseline), we conducted a visual inspection and survey to identify whether the stoves adopted in 2013 were still in place. About 63 per cent of those who received a stove were still using it 3.5 years after initial distribution, which is high considering that these stoves were approaching the end of their approximately five-year lifespans.

About 83 per cent of the 121 respondents who gave reasons for abandoning the stove said the driver of abandonment was breakage. Other reasons included 'I do not need it, because I do not bake *injera*' and 'I have a better improved stove.' In our model of abandonment, we also included the average number of times households used their Mirt stoves per week in period 4, which is the period immediately preceding the last period of data collection (and hence predetermined), to adjust for intensity of use, which may affect dis-adoption (mean = 2.4 times/week).

Table 3 presents results of probit regressions to examine potential drivers of dis-adoption 3.5 years after the introduction, where the outcome is coded as 1 if the stove is still in place and 0 otherwise. The results in columns 1 and 2 show that none of the treatments are correlated with retention of the stove when compared to the reference category of Free Treatment and results are unaffected when other covariates are added as shown in columns 3 and 4. Households with larger family size are more likely to dis-adopt, perhaps because additional members contribute to breakage of the stoves. Households who were randomly selected to participate in controlled cooking tests were more likely to still be using the stove in 2016 ($p < 0.05$), as were households that bake more *injera* at a time, perhaps because they are more reliant on the technology.

### 4.2 Stove use in the longer run

In our analysis of stove use in the longer run, we look at the extent of usage by households who provided valid data for period 5 and also use Heckman selection models to adjust for disuse. Our analysis focuses attention on period 5, with the objective being to analyze longer-run effects. Outcome variables and controls used are presented in tables 1 and 2 respectively.

Table 4 shows frequency of Mirt stove use by period and treatment, measured using the SUMs for households with valid observations in 2016, but excluding period 5 observations for households who had abandoned the stove (mainly due to breakage). The numbers represent average times the stove was used per week during each of the approximately 6-week monitoring periods. Results are broadly in accord with normal *injera* cooking patterns and the stated average usage reported in Gebreegziabher *et al.*

[14]SUM failures is the main reason that the number of observations in all models is smaller than the initial sample. We ran a probit regression to evaluate if SUM failures were correlated with treatments and find no relationship (table A1, online appendix). Other reasons for less than complete sample sizes include missing observations for specific variables.

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**Table 3.** Probit regression of whether Mirt stove was in place in 2016

| | Without control | | With controls | |
|---|---|---|---|---|
| Variable description | Coefficient | Std. error | Coefficient | Std. error |
| Incentive treatment (1 if yes, 0 otherwise) | 0.001 | 0.292 | 0.119 | 0.292 |
| Pay treatment (1 if yes, 0 otherwise) | 0.197 | 0.305 | 0.133 | 0.269 |
| One-time group training (1 if yes, 0 otherwise) | −0.319 | 0.238 | −0.279 | 0.230 |
| *Socioeconomic variables* | | | | |
| Age of respondent in years | | | 0.001 | 0.007 |
| Male household head (1 if yes, 0 if female) | | | 0.230 | 0.236 |
| Education (1 if literate, 0 otherwise) | | | −0.119 | 0.198 |
| Family size in adult equivalent | | | −0.105 | 0.044 |
| Number of livestock in tropical livestock units (TLU)[a] | | | 0.008 | 0.025 |
| Estimated coefficient of risk aversion | | | −0.082 | 0.067 |
| Corrugated roof (1 if yes, 0 otherwise) | | | 0.206 | 0.214 |
| Distance to all weather road in hours (two ways) | | | −0.104 | 0.119 |
| Randomly selected to participate in controlled cooking test (1 if yes, 0 otherwise) | | | 0.237 | 0.119 |
| *Cooking characteristics* | | | | |
| Frequency of stove use in period 4 | | | −0.051 | 0.031 |
| Uses stove for purposes other than baking (1 if yes, 0 otherwise) | | | −0.174 | 0.189 |
| Average number of *injera* baked at a time | | | 0.031 | 0.013 |
| Uses pure teff flour (1 if yes, 0 otherwise) | | | −0.404 | 0.349 |
| The stove is installed inside the house (1 if yes, 0 otherwise) | | | −0.204 | 0.231 |
| Constant | 0.408 | 0.279 | 0.545 | 0.535 |
| *N* | 310 | | 300 | |

*Notes:* Standard errors are clustered at the site level. Dependent variable is stove use, which is 1 if stove is still in use and 0 otherwise.
[a]TLU converts the different livestock types into one unit.

(2018). Average use per week was higher than two times per week in period 5, which is in line with regular usage. The data show an increase in average usage from period 1 to 2 ($p < 0.03$) and period 2 to 3 ($p < 0.01$), a decline from period 3 to 4 ($p < 0.08$) and a statistically insignificant increased usage from period 4 to 5 ($p < 0.26$). Average usage increased from period 1 to 5 ($p < 0.01$).[15]

[15]For households who did not abandon the stove in period 5, the percentage of households that used the stove at least twice per week in period 5 (52 per cent) was substantially higher than in period 1 (37 per cent).

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**Table 4.** Mean frequency of Mirt stove use per week by period and treatment

| | Pooled sample | Period 1 (June–August 2013) | Period 2 (August–October 2013) | Period 3 (March–May 2014) | Period 4 (May–July 2014) | Period 5 (Nov–Dec 2016) |
|---|---|---|---|---|---|---|
| 50 Birr use incentive (Incentive) | 2.30<br>(432) | 1.94<br>(91) | 2.24<br>(82) | 2.78<br>(100) | 2.24<br>(97) | 2.22<br>(62) |
| Paid 25 Birr (Pay) | 2.18<br>(447) | 1.57<br>(89) | 1.88<br>(91) | 2.59<br>(100) | 2.37<br>(96) | 2.52<br>(71) |
| Received stove for free (Free) | 2.61<br>(416) | 2.13<br>(91) | 2.48<br>(90) | 2.93<br>(93) | 2.80<br>(82) | 2.77<br>(60) |

*Notes:* Numbers of observations are reported in parentheses. For periods 1 to 4, the number of observations is for households with valid data for period 5. For period 5, the number of observations is for households who did not abandon the stove in period 5.

Table 5 presents household random effects probit regression coefficient estimates to examine whether treatments by period are related to regular stove use, which is defined as using the stove on average at least twice per week, with various temperature threshold definitions of cooking events (40°C, 45°C, and 60°C). We define use in terms of regular use to focus on adoption in the sense that households use the Mirt stove in accordance with normal *injera* baking frequency. Free Treatment period 5 is the omitted category.[16]

As a robustness check, we apply a Heckman selection model to analyze usage intensity after accounting for possible selection bias that may arise due to exclusion of those who do not use the stove (table 6). As an exclusion restriction, we include random assignment of a household to participate in controlled cooking tests as an explanatory variable only in the selection equation under the assumption that it does not affect cooking frequency. Tests of this exclusion restriction are shown in the online appendix, tables A2 and A3, where participation in controlled cooking tests is shown to be unrelated to regular usage. As demonstrated in table A5 (online appendix), participation in controlled cooking tests is positively related to whether the Mirt stove was used ($p < 0.01$). Tables 5 and 6 do not include details on socioeconomic and cooking characteristics, but these are included in tables A2 and A5 in the online appendix.

We find that for the 40°C definition of cooking events, estimates are statistically significant for Pay Treatment in periods 1 and 2 and Free Treatment in period 1. In all these cases the coefficient estimates are negative, suggesting that regular usage was generally higher for Free Treatment in period 5 compared with earlier periods. All other estimates are statistically insignificant. These results hold regardless of cooking event definition except that for the 45°C definition Incentive Treatment in periods 1 and 4 are also significant, but only at the 10 per cent level, and for the 60°C definition Free Treatment in period 1 is not statistically significant. Probit analysis with clustered standard errors at the site level for the 40°C definition shows similar results, except that Free Treatment in period 1 is statistically insignificant and Pay Treatment in period 2 is significant only at the 10 per cent level (online appendix table A3). A similar probit analysis only for period 5 with clustered standard errors at the site level shows that none of the treatments are statistically significant (online appendix table A4).

These results suggest some evidence of increased regular use over time, which we term persistence. This long-run persistence compared with early periods is similar to our previous results, which suggested that regular usage on average increased through period 4 for Free Treatment and also for Pay Treatment, which had very low regular usage in period 1 (Bluffstone *et al.*, 2021). Results from period 5 suggest that average usage leveled out, but there was little slippage in terms of regular usage.

We present the Heckman selection model, which adjusts for non-use of the stove, in table 6. Outcome and selection equations both include socioeconomic and cooking characteristics (table A5, online appendix). Results are generally similar to the random effects probit model. In the Heckman model, Incentive Treatment usage in periods 1 and 5 is lower compared with Free Treatment in period 5 ($p < 0.05$). Incentive Treatment usage in period 4 and Pay Treatment usage in period 1 are higher

[16]Clustered standard errors are not estimated with the random effects probit, as random effects are at the household level. As a robustness check, we estimated a probit model with household-level clustered standard errors and the results (in online appendices tables A3 and A4 for all periods and period 5 only) are similar to those in table 5.

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**Table 5.** Household level random effects probit model of regular use of Mirt stove (at least twice per week) with three cooking event thresholds (in degrees °C)

| Variable description | 40°C | 45°C | 60°C |
|---|---|---|---|
| Incentive treatment in period 1 (1 if yes, 0 otherwise) | −0.586<br>(0.389) | −0.651<br>(0.337) | −0.535<br>(0.330) |
| Incentive treatment in period 2 (1 if yes, 0 otherwise) | −0.261<br>(0.393) | −0.416<br>(0.342) | −0.114<br>(0.329) |
| Incentive treatment in period 3 (1 if yes, 0 otherwise) | −0.251<br>(0.385) | −0.467<br>(0.334) | −0.034<br>(0.319) |
| Incentive treatment in period 4 (1 if yes, 0 otherwise) | −0.344<br>(0.390) | −0.562<br>(0.337) | −0.244<br>(0.324) |
| Incentive treatment in period 5 (1 if yes, 0 otherwise) | −0.516<br>(0.417) | −0.082<br>(0.358) | 0.025<br>(0.339) |
| Pay treatment in period 1 (1 if yes, 0 otherwise) | −1.370<br>(0.399) | −1.477<br>(0.349) | −1.047<br>(0.339) |
| Pay treatment in period 2 (1 if yes, 0 otherwise) | −1.057<br>(0.391) | −1.205<br>(0.342) | −1.021<br>(0.337) |
| Pay treatment in period 3 (1 if yes, 0 otherwise) | −0.182<br>(0.383) | −0.393<br>(0.330) | −0.354<br>(0.318) |
| Pay treatment in period 4 (1 if yes, 0 otherwise) | −0.291<br>(0.385) | −0.645<br>(0.334) | −0.261<br>(0.319) |
| Pay treatment in period 5 (1 if yes, 0 otherwise) | −0.010<br>(0.408) | −0.313<br>(0.346) | −0.266<br>(0.335) |
| Free treatment in period 1 (1 if yes, 0 otherwise) | −0.762<br>(0.324) | −0.874<br>(0.293) | −0.444<br>(0.283) |
| Free treatment in period 2 (1 if yes, 0 otherwise) | −0.081<br>(0.316) | −0.303<br>(0.285) | 0.161<br>(0.274) |
| Free treatment in period 3 (1 if yes, 0 otherwise) | 0.213<br>(0.319) | −0.081<br>(0.286) | 0.148<br>(0.274) |
| Free treatment in period 4 (1 if yes, 0 otherwise) | −0.043<br>(0.328) | −0.316<br>(0.293) | 0.114<br>(0.282) |
| One-time group training (1 if yes, 0 otherwise) | −0.207<br>(0.225) | −0.237<br>(0.186) | −0.132<br>(0.178) |
| Socioeconomic variables | Yes | Yes | Yes |
| Cooking characteristics | Yes | Yes | Yes |
| Constant | −0.178<br>(0.716) | −0.049<br>(0.601) | −0.624<br>(0.574) |
| Observations | 1,244 | 1,242 | 1,242 |
| Number of households | 309 | 309 | 309 |

*Notes:* Standard errors in parentheses. Free treatment period 5 is the reference group.

than Free Treatment in period 5. Usage with other treatments and periods are not statistically significantly different from Free Treatment in period 5. Thus, the Heckman selection model generally shows longer-run persistence, but no other significant results.

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**Table 6.** Heckman selection model assuming 40°C definition of cooking events

| | Frequency of stove use per week (outcome equation) | |
|---|---|---|
| Variable description | Coefficient | Std. error |
| Incentive treatment in period 1 (1 if yes, 0 otherwise) | −0.016 | 0.008 |
| Incentive treatment in period 2 (1 if yes, 0 otherwise) | 0.063 | 0.269 |
| Incentive treatment in period 3 (1 if yes, 0 otherwise) | −0.058 | 0.172 |
| Incentive treatment in period 4 (1 if yes, 0 otherwise) | 0.212 | 0.067 |
| Incentive treatment in period 5 (1 if yes, 0 otherwise) | −0.062 | 0.028 |
| Pay treatment in period 1 (1 if yes, 0 otherwise) | 0.157 | 0.067 |
| Pay treatment in period 2 (1 if yes, 0 otherwise) | 0.081 | 0.207 |
| Pay treatment in period 3 (1 if yes, 0 otherwise) | −0.101 | 0.068 |
| Pay treatment in period 4 (1 if yes, 0 otherwise) | 0.809 | 0.315 |
| Pay treatment in period 5 (1 if yes, 0 otherwise) | 0.017 | 0.013 |
| Free treatment in period 1 (1 if yes, 0 otherwise) | −0.080 | 0.250 |
| Free treatment in period 2 (1 if yes, 0 otherwise) | −0.352 | 0.238 |
| Free treatment in period 3 (1 if yes, 0 otherwise) | −0.726 | 0.494 |
| Free treatment in period 4 (1 if yes, 0 otherwise) | −0.430 | 0.501 |
| One-time group training (1 if yes, 0 otherwise) | 0.343 | 0.655 |
| Socioeconomic characteristics | Yes[a] | |
| Cooking characteristics | Yes | |
| Constant | 1.832 | 0.720 |
| Observations | 1,246 | |
| Wald test of independent equations | Prob $> X^2 = 0.804$ | |

*Notes:* Standard errors are clustered at site level. Free treatment in period 5 is the reference group.
[a]Except participation in controlled cooking test, which is only included in the selection equation.

## 5. Discussion

Sustained use of improved technologies, such as biomass cookstoves, is critical to actually generating benefits from ICS promotion programs. Our results suggest that 3.5 years after receiving the stove, which is close to the expected 5-year lifespan, about 63 per cent of households covered by the survey still had their Mirt stoves in place, which appears to be quite high. Among those who still had their stoves, the average frequency of stove use in period 5 (i.e., 2016) is no different than the latter part of the first year (periods 3 and 4), but in several cases greater than shortly after initial distribution (periods 1 and 2). If users retain stoves as long as marginal benefits exceed marginal costs, these findings suggest that even after 3.5 years, the Mirt stove provides positive net benefits to users.

We find little systematic relationship between treatments and retention of the stove, which suggests that abandonment is due to reasons other than our randomized treatments. Based on our end line survey, the vast majority of those who dis-adopted their stoves report that it was because their Mirt stoves broke and therefore either became too

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inconvenient to use or could not be used at all. People therefore do not seem to have abandoned the Mirt stove simply because they did not like it.

Analysis of regular stove use, defined as use of the stove at least twice per week, suggests no differences across treatments 3.5 years after initial distribution. We acknowledge that our relatively small sample size in each period could mean we were simply unable to detect effects that actually existed, but that we were able to statistically identify effects with fewer observations over only one year (Bluffstone *et al*., 2021) gives us some confidence that indeed any treatment effects dissipated in the longer run.

We examine effects across time by treatment and find that between the two earliest periods and the end line, households who were randomly required to pay a monetary price for the stove show larger increases in regular usage, regardless of model or definition of cooking events (40°C, 45°C or 60°C). This result may simply be because Pay Treatment households initially on average used the Mirt stove so much less than those who randomly received the other two treatments. By period 5, average Pay Treatment usage was between the other two treatments.

## 6. Conclusions and policy implications

Achieving sustained, regular use of ICS technologies has been perhaps the major stumbling block for ICS promotion policies and programs. If households are not found to voluntarily regularly use improved stoves after distribution, those technologies cannot produce the benefits that were engineered into stoves, or perhaps after considering costs, benefits are not sufficient to warrant true adoption by households. This paper analyzes the extent to which the Mirt improved cookstove for baking *injera* continued to be regularly used by 360 randomly selected households in three regional states in rural Ethiopia, 3.5 years after it was distributed to them. We also examine if there are any lingering effects on stove usage of different monetary treatments commonly used in stove distribution programs (providing the stove for free, requiring a monetary payment and providing an incentive payment for stove use). The data come from a randomized field experiment begun in summer 2013.

The main conclusion of this paper is that households who randomly received the stove on average continued to regularly use it 3.5 years after distribution – about 70 per cent of the stove's expected life – unless it had broken.[17] This finding points to positive net benefits that users received from the stove, compared with exclusive use of the three-stone tripod for both *injera* baking and other cooking tasks. Over the longer-term period of stove use that we study in this paper, monetary treatments appear to be relatively unimportant. While requiring monetary payments from Pay Treatment users could potentially have created disgruntlement early-on, depressing usage, regular usage appears in the longer-run to be driven by factors other than our monetary treatments.

As the end of the Mirt stove life approaches, regular usage is similar across treatments and remains high. Persistent regular usage, combined with the reduction in fuelwood consumption and carbon emissions reported in Mekonnen *et al.* (2022), is likely to imply sustained benefits to households, as well as society at large through climate change mitigation benefits. These benefits are dependent on voluntary usage, which our analysis suggests continues into the long run. To ensure long-term use of Mirt stoves, it is

[17] Breakage after 3.5 years is not unexpected, but those promoting ICS need to explore ways to make their products sturdier or easier to repair, and to provide updated guidance to users about risks of breakage from incorrect use.

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important to have a plan on how to replace broken stoves. This could, for example, be done by direct replacement or by giving spare stoves to kebeles where broken stoves could be replaced.

Though over time the energy mix will shift to non-biomass fuels, the contemporary overwhelming dominance of biomass cooking fuels in Ethiopia suggests that ICS may be an important bridge technology and interim energy policy focus. As most households have chosen to regularly use Mirt for most of its useful life, the stove is low-cost and offers a variety of private and social benefits, policymakers should strongly consider investing more in the Mirt stove. It is unfortunate that the useful life of Mirt is only about five years, because with sometimes weak supply chains and rough roads, replacing stoves in rural Ethiopia can be a challenge. There are also recent developments to improve the technology to further reduce indoor air pollution. Policy and research attention should therefore at least partially focus on increasing durability or taking other steps to extend the expected stove life beyond the current five years.

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