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Early adoption of an improved household energy system in urban

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Abstract

Cooking with solid fuels and inefficient cookstoves has adverse consequences for health, environment, and human well-being. Despite the promise of improved cookstoves (ICS) to reduce these impacts, adoption rates are relatively low. Using a 2-wave sample of 144 households from the baseline and first midline of an ongoing 4-year randomized controlled trial in Rwanda, we analyze the drivers and associations of early adoption of a household energy intervention marketed by a private sector firm. Households sign an annual contract to purchase sustainably produced biomass pellets and lease a fan micro-gasification cookstove with verified emissions reductions in laboratory settings. Using difference-in-differences and fixed effects estimation techniques, we examine the association between take-up of the improved cooking system and household fuel expenditures, health outcomes, and time use for primary cooks. Thirty percent of households adopted the pellet and improved cookstove system. Adopting households had more assets, lower per capita total expenditures and cooking fuel expenditures, and higher per capita hygiene expenditures. Households with married household heads and female cooks were significantly more likely to adopt. Adjusting for confounders, we find significant reduction in primary cooks' systolic blood pressure, self-reported prevalence of shortness of breath, an indicator of respiratory illness, time spent cooking, and household expenditures on charcoal. Our findings have implications for marketing of future clean fuel and improved cookstove programs in urban settings or where stoves

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and fuel are purchased. Analysis of follow-up surveys will allow for estimation of long-term impacts of adoption of interventions involving pellets and fan micro-gasification cookstoves.

Keywords

Africa; Biomass; Charcoal; Cookstoves; Household air pollution

Introduction

Approximately three billion people use solid fuels and traditional technologies for cooking and heating (WHO, 2016). In Africa and Southeast Asia, over 60% of households are solid fuel users (Bonjour et al. 2013), and take-up of improved cookstoves (ICS) is persistently low (Lewis and Pattanayak, 2012). Household air pollution (HAP) resulting from using solid fuels in inefficient cooking technologies accounts for 3.7–4.8 million deaths according to WHO estimates, while the Global Burden of Disease (GBD) Study estimates between 2.2 million to 3.6 million deaths from HAP (Landrigan *et al* 2018). HAP-related preventable deaths include low birthweight and pneumonia among children, and non-communicable diseases such as stroke, ischaemic heart diseases, chronic obstructive pulmonary disease, and lung cancer among adults (Brook et al., 2010; Clark et al., 2012; Alexander et al., 2016; Giorgini et al., 2016; WHO, 2016). In low- and middle-income countries, HAP is the largest environmental risk factor for disease burden (Forouzanfar et al., 2015). In addition to health impacts, firewood for cooking is a leading cause of deforestation and environmental degradation (Hofstad et al., 2009; Kohlin et al., 2011), and black carbon from burning solid fuels is a major contributor to regional climate change (Ramanathan and Carmichael, 2008).

Though improved cooking technologies and clean fuels exist that are designed to reduce air pollution, adoption and sustained use in developing countries is a challenge. Systematic reviews focused on the state of knowledge of adoption of improved cookstoves find that higher education, income, household assets, and urban location increase uptake (Lewis and Pattanayak, 2012; Rehfuess et al., 2014). On the other hand, socially marginalized status (Lewis and Pattanayak, 2012), larger family size, costs associated with high-quality ICS, and requirements for processed or modern fuels to be used with ICS act as barriers to adoption (Rehfuess et al., 2014). Households that purchase instead of collect fuel are more likely to adopt an ICS, as money saving is a tangible benefit to households already paying for fuel. In the context of the enabling environment for ICS adoption, Puzzolo et al. (2013) find that success with early adopters, especially community opinion leaders, and characteristics of the stove and fuel are important determinants of adoption and sustained use, among other factors (e.g. providing loans for businesses producing and promoting ICS; developing an efficient and reliable network of suppliers).

ICS adoption studies are dominated by studies from rural settings. Specific to urban settings in Africa, Gebreegziabher et al., (2012) in urban Ethiopia find that household expenditure, household size, age and education of household head significantly explain household choice of the electric *mitad* stove, and Alem et al., (2013) find the price of electricity and firewood and credit access to be significant predictors of electric ICS adoption. Another study from

urban Ethiopia finds that ICS price, household income, and wealth (home ownership and separate kitchen) are significant determinants of *Mirte* and *Lakech* ICS adoption (Beyene and Koch, 2013). In urban Zambia, Tembo et al. (2015) reported that higher income residential area, lower household size, young household head, those with education levels above secondary school, and male-headed households are significantly more likely to use electricity as the sole source of energy. With respect to impacts, most rigorous ICS evaluation studies focus on health impacts (Ezzati and Kammen, 2002; Romieu et al. 2009; Clark et al. 2013; Mortimer et al. 2016), failing to consider a broader set of impacts, including socioeconomic and environmental outcomes (Bensch and Peters, 2012; Hanna et al., 2016).

Our study addresses the challenge of HAP in urban settings in sub-Saharan Africa (SSA) through examination of the determinants of early adoption of clean cooking solutions in Rwanda. We use the term ‘adoption’ to describe enrolment in the clean household energy program signified by signing of a contract with the firm marketing the household energy program. We focus on early adoption, meaning that household have relatively recently signed contracts with the private sector firm. Most households that ‘adopted’ (as per our definition), may not have exclusively switched to clean cooking. Throughout this paper, we use our definition of ‘adoption’ and ‘take-up’ (enrolment in the clean household energy program) interchangeably. In addition to explaining determinants of adoption as we have defined it, we explore initial associations with indicators of household health and well-being.

With a population density of 481.7 per square kilometer (United Nations Statistics Division, 2017), Rwanda is the most densely populated country in SSA. HAP is the fourth highest risk factor for disease burden in the country (Forouzanfar et al., 2015) and over 95% of the population relies on biomass for cooking (GACC, 2016). While the Rwandan government has been supportive of ICS projects, including promoting the locally produced clay stove, *Canarumwe* (Rayens, 2015), and the imported Tier 2 EcoZoom Dura ICS promoted through health centers by DelAgua Health, an environmental health technology firm that collaborates with governments in low income countries, the long-term impacts of these projects on improving health and well-being of household members, reducing particulate matter emissions and reducing biomass use are limited (Rosa et al., 2014; Kirby, 2017).

The private sector firm we study, *Inyenyeri*, is a for-profit fuel and ICS social enterprise, currently marketing renewable biomass fuel pellets and a fan micro-gasification stove to consumers in Gisenyi in western Rwanda. *Inyenyeri* is unique among household energy interventions in Rwanda, and in the region because (a) it is market-driven and customer service oriented, (b) it combines renewable energy fuel pellets with the currently best available biomass burning stove the Mimi Moto, which has been rated as an International Workshop Agreements (IWA) Tier 4 stove (GACC, 2015), (c) it focuses marketing efforts on both the incentives of household decision makers and cooks, and (d) the marketing model has been designed to be scalable and sustainable, with the objective of expansion throughout Rwanda and beyond.

Inyenyeri customers sign an annual contract to make a monthly purchase of renewable biomass pellets, while receiving the Mimi Moto stove at no additional cost on a lease basis.

Pellets are produced in a pelletizing factory on the shores of Lake Kivu from sustainably sourced biomass feedstock (e.g., small eucalyptus trees and branches, elephant grass, sawdust). *Inyenyeri* originally marketed to study participants using the Philips fan micro-gasification stove. For a variety of reasons, they transitioned to the Mimi Moto in early 2016 (Jagger and Das, 2018). When our baseline and midline data collections took place the structure of the marketing model was that customers had the option of signing up for 30, 45, or 60 kg of pellets per month, with the recommended quantity dependent on household size. The cost of each pellet package is 6,000, 9,000, and 12,000 Rwandan Francs (RWF) (7.80, 11.70, and 15.60 USD), respectively. Depending on the fuel-pellet package that households purchase, they received 1 (30 kg), 2 (45 kg), or 3 (60 kg) stoves. The current marketing model as of early 2018 is a fully pay-as-you-go system. As part of their business model, *Inyenyeri* offers free delivery, training, repairs, and replacement of stoves. For a detailed discussion of Inyenyeri's pilot activities and lessons learned between 2012 and 2017, as well as an overview of the study timeline see Jagger and Das (2018).

In this paper we examine the determinants of early adoption of the firm's improved household energy system among 144 households, and the initial associations of this program with household fuel expenditures, primary cooks' health and time use [1], 8 months after intervention. Our hypothesis is that among households that adopt *Inyenyeri*'s system, household expenditures on cooking fuel are lower, prevalence of health symptoms are reduced, and less time is spent cooking.

Methods

Study Design

Our analysis leverages data from a sub-sample of households from a large and ongoing household-level randomized controlled trial designed to evaluate the exposure, health, and welfare impacts of *Inyenyeri's* household energy system for a sample of 1,462 urban households in Gisenyi, Rwanda. The impact evaluation consists of a baseline survey (June 2015), two midline [midline1 (June 2016) and midline2 (June 2017)] surveys involving a sub-sample of 180 households, and an endline (scheduled for October 2018) survey on the full sample. The study takes place in 22 purposively selected neighborhoods in two cells (Bugoyi and Kivumu) of Gisenyi town in Rubavu District. Our surveys included structured household decision maker and primary cook questionnaires to collect socioeconomic and demographic data; information about all aspects of cooking and fuel use in the household; knowledge and preferences on stoves and fuels; knowledge and mitigation strategies for coping with the varied impacts of HAP, and customer experiences with *Inyenyeri.*

Sampling

The population of neighborhoods under consideration included *Inyenyeri's* existing and potential new urban markets in close proximity to the firm's two main retail locations. The sampling frame for the study comprised the population of households (N=2,354). Households that were existing customers of the firm were removed from the sampling

[1]Time spent on various activities (domestic chores, agriculture/livestock/fisheries and other) over the seven days prior to the survey.

frame. Using a random number generator, each household head was assigned a random number. The first 1,500 households were selected as the study population, and the remaining households in the final sampling frame were designated as replacement households. Two-thirds of the 1,500 selected households were randomly assigned to the intervention group (treatment), and the remaining one-third of households were assigned the delayed-entry control group.[2] A total of 1,462 households were surveyed at baseline.

A sub-sample of 180 households was randomly selected from the sample of 1,462 households for the comprehensive midline1 and midline2 Health, Poverty and Cooking (HPC) surveys. The subsample was originally split using the same ratio of treatment to control as the larger sample (2:1). After the baseline survey, completed in September 2015, the firm began marketing stoves to all households in the treatment group. Due to concerns about low take-up rates, the 60 control group households in our sub-sample were re-categorized as treatment and marketed to by Inyenyeri prior to the midline1 data collection.[3], [4] After midline1 we were only able to verify that 144 households had contact with *Inyenyeri,* thus, because we focus on the average treatment effect (ATE), the our sample for this analysis is 144 households.

Household, Poverty and Cooking Survey (HPC)

The midline1/midline2 HPC is a shortened version of the full baseline/endline questionnaire. Modules include: household roster; education; assets; housing and cooking infrastructure, facilities and access to services; perceptions of fuels and cooking technologies and their impacts; risk and time preferences and social capital; health of family members and primary cook; time use for household members and primary cook; and cook history (e.g., duration as primary cook and experience with cooking). Modules on adoption and sustained use were added to the midline1 HPC to learn about respondents' experiences with the firm and the design of the marketing model.

Attrition from our sample between baseline and midline1 was a challenge as is common in urban-based longitudinal surveys. At midline1, we were able to collect data from 115 baseline households. Sixty-five households had to be replaced, because they had either moved outside the study area or were not available to be interviewed.[5] The 65 replacement households were drawn at random from the 435 baseline delayed-entry control households. The sample for the analysis in this paper includes 144 of the 180 sub-sample households where the firm conducted their door-to-door marketing after our baseline survey was concluded in September 2015. In 91 of the 144 households (63%), we were able to interview

[2]A household was excluded from the sample if (a) the main respondent and/or the primary cook refused; (b) the primary cook was less than 15 years old; (c) no cooking was done in the household; (d) the household was currently using or had previously used an improved stove such as the Philips gasifying stove; (e) a sampled household was in the same plot as another that has already been surveyed; and (f) the village chief, key people in the village (such as community health worker) or neighbors had no information about the household sampled. If there was a new household residing in the same plot as the sampled household, and the original inhabitants listed in the sampling frame had moved to a different location, the survey was conducted with the new household.

[3]Households were contacted by arranging appointments and making home visits to demonstrate the ICS and biomass pellets combination.

[4]Personal and area exposure monitoring of carbon monoxide, particulate matter 2.5, and polycyclic aromatic hydrocarbons was conducted at baseline, midline1, and midline2, and is planned for endline for the the sub-sample of 180 households.

[5]Attritor households are renters and households with ties to other regions of Rwanda or the Democratic Republic of Congo (i.e., more likely to move out of the study area), and households with several people engaged in daytime employment (i.e., more likely to be difficult to locate or schedule an interview with).

the same primary cook at baseline and midline1. Tracking individuals over time is important for understanding health impacts, but also mitigating confounding that can occur when a household transitions from one primary cook to another.

Analysis

A logit model (Eq. 1) was used to estimate the relationship between socio-economic determinants of the household and adoption of the improved household energy system in Midline1:

$$P_r(Y_j = 1 \mid X) = \left[1 + e^{-(\beta_0 + \beta_1 Household\ characterstics + \beta_2 Primary\ cook\ charactersticks + \beta_3 Household\ head\ characterstics + \varepsilon_j)}\right]^{\wedge} - 1 \quad (1)$$

where Y_j denotes signing a contract for household *j* and ε_j is the error term. Household-level characteristics included household size; stove used in the 30 days prior to baseline survey; number of durable goods[6]; ownership of land; and log of per capita total expenditures, cooking fuel expenditures, hygiene expenditures (in the 4 weeks prior to baseline survey). We included binary indicators for whether the primary cook was hired and female. For the characteristics of the household head, we considered age, sex, education level, whether s/he thought that some stoves and fuels produce less smoke than others, and whether household head was aware of the environmental health impacts of cooking with biomass.

Second, to assess the average treatment effect (ATE) of *Inyenyeri*'s household energy system on household expenditures, we used the following model (Eq. 2):

$$Y_{jt} = \beta_0 + \beta_1 Contract_j + \beta_2 Time_t + \beta_3 Contract * Time + \delta_i + \alpha_j + \varepsilon_{jt} \quad (2)$$

where Y_{jt} denotes cooking fuel expenditures or charcoal expenditures for household *j* at time *t*, $Contract_j$ is an indicator that equals 1 if household *j* signed a contract with *Inyenyeri*, $Time_t$ equals 1 if time period is midline1, and β_3 is the ATE estimator, or the effect of signing a contract with *Inyenyeri*. δ_i are individual-level controls, α_j are household-level confounding variables, and ε_{ij} is the error term.

[6]The following were the durable goods/assets considered in this analysis: living room suite, refrigerator, freezer, radio, TV set, satellite dish, cooker, video/DVD player, computer and accessories, music system, electric fan, air-conditioner, sewing machine, bed, cupboard/bookcase, table-chair, car, motorcycle (for home use only) and bicycle (for home use only). Our asset variable is a simple count of assets each household owns.

Third, to assess the average treatment effect (ATE) of *Inyenyeri*'s household energy system on primary cooks' blood pressure[7], and time use, we used the following model (Eq 3):

$$H_{ijt} = \beta_0 + \beta_1 Contract_j + \beta_2 Time_t + \beta_3 Contract * Time + \delta_i + \alpha_j + \varepsilon_{ijt} \quad (3)$$

where H_{ijt} denotes blood pressure, or time use for primary cook *i* in household *j* at time *t,* and the remaining variables are the same as in Equation 2.

Fourth, to assess the ATE of *Inyenyeri*'s household energy system on binary indicators of self-reported health symptoms of primary cooks, we used the following model (Eq. 4):

$$P_r(H_{ijt} = 1 \mid X) = [1 + e^{-(\beta_0 + \beta_1 Contract_j + \beta_2 Time_t + \beta_3 Contract * Time + \Omega_i + \alpha_j + \varepsilon_{ijt})}]^{\wedge} - 1 \quad (4)$$

where H_{ijt} denotes health symptom for primary cook *i* in household *j* at time *t,* and the remaining variables are the same as in Equation 2.

In equations 1-3, we use robust standard errors and in equation 4, we use bootstrapped standard errors.

The key variable of interest is β_3, which provides the difference-in-differences (DiD) in the outcome with respect to signing a contract with the firm. Since contract signing was a choice, the interpretation of β_3 in the models above are unlikely to be causal since unobserved (to the researcher) factors could determine both stove take-up and the outcomes (e.g., innate ability or superior information-processing skills of household members). To account for this, we also estimated household fixed effects (FE) models for all outcomes, which eliminate time-invariant unobserved differences across households, which are likely to be the main source of endogeneity in this context.[8] Estimates from these models are more likely to provide an estimate of the causal effect of signing a contract on the outcome of interest.

Results

Implementation of the improved household energy program

Inyenyeri's marketing campaign, launched in September 2015 immediately after the completion of our baseline data collection, consisted of several targeted strategies: (1) marketing using billboards and radio programs with core messages such as "cook fast", "stay clean", "life made easy", and "always the cheapest fuel"; (2) village-level cooking

[7]We took three consecutive measurements of primary cooks' blood pressure after the cook had been at rest for at least 20 minutes. We used the Omron 5 Series blood pressure monitor which has been validated for measurement of blood pressure according to European standards (Topouchian et al. 2011). Enumerators received focused training on how to use electronic blood pressure measurement instruments. For our analysis, we use the average of the three measurements.

[8]We conducted the Breusch-Pagan and Hausman tests to test for differences between the pooled ordinary least squares (OLS), fixed effects (FE) and random effects (RE) model, and report results where coefficients are significantly different.

demonstrations; and (3) door-to-door visits from Customer Service Representatives (CSRs) to explain the contract model and conduct in-home cooking demonstrations.

From our midline1 survey, we observed that 81.9% of households indicated that they had heard of *Inyenyeri*. The majority of households had seen *Inyenyeri* billboards (83%), learned about the firm from friends (81.4%), and had been visited by a customer service representative (72.7%). A smaller percentage attended village cooking demonstrations (49.2%), and/or heard an *Inyenyeri* radio program (22.9%). Adoption (i.e., households that signed contracts with the firm) was 29.9% at midline1. Contract-signing households, generally had two ICS (i.e., opted to sign up for the firm's mid-range pellet package).

To assess the extent to which household's adoption the household energy system made a partial or total switch to using pellets and the fan micro-gasification stove we collected detailed information on the share of meals cooked during the past 30 days on various technologies (Figure 1). Households that adopted the *Inyenyeri* system appeared to be replacing cooking on both portable and fixed charcoal stoves with the biomass pellet and fan micro-gasification stove combination.[9] However, even among adopter households, there was evidence of stove stacking; households continued to use pre-existing technologies for a large share of cooking events. For the midline1 HPC survey, households were also asked to recall what technologies and fuels they used to cook each meal over three days immediately prior to the survey. Households that had adopted the *Inyenyeri* household energy system reported using the fan micro-gasification stove for 3.5 out of nine possible cooking events during the past three days. For both of these subjective measures of stove use, fuel use perfectly corresponded to stove use; households using forced-air gasifier stoves reported using them only with biomass pellets.

Motivators and barriers to adoption of *Inyenyeri*'s improved household energy program

We observed that on average, households had 6 members, 7.4 durable goods/assets, and fixed charcoal stoves were the most used cooking technology (Table 1). Per capita total expenditure in the four weeks prior to the baseline survey was approximately 57,797 RWF (75.14 USD), of which cooking fuel expenditure was 2,633.7 RWF (3.42 USD), and hygiene expenditure[10] was 2,607.2 RWF (3.39 USD). Over 32% of households hired a cook, 78% cooks were female and 29% households had a female household head. The average age of household head was 48 years, 66% were married, and over 57% were educated at the secondary level and above. Over 65% household heads had heard of the negative impacts of cooking with biomass and more than 87% perceived some fuels and stoves to be less smoke-producing than others. Households that adopted the *Inyenyeri* system had significantly more durable household goods (8.7) than non-adopters (6.9), higher per capita hygiene expenditures (3,678.5 RWF (4.78 USD) compared to 2,151.1 RWF (2.80 USD) of non-adopters), and more married household heads (83.7%) than non-adopters (59.4%). Weak statistically significant differences were observed between adopter and non-adopter

[9]Anecdotal evidence gathered from the firm's customer service representatives suggest that the decision to change from the Philips stove to the Mimi Moto affected take-up of the household energy system.

[10]These expenditure items included broom/brush, sponge, shoe brush and polish, disinfectant and cleaners, laundry services, rubbish collection services, and wages for household domestic help.

households on hired primary cooks and female household heads, but on other independent variables, there were no significant differences.

In our first logistic regression model (Table 2), we did not consider perceptions of the household main decision maker on the health, environmental and climate impacts of reliance on biomass for cooking, but included their perceptions about some stoves and fuels being less smoke-producing than others. The second regression model included variables indicative of main decision maker's level of awareness about health, environmental and climate impacts.

We observed that households with more durable goods, high per capita hygiene expenditures, and female primary cooks were significantly more likely to adopt stoves (p=0.05).

Per capita total expenditures and per capita fuel expenditures had statistically significant weak negative association with likelihood of adoption of *Inyenyeri*'s system (p=0.10). On including variables about awareness of health, forest and climate impacts, we found that where household heads had knowledge of the health impacts for cooks and children from cooking with biomass on traditional stoves, households were more likely to adopt the new household energy system (p=0.10). However, awareness of the environmental impacts of cooking with charcoal and other unsustainably harvested biomass was associated with significantly lower likelihood of adoption of the *Inyenyeri*'s system (p=0.05).

Association between the improved household energy program, health and well-being

Health of primary cooks—We observed a high prevalence of shortness of breath among primary cooks at baseline (44.1%), followed by burns (18.9%) and night phlegm (9.1%). The average systolic blood pressure among primary cooks was 120.6 mmHg and average diastolic blood pressure was 78.3 mmHg (Table 1). We restricted our sample to households with the same primary cook at baseline and midline1 (N=91). Our first empirical strategy was to investigate the differences in the means between the prevalence of health symptoms at baseline and midline1. Among self-reported health symptoms where we observed statistically significant differences (reductions in prevalence of burns, night phlegm, shortness of breath and blood pressure), we estimated the ATE of adoption of the household energy system (Table 3).[11] In the household FE model, we observed a statistically significant decreased prevalence of shortness of breath (p=0.01) and decrease in systolic blood pressure (p=0.10) in primary cooks among households that adopted the *Inyenyeri* household energy system. Diastolic blood pressure also decreased, although this decrease was not statistically significant.

There were no significant differences between the two groups of households on other dependent variables with the exception of time spent in other activities where the mean was significantly higher among non-adopters (1.9 versus 0.7 h).

[11]The Breusch-Pagan and Hausman tests between pooled OLS and RE, and pooled OLS and FE, respectively, for blood pressure indicate that the pooled OLS model is inappropriate. The Hausman test indicates significant differences between FE and RE estimates only for night phlegm and shortness of breath, suggesting unobserved heterogeneity.

Household fuel expenditures—The *Inyenyeri* model is designed to be less expensive, or at least directly equivalent to cooking with charcoal. On average, households purchased cooking fuel worth 12,480 RWF (16.22 USD) during the four weeks prior to the survey, of which 11,431 RWF (14.86 USD) were on charcoal (Table 1). We assessed the association between adoption of the *Inyenyeri* household energy system and overall fuel expenditures, specifically charcoal expenditures (Table 4). We observed no statistically significant relationship between adoption and overall cooking fuel expenditures. However, we observed a strong statistically significant reduction in expenditures on charcoal (p=0.01) in the fixed effects model, which accounts for unobserved differences between those who signed a contract and those who did not.[12] Specifically, the pattern of results suggest that those who signed a contract had higher pre-contract charcoal expenditures than those who did not sign a contract.

Time use of primary cooks—As expected, cooks at baseline spent most of their time in the past 7 days cooking (22.7 h), followed by childcare and cleaning (15.4 h) and non-agricultural activities (4.9 h) (Table 1). In keeping with our hypothesis, we found a statistically significant negative association between adopting the improved household energy system and time spent cooking (p=0.05) in the FE model (Table 5).[13] We did not find significant changes in time spent on any other activity.

Discussion

Our study finds an adoption/take-up rate of 30% for the pellet/fan micro-gasification improved household energy system, which is one-third the adoption rate reported by Barstow et al. (2014) for the EcoZoom Dura ICS, in Rwanda's Western Province. However, unlike the more sustainable *Inyenyeri* business model, the DelAgua program provided free distribution of ICS and water filters and [unsuccessfully] sought to earn carbon credits from verified reduced use of fuelwood (Barstow et al., 2014).

Our analysis of the determinants of early improved household energy adoption is consistent with findings from Rehfeuss et al. (2014) indicating that households that are significantly more likely to adopt are those with higher assets, married household heads, female cooks, and where the household head is aware of the negative impacts of traditional cooking methods on human health. Though knowledge of the negative impacts of biomass on local air quality has no significant association with ICS and clean fuel adoption, the negative sign of the coefficient is perhaps indicative of households' lower valuation of the environment and climate compared to health. These findings have implications for the target group for future interventions and messaging of ICS programs. Similar to Barstow et al.'s (2016) study that did not find any association between household size and stove stacking behavior, we observed no significant relationship between number of household members and improved energy adoption. Unlike Gebreegziabher et al. (2012) and Tembo et al. (2015),

[12]While there were significant differences between the pooled OLS, and FE and RE estimates, the FE and RE estimates were not significantly different for charcoal expenditures.

[13]The Breusch-Pagan and Hausman tests between pooled OLS and RE, and pooled OLS and FE, respectively, for time spent in all activities except labor and other activities, show significant differences. Among all activities, the Hausman test indicates significant differences between FE and RE estimates for time spent in cooking and childcare activities.

who undertook ICS adoption studies in urban settings in Ethiopia and Zambia respectively, we did not find any significant association between overall household expenditure, age, sex, or education of household head and improved energy adoption. Our findings should be framed in the context of the location where the study took place. Cooking needs may vary between sites (e.g. cooking of injera in Ethiopia vs. maize meal in Zambia, or dominance of one staple vs. preferences for multiple staples with different cooking requirements as in Rwanda), influencing take-up of new ICS. We also emphasize that the evidence base is very limited for ICS adoption in urban settings in Africa, making it difficult to generalize.

We note that in the months immediately following intervention roll-out, *Inyenyeri* had only 1-5 tons of pellets in stock owing to problems with their pelletizing equipment, which limited their ability to market aggressively, aggressively to new customers (Jagger and Das, 2018), thereby affecting adoption in our study. Thurber et al. (2015) noted similar supply chain concerns (increases in costs of raw materials) with bagasse[14] feedstock inputs for pellets, that wore out *Oorja's* value proposition compared to stove alternatives, particularly LPG, over time.

As our study is powered on an expected take-up of ~60%, our ability to detect reductions in health symptoms or economic impacts is limited due to a low ICS and clean fuel take-up rate of approximately 30% in our sample of 144 households, and by our sample size (N=91) for primary cooks we are able to track during the first two years of our study. The simultaneous use of other cooking technologies is another plausible reason for not observing significant reductions in total cooking fuel expenditures and primary cooks' time spent cooking. Because our data were collected in the same season in each of the two years that we cannot reflect on seasonal variation and health or economic impacts.

Based on Beyene and Koch's (2013) finding that adoption rates of ICS in urban Ethiopia increased over time, and Barstow et al.'s (2016) finding that rural households in Rwanda reduced their use of stoves other than the EcoZoom Dura ICS by 20% over the duration of their study, we are hopeful that we may see reductions in stove stacking behavior in subsequent follow-up surveys. Additionally, it is important to compare stove use data from surveys and electronic sensors[15], as studies from Rwanda show lower ICS use from sensors compared to surveys (Thomas et al., 2013).

Although adopter households continue to use charcoal stoves alongside newly introduced fan micro-gasification stoves, there were significant reductions in their charcoal expenditures in the four weeks prior to the survey. This finding is aligned with the firm's rationale of pricing the biomass pellets competitively with charcoal, with the aim of replacing it in the long-run. Those who signed contracts also showed a significant reduction in time spent cooking, most of which was subsequently devoted to non-agricultural activities although the effect on the latter was not statistically significant.

[14]Bagasse is the dry pulpy residue left after the extraction of juice from sugar cane, it is commonly used as fuel for electricity generators.

[15]Our study also collected objective data on stove use using temperature loggers (Stove Use Monitoring System-SUMS). Analysis from the same will be published separately.

Conclusion

The analysis of the first two rounds of data collected for a large household energy randomized controlled trial aims to shed light on the determinants of early adoption and associations between adoption and indicators of health and well-being of an improved household energy system. Our study is set in western Rwanda, in sub-Saharan Africa, a region with limited ICS intervention studies, particularly in urban settings. We found considerable influence of sociodemographic variables on household adoption of the improved energy system, and evidence of improvements in health and time use for primary cooks, and significant reduction in monthly charcoal expenditures for households. We acknowledge that these results from our ongoing study have limitations. First, we use a small sample of 144 households from our full sample of 1,462 households where we collect repeated measurements between baseline and endline, to detect impacts of a private sector initiative promoting sustainability produced biomass pellets in tandem with fan micro-gasification stoves. Second, the time lag between the intervention roll out and follow-up survey (8 months) is insufficient to see high uptake and substantial impacts on many of the variables we are collecting data on. Third, the potential effects of the stove if used exclusively could not be assessed in this study given widespread concurrent use of charcoal in the adopting households.

We will continue to track these 144 households in subsequent surveys prior to endline, in order to ascertain the determinants and impacts of late adopters compared with early adopters. Data from our endline survey with the full sample of 1,462 households will enable us to better understand cost and time savings, and potential health improvements from adoption of the *Inyenyeri* household cooking energy system over a two-year timeframe, and allow us to make stronger causal claims about the effect of stove use *per se* on these outcomes.

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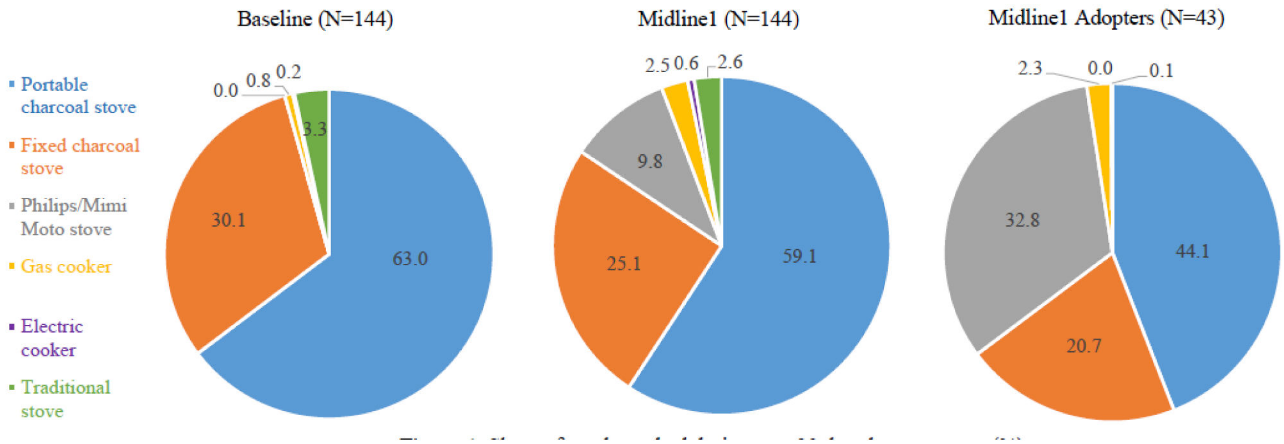

Figure 1.
Share of meals cooked during past 30 days by stove type (%)

Table 1.

Summary Statistics: Baseline Results (N=144)[ɫ]

	Total (N=144)	Adopters (N=43)	Non-Adopters (N=101)	Diff. in means	p-value
A. Dependent Variables					
Household fuel expenditures (in RWF): past 4 weeks					
Cooking fuel purchased	12,479.9 (6,775.0)	13,234.9 (6,332.0)	12,158.4 (6,960.6)	1076.47	0.36
Charocal purchased for cooking	11,430.6 (5,734.7)	12,558.1 (5,183.8)	10,950.5 (5,912.9)	1607.64	0.10
Primary cooks' health symptoms: past 12 months					
Burns (%)	18.9	20.9	17.8	0.03	0.67
Night phlegm (%)	9.1	4.7	10.9	−0.06	0.17
Shortness of breath (%)	44.1	48.8	41.6	0.07	0.43
Average systolic blood pressure (mmHg)	120.6 (16.1)	119.0 (13.7)	121.2 (17.0)	−2.24	0.40
Average diastolic blood pressure (mmHg)	78.3 (10.4)	78.7 (9.0)	78.1 (11.0)	0.53	0.76
Primary cooks' time use (in hours): past 7 days					
Cooking-related activities	22.7 (10.7)	24.0 (9.6)	22.1 (11.1)	1.82	0.32
Childcare and household cleaning	15.4 (17.4)	19.1 (19.2)	13.8 (16.4)	5.35	0.11
Non-agricultural activities	4.9 (15.4)	3.3 (12.5)	5.6 (16.5)	−2.32	0.35
Wage labor	2.2 (9.9)	4.2 (12.8)	1.4 (8.3)	2.84	0.18
Casual or day labor	1.2 (8.5)	0.2 (1.5)	1.7 (10.0)	−1.43	0.16
Other activities (firewood collection, water collection etc.)	1.5 (4.7)	0.7 (2.2)	1.9 (5.4)	−1.16	0.07*
B. Independent Variables					
Household characteristics					
Total number of members (mean)	6.0 (2.6)	6.4 (2.2)	5.8 (2.7)	0.61	0.16
Stove used in the past 30 days (%)					
Portable charcoal stove	6.3	2.3	7.9	−0.06	0.12
Fixed charcoal stove	63.6	65.1	62.4	0.03	0.76
Traditional three-stone fire	30.1	32.6	29.7	0.03	0.74
Number of durable goods (mean)	7.4 (3.0)	8.7 (2.5)	6.9 (3.0)	1.77	0.00***
Ownership of any land (%)	19.6	23.3	17.8	0.05	0.47

	Total (N=144)	Adopters (N=43)	Non-Adopters (N=101)	Diff. in means	p-value
Per capita hygiene expenditure in last 4 weeks (in RWF)	57,797.2 (38,400.4)	62,306.3 (36,486.7)	55,877.5 (39,205.4)	6,428.87	0.34
Per capita hygiene expenditure in last 4 weeks (in RWF)	2,607.2 (2,610.5)	3,678.5 (3,399.8)	2,151.1 (2,046.1)	1,527.37	0.01**
Primary cook characteristics					
Hired (%)	32.9	44.2	28.7	0.16	0.08*
Female (%)	77.6	81.4	75.2	0.06	0.40
Household head characteristics					
Female (%)	29.4	18.6	33.7	−0.15	0.05*
Age in years (mean)	47.9 (13.8)	47.7 (11.4)	48.1 (14.8)	−0.38	0.87
Married (%)	66.4	83.7	59.4	0.24	0.00***
Education at secondary and above level (%) Ever heard about cooking practices	57.3	55.8	58.4	−0.03	0.77
Ever heard about cooking practices					
negatively impacting own health and health of young children (%)	65.7	69.8	63.4	0.06	0.45
Ever heard about cooking practices negatively impacting forests (%)	70.6	65.1	73.3	−0.08	0.34
Ever heard about cooking practices negatively impacting local air quality (%)	69.2	69.8	69.3	0.01	0.96
Think that some stoves produce less smoke than others (%)	88.1	90.7	87.1	0.04	0.52
Think that some fuels produce less smoke than others (%)	87.4	90.7	86.1	0.05	0.42

ⱡ Standard deviation in parentheses for continuous variables

Table 2.

Logit regression analyses for association between contract-signers and socio-demographics of household at baseline

Dependent variable:	Contract signed	Contract signed
Explanatory variables		
Household characteristics		
Total number of members	−0.02 (0.10)	−0.01 (0.11)
Stove used in the past 30 days: baseline		
Portable charcoal stove	2.06 (1.28)	1.98 (1.29)
Fixed charcoal stove	1.73 (1.29)	1.59 (1.29)
Number of durable goods	0.23** (0.11)	0.23** (0.11)
Own any land	−0.22 (0.60)	−0.27 (0.70)
Log of per capita total expenditure in last 4 weeks (in RWF)	−1.04* (0.61)	−1.07* (0.55)
Log of per capita cooking fuel expenditure in last 4 weeks (in RWF)	−0.29 (0.19)	−0.31* (0.18)
Log of per capita hygiene expenditure in last 4 weeks (in RWF)	1.00*** (0.36)	1.11*** (0.37)
Primary cook characteristics		
Hired	0.85 (0.58)	0.94 (0.59)
Female	1.28** (0.56)	1.07** (0.52)
Household head characteristics		
Female	−0.17 (0.69)	0.01 (0.62)
Age (in years)	0.01 (0.02)	0.00 (0.02)
Married	0.97 (0.64)	1.09* (0.64)
Secondary and above education level	−0.37 (0.46)	−0.34 (0.45)
Think that some stoves produce less smoke than others	−1.03 (1.26)	
Think that some fuels produce less smoke than others	1.08 (1.22)	
Ever heard about cooking practices negatively impacting own health and health of young children		1.10* (0.65)
Ever heard about cooking practices negatively impacting forests		−1.60** (0.74)
Ever heard about cooking practices negatively impacting local air quality		−0.09 (0.60)
Constant	−0.56 (5.59)	−0.33 (5.28)

Dependent variable:	Contract signed	Contract signed
Observations	144	144
Adjusted R-squared	0.20	0.23

Robust standard errors in parentheses.

*** p<0.01,

** p<0.05,

* p<0.1

[1.] Traditional stoves is the referent category for 'stove used in the past 30 days: baseline'.

[2.] TVET and levels below (primary, pre-primary and no education) is the referent category for 'secondary and above education level of household head'.

Table 3.

Regression analysis for health symptoms of primary cooks (past 12 months)[1,2,3]

Dependent variables:	**Burns**	**Night phlegm**	**Shortness of breath**	**Systolic BP**	**Diastolic BP**
DiD coefficient (treatment effect)	−1.64 * (0.96)	−0.37 (7.95)	−1.80 ** (0.86)	−3.32 (5.21)	−2.37 (3.21)
FE coefficient	0.00 (0.10)	0.00 (0.09)	−0.41 *** (0.12)	−5.44 * (2.93)	−3.00 (2.24)
Observations	182	182	182	182	182

Robust standard errors in parentheses.

*** $p<0.01$,

** $p<0.05$,

* $p<0.1$

1. Household characteristics controlled for: household size, baseline stove used in past 30 days, number of durable goods, ownership of land, log of per capita baseline total expenditure in last 4 weeks (in RWF), log of per capita baseline cooking fuel expenditure in last 4 weeks (in RWF), log of per capita baseline hygiene expenditure in last 4 weeks (in RWF). Traditional stoves is the referent category for 'stove used in the past 30 days: baseline'.

2. Primary cook characteristics controlled for: hired, female. Household head characteristics controlled for: female, age (in years), married, secondary and above education level. TVET and levels below (primary, pre-primary and no education) is the referent category for 'secondary and above education level of household head'.

3. The sample is truncated to 91 primary cooks only who were present at baseline and midline1 data collection rounds.

Table 4.

Regression analysis for cooking fuel expenditures (in RWF): past 30 days1,2

Dependent variables:	Cooking fuel purchased	Charcoal purchased for cooking
DiD coefficient (treatment effect)	0.28 (0.39)	−1.02* (0.60)
FE coefficient	0.08 (0.38)	−1.23*** (0.44)
Observations	288	288

Robust standard errors in parentheses.

*** $p<0.01$,

** $p<0.05$,

* $p<0.1$

1. Household characteristics controlled for: household size, baseline stove used in past 30 days, number of durable goods, ownership of land, log of per capita baseline total expenditure in last 4 weeks (in RWF), log of per capita baseline cooking fuel expenditure in last 4 weeks (in RWF), log of per capita baseline hygiene expenditure in last 4 weeks (in RWF). Traditional stoves is the referent category for 'stove used in the past 30 days: baseline'.

2. Primary cook characteristics controlled for: hired, female. Household head characteristics controlled for: female, age (in years), married, secondary and above education level. TVET and levels below (primary, pre-primary and no education) is the referent category for 'secondary and above education level of household head'.

Table 5.

Regression analysis for total time of primary cooks spent on activities (past 7 days)[1,2,3]

Dependent variables:	Cooking	Childcare and cleaning	Non-agricultural activities	Wage labor	Casual or day labor	Other
DiD coefficient (treatment effect)	−3.41 (2.96)	−3.44 (5.35)	3.74 (5.11)	−2.74 (3.56)	−0.23 (0.65)	1.19 (0.82)
FE coefficient	−4.86** (2.20)	0.21 (3.59)	2.17 (3.29)	−0.93 (2.35)	0.00 (1.10)	0.14 (0.91)
Observations	182	182	182	182	182	182

Robust standard errors in parentheses.

*** $p<0.01$,

** $p<0.05$,

* $p<0.1$

1. Household characteristics controlled for: household size, baseline stove used in past 30 days, number of durable goods, ownership of land, log of per capita baseline total expenditure in last 4 weeks (in RWF), log of per capita baseline cooking fuel expenditure in last 4 weeks (in RWF), log of per capita baseline hygiene expenditure in last 4 weeks (in RWF). Traditional stoves is the referent category for 'stove used in the past 30 days: baseline'.

2. Primary cook characteristics controlled for: hired, female. Household head characteristics controlled for: female, age (in years), married, secondary and above education level. TVET and levels below (primary, pre-primary and no education) is the referent category for 'secondary and above education level of household head'.

3. The sample is truncated to 91 primary cooks only who were present at baseline and midline1 data collection rounds.