Adoption and Use of Liquified Petroleum Gas for Household Cooking in Rwanda

By

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Abstract

Nearly all of Rwanda's population relies on burning high polluting fuels, such as charcoal or fuelwood, for cooking their meals. Household air pollution (HAP) from burning these fuels leads to severe health conditions and is one of the leading causes of premature death in Africa, and the collection and burning of woodfuels leads to forest degradation and has climate change implications. Using data from a randomized control trial studying the uptake of biomass pellet gasification stoves in urban Rwanda, I asses the determinants of the transition from cooking with solid fuels to Liquified Petroleum Gas (LPG) with a set of regression models. In our sample we see a rapid transition occurring from 2015, when only 5% of households are using LPG at all, to 2020 when 36% of households are cooking with LPG. I find that survey respondents with higher education levels have a much higher likelihood to adopt LPG, higher asset wealth is strongly associated with likelihood of adoption, and that the larger the household, the less likely they are to use LPG. Households that have access to flush toilets and clean water are much more likely to make the transition to cooking with LPG. This finding suggests synergies between Water and Sanitation Health (WASH) efforts and clean cooking programs, and that efforts in one field may lead to gains in the other. I also add to the energy ladder and fuel switching hypotheses of household energy transitions. I find that those higher up the socioeconomic ladder adopted LPG at a higher rate, but almost no households completely abandoned cooking with charcoal - even if they were using LPG primarily. The biomass pellet solution central to the randomized control trial shows an opposite pattern. LPG appears to be cost-prohibitive, while the pellet solution was reaching the poorest households in the sample. However, the pellet company went out of business before the end of the study. Households are not fuel switching as they move up the energy ladder, and whether LPG is displacing enough of the cooking with high polluting fuels in a household to meaningfully reduce HAP is up for debate. Future efforts should be focused on the suspension of solid fuel use alongside the adoption of clean fuels.

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1. Introduction

About half of the world's population depends on highly polluting fuels such as charcoal, firewood, dung and other biomass fuels for cooking and lighting (Health Effects Institute, 2020). The use of solid fuel has been declining over the past decade around the world but remains persistently high in sub-Saharan Africa. While reliance on solid fuels is expected to diminish in coming decades in other regions of the Global South, the total population using solid fuels in sub-Saharan Africa is expected to grow through 2030 (Nakićenović et al., 2012).

Reliance on solid fuels is associated with significant health burden, environmental degradation, contributing to climate change, and decreasing the overall quality of life for women and children tasked with collecting biomass fuels. Exposure to household air pollution (HAP) from the burning of solid fuels is known to contribute to heart diseases, lung cancer, low birth weight, pneumonia in children, and other preventable diseases (Alexander et al., 2017; Brook et al., 2010; M. L. Clark et al., 2013; Giorgini et al., 2016). The World Health Organization's newest estimates claim that 3.8 million people die prematurely each year from these illnesses attributable to the pollution burden of cooking with solid fuels (World Health Organization, 2021). The HAP burden disproportionately affects low-and middle-income countries (LMICs) as nearly all deaths from HAP are from the world's poorest countries (Landrigan et al., 2018). Alongside the health impacts of burning biomass-based fuels, the reliance on such fuels has environmental and climate change impacts. The collection of woodfuels can lead to deforestation and degradation (Stad et al., 2009), while charcoal production and burning of woodfuels contribute to climate change (Bailis et al., 2003, 2005; O. Masera et al., 2015), and can contribute to regional climate change through releases of black carbon (Bailis et al., 2015; O. Masera et al., 2015; Serrano-Medrano et al., 2018). Reliance on biomass-based fuels often means that household members, typically women, spend time outside of the house collecting fuel. Reduction in time spent collecting fuelwood provides women the opportunity to put additional time toward other productive activities (i.e., income generation or education) or relaxation. Adoption of cleaner stoves has been shown to significantly reduce time spent collecting biomass for cooking and time spent cooking in India (Anderman et al., 2015; Lewis et al., 2017), Rwanda (Bedi et al., 2015), Kenya (Jagoe et al., 2020), and elsewhere.

To address the myriad of negative externalities associated with reliance on biomass fuels, governments, international organizations, and private sector firms in LMICs have attempted to increase the uptake of clean cooking practices, such as the use of liquified petroleum gas (LPG), electric cooking, and fan microgasification stoves that use biomass pellets (Champion & Grieshop, 2019; Gill-Wiehl et al., 2020; Thoday et al., 2018). While improved cooking stoves and cleaner-burning fuels are available and can dramatically reduce the burden of household air pollution, adoption in lower-income countries, particularly sub-Saharan Africa, has been limited despite being a policy priority (Health Effects Institute, 2020).

This study examines the determinants of the transition from high polluting fuels (primarily charcoal) to LPG in Gisenyi, the second largest city in Rwanda. Rwanda, the most densely populated country in Africa is a geographically small country facing rapid population growth and, thus, growing household energy demand. Bailis et al., 2015, identified Rwanda as one of a few countries in which most of the harvested woodfuel is unsustainable. The combination of population pressure and constrained biomass resources suggest that Rwanda is poised for a cooking energy transition (Bailis et al., 2015). Over 97% of Rwanda's population depends on biomass for cooking (Health Effects Institute, 2020). Due to the high rate of cooking with polluting fuels, HAP is a major contributor to the burden of disease in the country (IHME – Rwanda country study). Air pollution is the second leading risk factor for premature death and HAP alone accounts for the loss of one and a half years of life expectancy for Rwandans (Health Effect Institute, 2019). The government is also involved in the promotion of improved cookstove policy and projects, though they have had limited documented success (Jagger et al., 2019). However, in 2020 Rwanda updated their Nationally Determined Contributions (NDC) to the Paris agreement with new goals of reducing reliance on inefficient stoves as a greenhouse gas mitigation strategy (Clean Cooking Alliance, 2021). Also, the Ministry of Infrastructure's new Biomass Energy Strategy (2019-2030) has ambitious targets to phase out charcoal in urban settings and reduce the share of households using firewood from 79.9% to 42% by 2024 (Development Bank of Rwanda, 2021).

We leverage data from a randomized controlled trial designed to assess the impact of adoption of biomass pellet stoves on health and well-being. By chance, the availability of LPG in the local market increased, leading to considerable adoption of LPG between 2015 (baseline) and 2020 (endline) in our study population. We study this transition by analyzing data on adoption (ownership of at LPG stove or use of LPG or both), the share of cooking done with LPG, expenditure on cooking fuels, and fuel stacking behavior in a sample of 1,852 households. Looking at adoption and use of clean fuels with a range of indicators allows us to tell a nuanced story about transitions from biomass to clean cooking fuels, and to make robust claims regarding household energy transitions in this setting.

Literature Review

Adoption of LPG

Lewis and Pattanayak conducted a systematic review in 2012 to synthesize the current state of knowledge on the adoption of improved cookstoves and clean fuel. They found that income, education, and urbanicity were generally associated with adoption in most of the studies. In other literature, several studies have quantitatively studied the adoption of improved cookstoves (Alem et al., 2014; Beyene & Koch, 2013; Bonan et al., 2021; Jagger et al., 2019) and the uptake of clean fuels (Arthur et al., 2010; Mani et al., 2020; Ouedraogo, 2006; Pope et al., 2018; Shupler et al., 2019, 2021). In 2022, Guta et al. conducted a systematic review of household energy transitions and examined studies of adoption (drivers and barriers) alongside studies of reduction or suspension of biomass fuels and stoves. For the most part, they find that studies show a positive influence of wealth and education on the uptake of cleaner fuels. In the adoption literature, there are heterogeneous findings in terms of drivers and barriers of adoption due to the range of study domains and settings (rural, urban, cultural differences, etc.). Studies of LPG adoption typically show that household size is negatively associated with adoption (Guta et al., 2022; Karimu et al., 2016). The gender of the household head has been shown to be associated with LPG and other clean stove adoption, but results have been heterogeneous. Some studies show a higher probability of adoption for female-headed households (Karimu, 2015; Lewis & Pattanayak, 2012) and some for male-headed households (Karimu et al., 2016). Household wealth and income have been shown to influence the adoption and use of LPG in many studies, reflective of the affordability challenge of LPG (Karimu, 2015; Karimu et al., 2016; Stanistreet et al., 2019; Troncoso et al., 2019). Wealth is often measured by a wealth index or simpler asset counts and has been found to be positively associated with LPG and LPG stove use (Pope et al., 2018; Wolf et al., 2017), and adoption of LPG stoves (Menghwani et al., 2019). It is clear that higher levels of education positively influence the adoption of LPG, as have been shown repeatedly in empirical studies around the world (Guta et al., 2022; Karimu et al., 2016; Ozoh et al., 2018; Pope et al., 2018). Interestingly, access to electricity has been shown to be a potential driver of LPG adoption (Dendup & Arimura, 2019; Guta et al., 2022; Karimu et al., 2016). In our study, access to electricity is ubiquitous but use rates of electricity vary.

The clean cooking uptake and adoption literature largely comprises studies from rural settings (Guta et al., 2022; Jagger et al., 2019). Urban areas present an interesting case as solid fuels such as firewood are likely not freely accessible as an alternative fuel as they are in many other study sites in sub-Saharan Africa. Rehfuess et al., 2014, find that households that are already purchasing instead of collecting fuel are more likely to adopt improved stoves. Shupler et al., 2021, conducted a large quantitative assessment of supply-side determinants of LPG adoption in peri-urban sub-Saharan African sites. They find that inconsistent fuel supply and refill and transportation costs are barriers to adoption for households in SSA. They point to the importance of proximity to refill stations to limit transportation costs for households. In a study of improved cookstove adoption in urban Ethiopia, (Beyene & Koch, 2013) find that economic factors, like price and household wealth, are determinants of adoption. In an urban SSA setting, (Alem et al., 2016) found that, while adoption of cleaner fuels is likely among wealthier households, wealthier households are stacking more fuels as well.

Fuel Stacking and the Energy Ladder

The household energy transition is often explained through an "energy ladder" model. This suggests that as a household's wealth and socioeconomic status increases a progression from traditional biomass fuels to cleaner burning "modern" fuels takes place. As families gain wealth, they stop using inefficient and highly polluting fuels that are "lower" on the energy ladder and switch to cleaner alternatives (Hosier & Dowd, 1987; Van Der Kroon et al., 2013). The energy ladder is described as a linear transition from solid fuels to clean fuels and relies on this switching behavior. A simple progression from biomass to clean fuels has been repeatedly refuted, however, as data often show that household's use multiple fuels or "fuel-stack" instead of transition from one to another. Often solid fuels are used across the spectrum of wealth, even while cleaner alternatives are being partially adopted by wealthier households (Choumert-Nkolo et al., 2019; Hiemstra-van der Horst & Hovorka, 2008; O. R. Masera et al., 2000).

Due to high rates of fuel stacking, adopting a cleaner-burning stove does not signify a full transition to clean cooking. This is an issue because partial use of clean fuels, accompanied by the burning of solid fuels, does not provide relief from HAP, specifically PM 2.5, to below the World Health Organization (WHO) recommendations. However, adopting LPG to some extent still can have beneficial health outcomes, even if WHO targets are not met (Steenland et al., 2018). Studies have repeatedly shown that households adopting cleaner-burning stoves or fuels are typically fuel-stacking, using other solid fuel stoves and fuels concurrently to meet household energy demands (S. Clark et al., 2017; Guta et al., 2022; O. R. Masera et al., 2000; Shankar et al., 2020). Fuel switching up the ladder is not absolute, as it is much more common to continue solid fuel use as newer fuels are adopted. Additionally, the movement on the energy ladder is not necessarily linear or one directional. Households may move down the ladder to solid fuels after adopting cleaner alternatives as fuel prices, supply, and other factors change (Maconachie et al., 2009; O. R. Masera et al., 2000; Van Der Kroon et al., 2013). Thus, since switching may not be absolute, nor one-directional, research and policy focused on the discontinuation of biomass-based fuels are important to be paired with adoption efforts (Shankar et al., 2020).

Gaps in the Literature

Our study fills several gaps in the literature on energy access and energy transitions in the Global South. First, we contribute to the relatively sparse literature on urban LPG adoption in sub-Saharan Africa, as well as the greater discussion of factors influencing the uptake of cleaner fuels in low-income countries. With the urban population in sub-Saharan Africa projected to double by 2050 (Saghir & Santoro, 2018), clean cooking studies in urban areas are needed. Second, we are able to address energy transitions by using panel data spanning a 6-year time period. In a recent systematic review of household energy transitions, Guta et al., 2022, point out that there is a dearth of longitudinal studies examining the factors driving adoption. The household cooking fuel transition is dynamic, and thus longitudinal data are best suited to study use and adoption of clean fuels. Third, we are able to test the hypothesis that transitions to clean fuels are catalyzed by taking a first step up the energy ladder. Our study provides experimental evidence from a rigorous randomized control trial on improved biomass pellet adoption alongside the LPG adoption data. Between 2019 and 2020 data collection, the biomass pellet company Inyenyeri went out of business in Rwanda causing a supply shock providing a unique opportunity to see how early adopters of a cleaner cooking technology (e.g., biomass pellet and microgasification stoves) behave during a period of a fuel supply shock.

2. Methods

Study design

The data for this analysis come from a quantitative impact evaluation study conducted in Gisenyi, Rwanda between 2015 and 2020 (Das et al., 2018; Jagger et al., 2019; Jagger & Das, 2018; Seguin et al., 2018). The study was designed to evaluate the impact of a for-profit household energy company in Rwanda, Inyenyeri, that sold fuel pellets made of biomass and leased the accompanying gasifying cookstove to customers. Inyenyeri chose Gisenyi as the location for their operations due to a pressing need for cleaner household energy in Rwanda and neighboring DRC, the relative ease of doing business in Rwanda, and access to both rural and urban customers. The objective of Inyenyeri was to provide a market-based solution for access to clean energy by leveraging a local supply of renewable biomass for pellet production. Customers signed up to purchase biomass pellets for a defined period of time, and the gasifier stove was leased to them for a small sign-up fee for the duration of the contract. Pellets were priced to be competitive with charcoal, which is the main source of cooking in the city. The assumption was that consumers would upgrade their cooking system with a cleaner fuel and stove without much of a difference in cooking energy expenditures.

The design of the impact evaluation of Inyenyeri's household energy system is a household-level randomized encouragement design. Baseline data were collected prior to the intervention, in 2015, to allow the team to confirm balance between treatment and control groups. The sampling frame was made up of 2,418 households provided by a district official in neighborhoods nearby Inyenyeri's retail locations. Duplicate households and existing customers of Inyenyeri's were removed, leaving a sampling frame of 2,334 households. 1,500 households were selected out of the frame through a randomization process, and then two-thirds of the households were assigned to intervention and the others to control through randomization. The intervention group received "encouragement," which consisted of a household visit from Inyenyeri staff to market the stoves and their benefits.

Study area

The data were collected in Gisenyi, Rubavu District in the northwest corner of Rwanda near the border with the Democratic Republic of the Congo along Lake Kivu, one of the African Great Lakes. Gisenyi is an urban center and Rwanda's second largest city with a population of 83,623 (*Population of Cities in Rwanda (2021*). The city is immediately adjacent, and across the international border from Goma in the Democratic Republic of the Congo (DRC), making it part of a major metropolitan area. The area is becoming a popular tourist destination for Rwandans and international travelers and boasts some of the best service sector infrastructure in the country along the lake's beaches. The city is also home to Bralirwa, a brewery and beverage maker that creates many of the favorite local beverages as well as Coca-Cola, Heineken, and Amstel. Outside of the urban center are rolling hills of coffee and tea plantations.

Sampling

In 2015 the data were collected from 1462 households from twenty-two different Umudugudus (neighborhoods/subdivisions) in two cells (Bugoyi and Kivumu). There were two "midline" data collection efforts between 2015 and 2019 of sub-samples of the greater sample. The midline efforts were focused on exposure monitoring and employed high-tech stove monitors. These waves of data collection are ignored in this analysis as the samples were small (180 households) and exposure monitoring is outside the scope of this paper. The later data collection effort in 2019 was supplemented with 460 new households to account for attrition and low adoption of the pellet technology in the original sample. In 2020, as many households were reached as possible before an interruption from the covid-19 pandemic. The 2020 survey effort reached 753 households before the interruption. In the dataset used for this analysis, there are 1,852 separate households included across three survey waves in 2015, 2019, and 2020 and a total of 3,148 observations (household years). 453 households were surveyed across all three waves of data collection, and an additional 435 were present for the first two, from 2015 to 2019. Thus, there are 888 of the same households in the 2015-2019 panel and 453 in the 2015-2019-2020 panel. The sample structure is portrayed below in figure 1.

Data collection

The data collection effort consisted of three distinct components. First, and where the data for this analysis comes from, is the Household, Poverty and Cooking (HPC) Survey administered to the main respondent and main cook of the household. The household survey collected demographic and behavioral information from the household. The second effort was exposure monitoring with personal and area monitors to evaluate the impact of the adoption of this cleaner cooking technology on the exposure of cooks and family members to carbon monoxide, PM2.5, and hydrocarbons. The third effort within the evaluation was stove use monitoring for a sub-sample of households. For the purpose of this analysis, we are working with the full sample of households in the HPC survey. The HPC has seventeen modules, and the survey took about two and a half hours to complete, depending on household size.

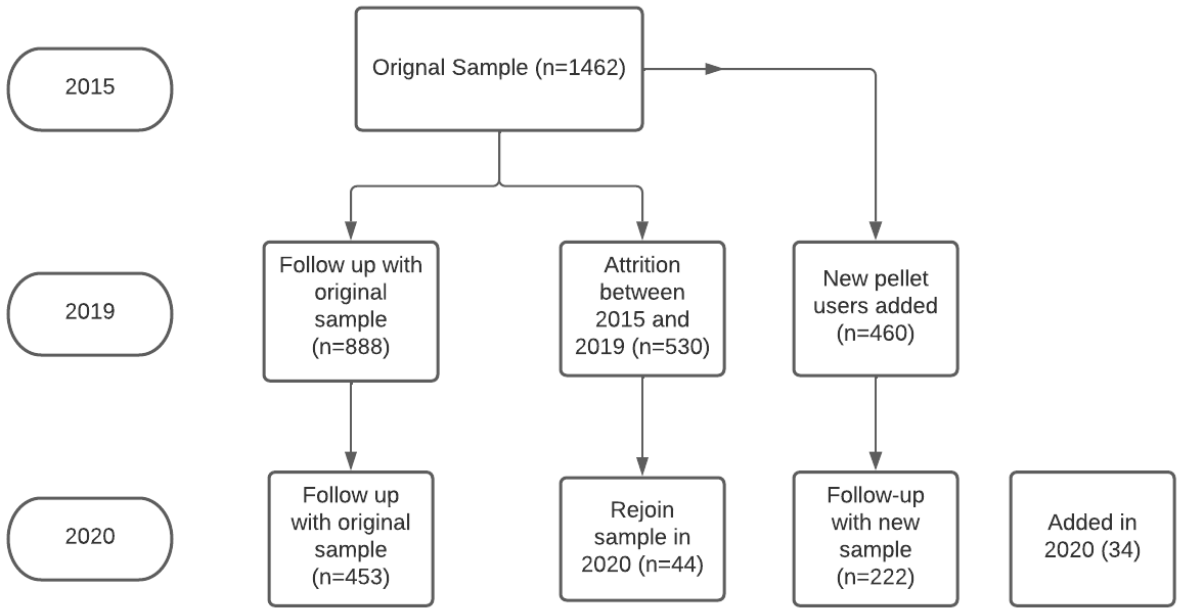


Figure 1. Study Sample

Measures

Dependent variables

There is a range of ways to look at LPG adoption and LPG use given the data. The five metrics that have been selected to represent adoption and use are 1) whether LPG is the primary cooking fuel, 2) whether the household owns a gas stove, 3) whether the household has used LPG to cook in the last 30 days, 4) the total expenditure on LPG by the household in the last 30 days, and 5) and the share of cooking (%) done with LPG in the last 30 days. Each of these variables tells a slightly different story, and thus are each included in the analysis. Primary fuel is often the dependent variable in analyses of fuel adoption or uptake in LMICs (Shupler et al., 2021; Mani et al., 2020; Ouedraogo, 2006; Shupler et al., 2019). Similarly, use of LPG at any level has been analyzed (Arthur et al., 2010; Pope et al., 2018; Walekhwa et al., 2009), and in this analysis, this is captured by whether the household has used any LPG for cooking over the last 30 days. Ownership of an improved stove at the household level is also commonly used as the outcome variable in the literature to understand adoption (Alem et al., 2014; Beyene & Koch, 2013; Bonan et al., 2021). The expenditure on LPG provides a look into what influences how much households spend on LPG, and, lastly, the share of cooking with LPG fuel (and other fuels) provides detailed information about fuel stacking behavior. Fuel stacking and fuel switching have been extensively studied, and it is common in sub-Saharan Africa and other lower-income countries for households to use multiple kinds of household fuel instead of switching completely from polluting to clean fuels (Alem et al., 2016; Choumert-Nkolo et al., 2019; Ochieng et al., 2020; Pope et al., 2018; Shupler et al., 2021). Each of these variables can provide added nuance to the explanation of the relatively rapid uptake of LPG that is observed in the sample.

Independent variables

The independent variables chosen for this analysis were chosen based on the relevance in the literature and availability of data. The variables include education, sex, and age of the main survey respondent, age of the main cook, size of household, count of durable assets, expenditure on electricity, food, and cooking fuel, and dwelling characteristics. In their systematic review of quantitative stove and fuel adoption literature, Lewis and Pattanayak found that three variables were included in more than half of the analyses: education of household head, income, and household size. Other common variables from the adoption literature that are included in this analysis are whether the household has a separate kitchen (Beyene & Koch, 2013; Ouedraogo, 2006), dwelling status (Beyene & Koch, 2013; Ouedraogo, 2006). A household's ownership of assets, toilet and sanitation, and dwelling characteristics are commonly used to measure a household's wealth, like the International Wealth Index and DHS Wealth Index (Smits & Steendijk, 2015). In a recent systematic review of household energy transitions, (Guta et al., 2022) found that the most common explanatory variables included in analyses of household uptake of cleaner fuels include Household income/expenditure, education, price, gender of household head, household size, a wealth measure, subsidies, and access to credit. Our analysis includes all of these explanatory variables except we don't have information on fuel prices, our financial service data has many missing observations (and is thus left out of the analysis), and there is not a large-scale subsidy program.

Coding decisions

The asset variable is used as an independent variable in each regression model and is an aggregate measure of household durable assets. Households were asked if they owned X asset for a range of assets. The assets variable is a summation of how many kinds of assets the household owns (i.e., a household would have a three if they owned a radio, television, and three cookers). These include refrigerator, radio, television, satellite dish, "cooker," DVD or video player, computer, music system, electric fan, and car. Questions about assets were included in both the 2015 and 2019 surveys, but not 2020.

The modern water variable is a measure of the household's drinking water. Households with their drinking water piped into their dwelling or coming from purchased water bottles are coded as 1. The other options, public borehole, piped to a location outdoors on their plot of land, and rainwater, are coded as 0.

The expenditure variables include expenditure on cooking fuel, expenditure on household electricity, and expenditure on food per household member. Household monthly spending on LPG fuel, specifically, is used as a dependent variable in figure 11. Each expenditure variable is reported as "per-capita" (the total household expenditure is divided by the number of household members). All expenditure variables were measured in Rwandan Francs (RWF) and deflated to 2015 values using the consumer price index for Rwanda and then converted to USD with the 2015 World Bank exchange rate of 719.86 RWF = $1 USD (*Statistical Reports | National Institute of Statistics Rwanda*, 2015).

Analysis

A logistic regression (see equation) was used to analyze the relationship between household, main respondent, and cook characteristics and the adoption of LPG.

$$P_r(X) = \left[1 + e^{-(\beta_0 + \beta_1 Household\ characteristics + \beta_2 Main\ respondent\ characteristics + \beta_3 Primary\ cook\ characteristics + \varepsilon_j)}\right]^{-1}$$

Three logistic models are run with the same independent variables but different definitions of adoption as the dependent variable. Y_j, in the equation above, represents something different in each model, for household j, while e_j represents the error term. In the Primary Fuel model, Y_j=1 if the household uses LPG as their primary fuel, 0 otherwise. In the LPG in the last 30 days model, Y_j=1 if the household said that they have used LPG to cook in the last 30 days, 0 otherwise. In the Gas Stove Ownership model, Y_j=1 if the household claimed to own a gas stove, 0 otherwise. Household characteristics include household size; number of different durable assets owned by the household; per household member expenditure on food; per household member expenditure on electricity; per household member expenditure on cooking fuel; a binary indicator for whether the home is owned as opposed to rented; a binary indicator for whether the home has a flush toilet; a binary indicator for whether the household owns any land; and a binary indicator that equals 1 if the household has water piped into the dwelling or drinks bottled water, 0 otherwise. The main respondent characteristics include age; sex; and education level (none or primary, secondary or technical school, or university). Age of the primary cook is included as well.

Two linear models with random effects were run on LPG monthly expenditure (USD) and share of cooking done with LPG (%).

$$Y_j = \beta_0 + \beta_1 Household\ characteristics + \beta_2 Main\ respondent\ characteristics + \beta_3 Primary\ cook\ characteristics + \varepsilon_j + \upsilon_j$$

Robust standard errors are reported for all models. The logistic regression results report odds ratios and the linear regressions report coefficients. Full regression output can be found in the appendix.

3. Results

Clean Fuel Adoption

Between 2015 and 2020 there were significant changes in cooking energy among our study population in Gisenyi. In 2020, charcoal remained by far the most prevalent household cooking fuel with 75% of the total sample using it as their primary fuel. However, the pattern of primary fuel use over time is quite dynamic. In the 2015 baseline sample, 94% of households used charcoal as their primary fuel, and the next most common primary fuel was fuelwood at 3%. By 2019, charcoal was the primary fuel for 54% of households. This magnitude of change can be partially explained by the influx of biomass pellet users into the sample in 2019. 460 pellet using households were added in 2019 to increase the number of pellet users in the sample. By 2020, when the pellet company had shut down operations in Rwanda, the proportion of the sample using charcoal as the primary fuel rebounded to 75%. i.e., in absence of pellets as an option, most of that new sample of households would have been using charcoal. Not all the change in charcoal use can be explained by the new sample, though. The details are shown below in figure 2.

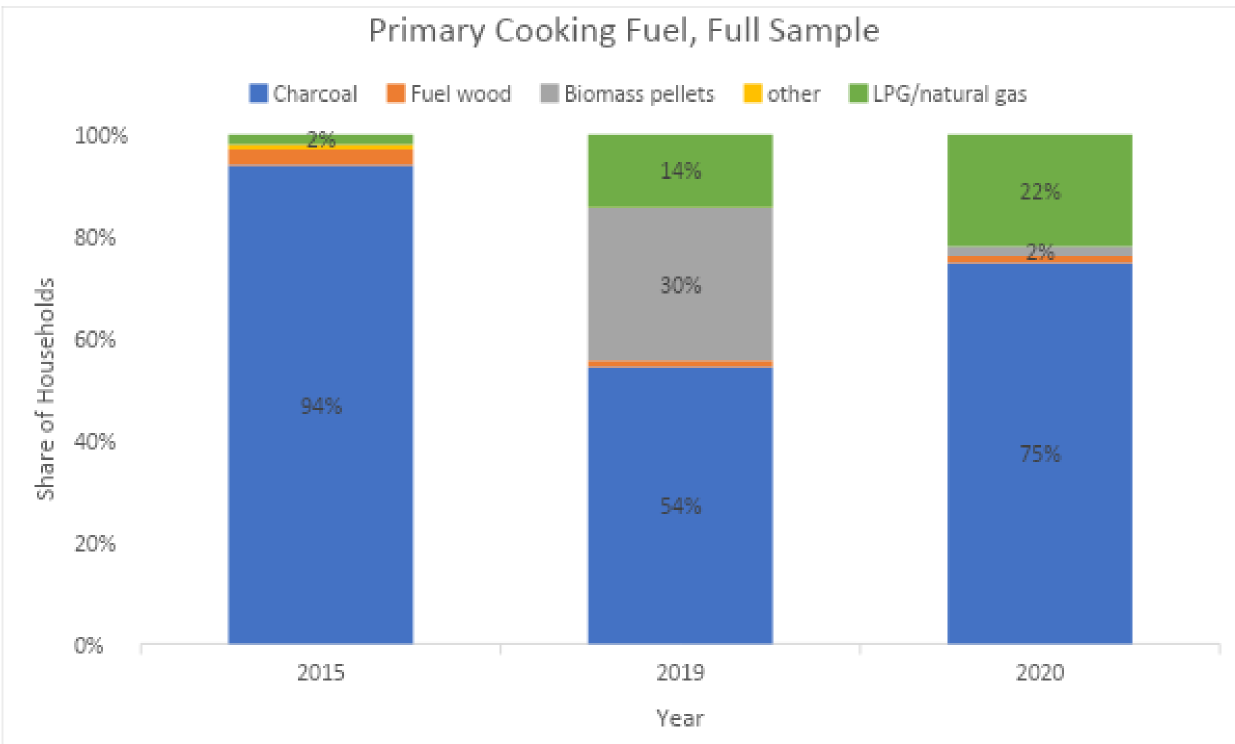


Figure 2: Primary cooking fuel over time for the entire sample

In table 1. the statistics are shown for the 453 households (known as the "pure panel") that were surveyed in each 2015, 2019, and 2020. The percentage of households that used charcoal as a primary fuel dropped from 96% in 2015 to 73% in 2019 in the pure panel (see figure 3). Part of the decrease in charcoal usage is explained again by pellet adopters as part of the randomized control trial, but a much larger proportion of the decrease is explained by the increase in LPG use from only 1% in 2015 to 18% in 2019. This trend continues into 2020. The share of the pure panel using LPG as a primary fuel jumps to 25% and the share of the total sample jumps to 22%.

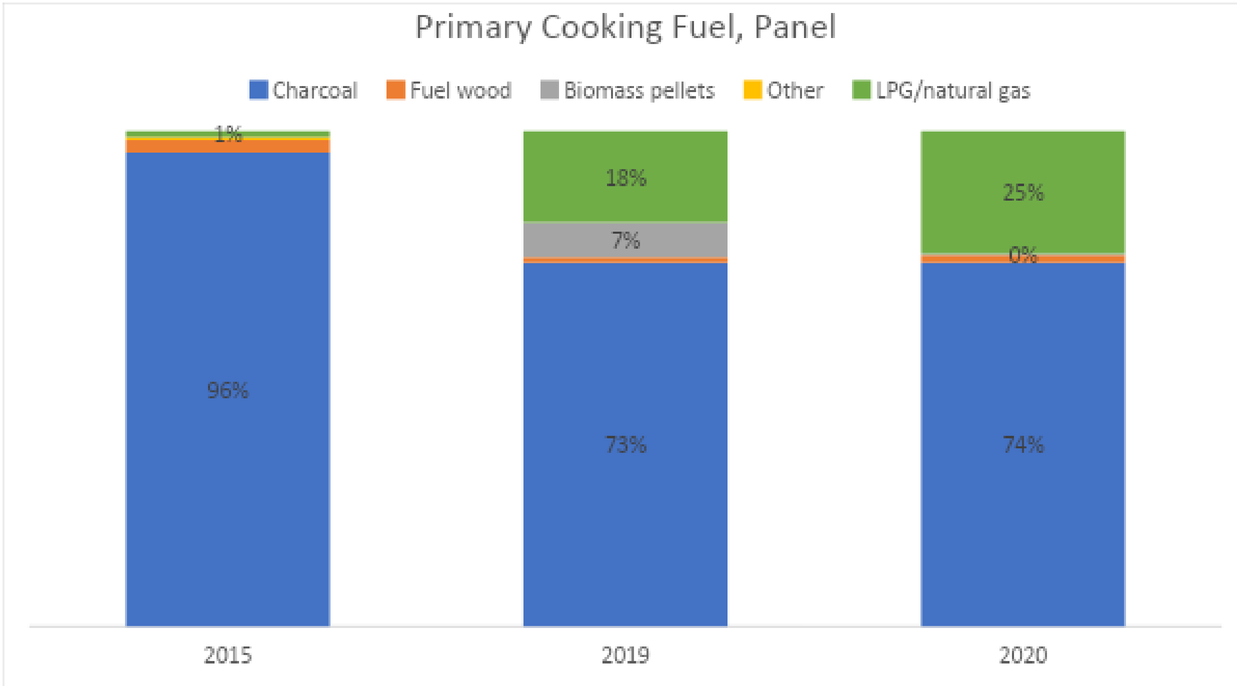


Figure 3: Primary Cooking Fuel across time in the panel

The increases in other measures of LPG adoption grow even more rapidly over the five-year period. In the full sample, only 6.1% of households own a gas stove in 2015. By 2020 41% of households owned a gas stove. The proportion of households that used LPG in the last 30 days jumped from 5.3% in 2015 to 36% in 2020. In the pure panel of 453 households, the magnitude of change is larger. 4.3% of households owned a gas stove in 2015 and 46.4% did in 2020. Only 3.8% of households used LPG within the last 30 days when surveyed in 2015 and by 2020 41.7% were using LPG to some extent. Refer to figures 2 and 3 for a visualization of how primary fuel use changed over time.

A majority (82%) of the main respondents of the survey were women. While this does not signify head of household status necessarily, the main respondent has decision making power and is the member who makes purchasing decisions. The average age for main respondents was 40 years old and they had completed at least secondary education (73%). The average household had a size of 5.3 members, owned approximately 3.6 durable assets, and spent $1.67 a month on electricity per member. 18% owned any amount of agricultural land, 56% owned their home, 39% had a flushing toilet (opposed to a pit latrine), and 62% of households had a kitchen structure outside of their dwelling.

Fuel Stacking

Households "stack", or use multiple kinds of, fuels to meet their cooking needs. A household's fuel portfolio looks different depending on their primary fuel choice (see figure 4). Those indicating that charcoal is their primary cooking fuel typically cook 93% of their meals with charcoal. Seventy nine percent of households that use charcoal as their primary fuel used charcoal exclusively, for 100% of their meals, in the month leading up to the survey. The story is different for LPG and biomass pellet users. Households using LPG as their primary fuel typically cook 77% of their meals with LPG and the rest primarily with charcoal. The starkest difference is that only 18% of households using LPG as the primary fuel used it exclusively. 82% of LPG users supplemented LPG with at least one other fuel during the month. Pellet users stacked more than charcoal users, but less than LPG users. Those depending on pellets used them for around 84% of their meals and 44% of them used pellets exclusively.

A household's fuel stack also looks different across the wealth spectrum, measured by asset ownership. Figure 7 shows the cooking share averages for each quintile of asset ownership. Households with greater wealth use LPG at much greater rates, and charcoal is used across the spectrum. Pellets are more frequently used by those at the lower end of asset wealth. Figure 6 displays a detailed look at how the average cooking share changes with increases in wealth.

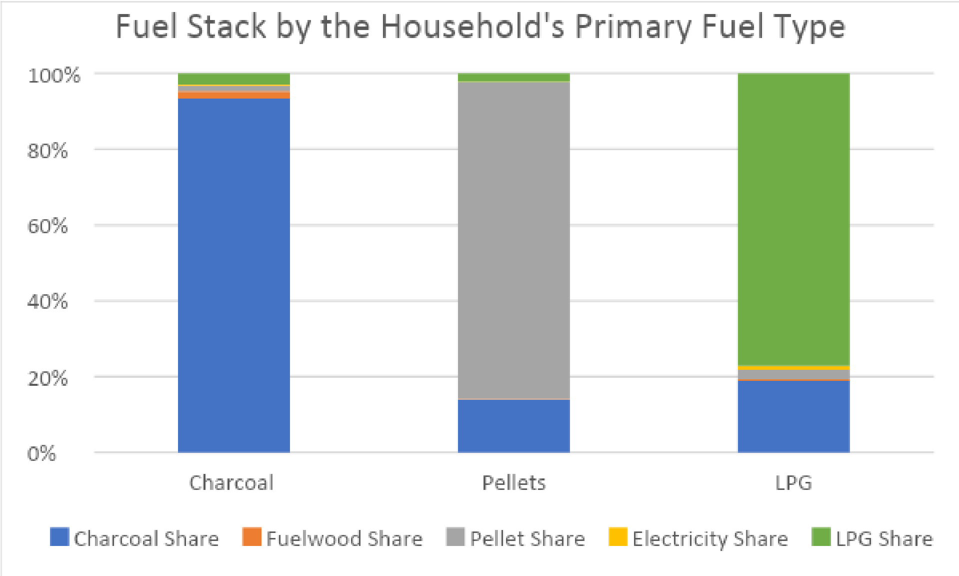


Figure 4. Cooking share by primary fuel

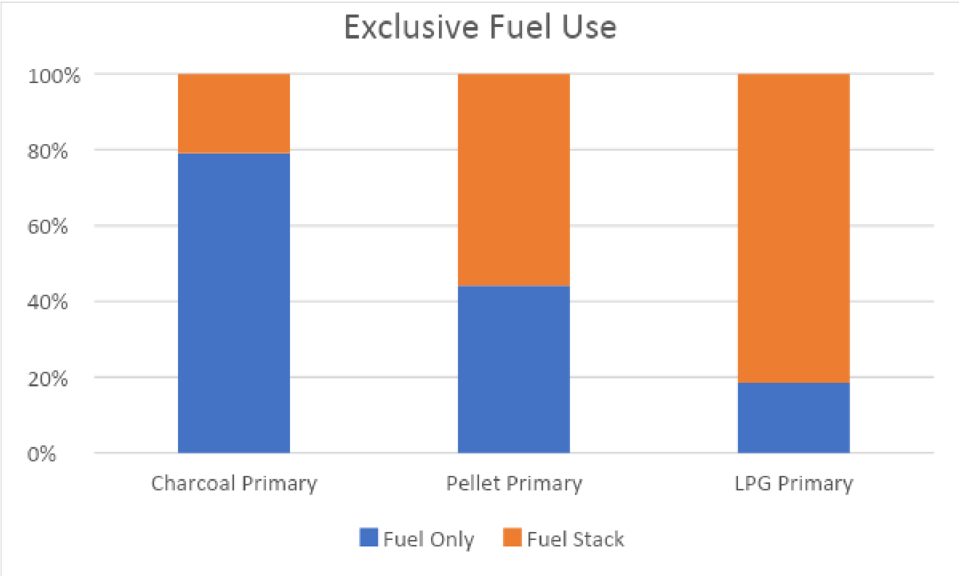


Figure 5. Exclusive use vs. fuel stacking by households' primary fuel use

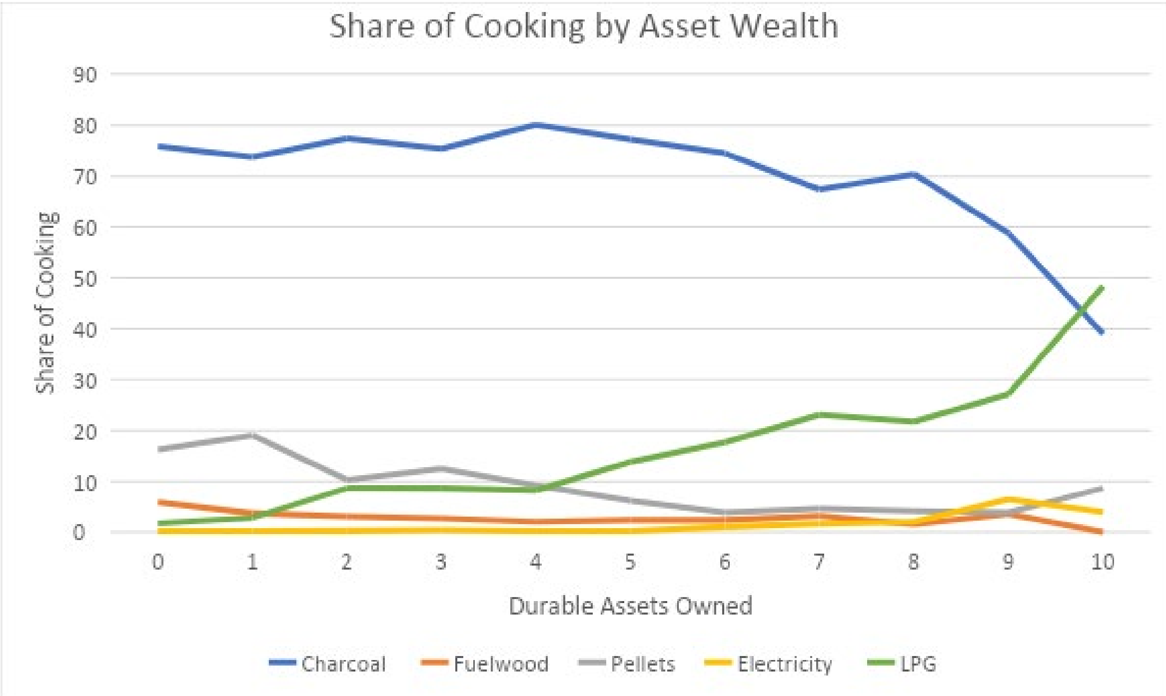


Figure 6. Fuel share by asset wealth

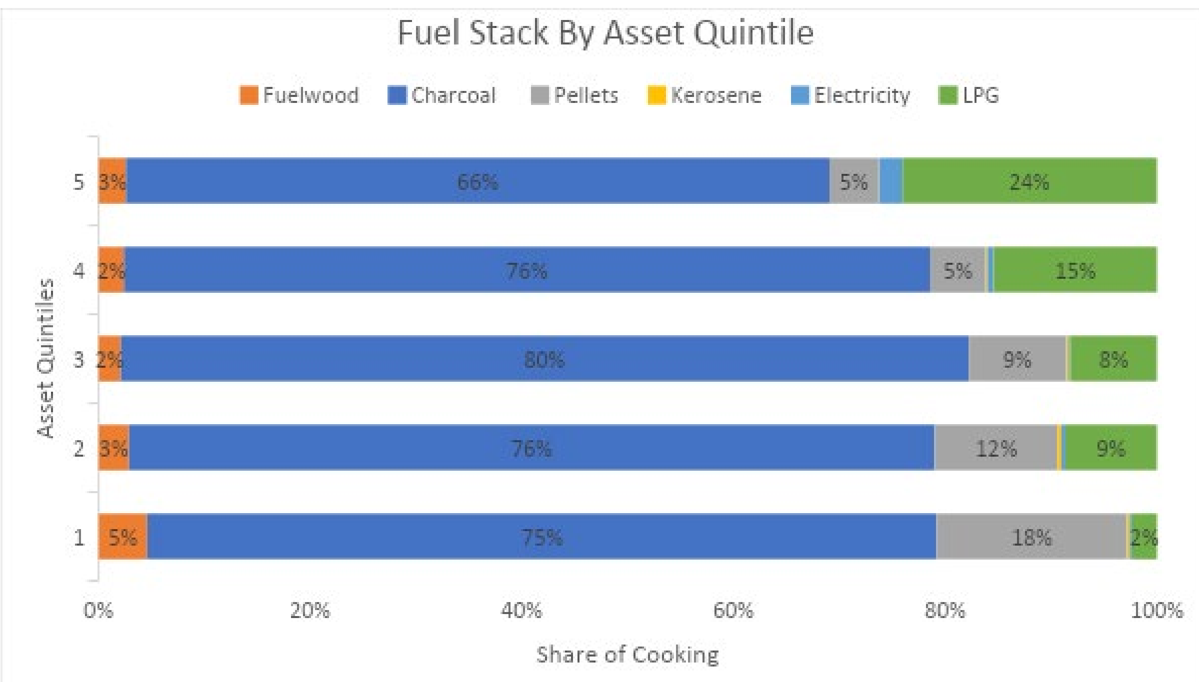


Figure 7. Fuel stack by Asset Quintile

Table 1. Summary Statistics of Dependent Variables

Household Cooking	2015	2019	2020	Total
Full Sample				
Own a Gas Stove				
No	94%	71%	59%	79%
Yes	6%	29%	41%	21%
Used LPG in the Last 30 Days				
No	95%	75%	64%	82%
Yes	5%	25%	36%	18%
Share of cooking done with LPG	2.48 (12.99)	14.05 (28.34)	21.8 (33.74)	10.38 (25.35)
Per Capita Expenditure on LPG (USD)	0.29 (1.78)	0.95 (2.28)	1.35 (2.93)	0.73 (2.27)
Observations	3,148			
Panel				
Own a Gas Stove				
No	96%	63%	54%	72%
Yes	4%	37%	46%	28%
Used LPG in the Last 30 Days				
No	96%	67%	58%	75%
Yes	4%	33%	42%	25%
Share of cooking done with LPG	1.56 (10.52)	18.37 (31.1)	24.49 (34.25)	14.34 (28.7)
Per Capita Expenditure on LPG (USD)	0.14 (0.94)	1.29 (2.77)	1.46 (2.82)	0.93 (2.38)
Observations	1,212			

Table 2. Summary Statistics for Independent Variables

Variable	Mean (SD)	Range
Full Sample		
Age of Main Respondent	39.86 (14.07)	17-89
Household Size	5.3 (2.56)	1-19
Age of Cook	32.07 (14.12)	13-84
Assets Owned	3.6 (2.27)	0-10
Per Capita Expenditure on Food (USD)	29.81 (25.83)	0-293.39
Per Capita Expenditure on Electricity (USD)	1.67 (3.16)	0-69.46
Per Capita Expenditure on Cooking Fuel (USD)	4 (3.43)	0-69.46
Female Main Respondent	81.60%	
None or Primary Edu	27.35%	
Secondary Edu	42.92%	
University Edu	29.73%	
Kitchen Structure Outside of Dwelling	62.36%	
Piped or Bottled Drinking Water	25.98%	
Flush Toilet	38.79%	
Own Home	56.16%	
Own Land	17.88%	
N	3,148.00	
Panel		
Age of Main Respondent	44.52 (13.93)	17 - 89
Household Size	5.81 (2.54)	1 - 14
Age of Cook	34.49 (15.42)	13 - 83
Assets Owned	3.73 (2.15)	0 -10
Per Capita Expenditure on Food (USD)	26.49 (21.67)	0 - 208.48
Per Capita Expenditure on Electricity (USD)	1.56 (2.4)	0 - 34.73
Per Capita Expenditure on Cooking Fuel (USD)	3.91 (2.99)	0 - 27.78
Female Main Respondent	85.31%	
None or Primary Edu	31.19%	
Secondary Edu	43.81%	
University Edu	25.00%	
Kitchen Structure Outside of Dwelling	66.50%	
Piped or Bottled Drinking Water	27.64%	
Flush Toilet	42.66%	
Own Home	65.92%	
Own Land	19.47%	
N	1,212.00	

Determinants of LPG Adoption

The econometric analysis of determinants of adoption of LPG shows clear patterns across all models, with some slight variation depending on how adoption is defined. Modeling the likelihood that LPG is the households primary cooking fuel, figure 8 below, we observe that the main respondent having secondary education compared to primary education or less increases the odds of using LPG as the household's primary fuel by 2.61 ($p < 0.01$). Having a university education further increases the odds of LPG being the primary cooking fuel, by 4.08 ($p < 0.01$). Other statistically significant factors that increase the likelihood of primary use of LPG include a household having a flush toilet as opposed to a pit latrine (OR (odds ratio) 2.12, $p <0.01$), having water piped into the household or drinking bottled water (OR 3.34 $p < 0.01$), and owning (vs. renting) (OR 1.40 $p < 0.10$). Some measures of wealth were also associated with higher likelihood of primary LPG use. The more durable assets a household has (OR 1.34 $p < 0.01$), and the more it spends on fuel (odds ratio 1.08 $p < 0.01$), the more likely it is to use LPG as the primarily cooking fuel. While the age of the main respondent is not statistically significantly associated with LPG use, older primary cooks are more likely to use LPG as the primary fuel (OR 1.019 $p < 0.01$).

A range of factors are associated with reduced odds of using LPG as the primary cooking fuel. Households that cook in a separate structure from their dwelling have a lower likelihood of using LPG primarily (OR 0.42, $p < 0.01$). The more members there are in a household (odds ratio 0.86, $p < 0.01$) and the more money spent on food per person in the household (odds ratio 0.99 $p < 0.01$), the less likely the household is to be using LPG primarily. All of these factors are robust, or significant at the 0.05 level, in the parallel regression of just the panel of 453 households, besides ownership of home and the expenditure variables. Full regression output for each sample and all models is in the appendix.

The logistic regression on the indicator of LPG use at any level over the past 30 days (figure 9) shows similar results to the LPG as the primary fuel model. The only differences between the two models in terms of statistical significance, is that household size and age of the main cook is no longer statistically significant, and there is suggestive evidence ($p < 0.10$) that female main respondents are more likely to have used LPG in the last 30 days. Besides these exceptions, the factors that had significant associations with LPG use as a primary fuel have significant associations in the same direction with LPG use at any level over the last month.

The results from the logistic model on gas stove ownership provide an analysis of factors that are associated with adoption of the stove as opposed to use of the fuel. When the main respondent has a secondary education or university education as opposed to only primary, the odds of ownership are 2.83 ($p<0.01$) and 4.78 ($p<0.01$) higher, respectively. Cooking in a separate kitchen outside of the dwelling and the number of members of the households are not statistically significantly associated with stove adoption, as they were with primary LPG use. The older the household's primary cook, the more likely that household is to own a gas stove (odds ratio 1.01 $p < 0.10$). Owning a flush toilet (odds ratio 2.04 $p < 0.01$), using piped or bottled drinking water (odds ratio 2.48 $p <0.01$), and owning the home as opposed to renting (odds ratio 1.66 $p <0.01$) are all associated with higher likelihood of gas stove adoption. Similar to the models of LPG use, owning more assets increases the likelihood that the household owns a gas stove (odds ratio 1.26 $p <0.01$) and the more the household spends on fuel, the higher the likelihood of ownership (odds ratio 1.21 $p < 0.01$). The more the household spends on food, however, the lower the likelihood of ownership (odds ratio 0.98 $p < 0.01$).

Figure 11 is a visual representation of the coefficients of the regression on the amount of money spent on LPG per month per household member. When the household's main respondent has attained a secondary education as opposed to a primary, the expenditure on LPG per month is $0.22 higher per household member ($p < 0.05$), and university education is associated with a $0.42 higher expenditure ($p < 0.01$). For every added household member, the spending on LPG drops by around $0.06 per month ($p < 0.01$). The older the main cook, the more is typically spent on LPG (0.01 $p < 0.01$). As in previous models, water and sanitation indicators show up as statistically significant. Drinking piped or bottled water is associated with spending $0.56 more a month on LPG per household member ($p < 0.01$). Each additional asset a household owns is associated with a $0.09 monthly increase in expenditure, and spending on electricity is also positively associated with LPG expenditure with a coefficient of 0.17 ($p < 0.01$).

The extent to which households use LPG in a month is measured by the percentage of cooking done with the fuel. We model this variable in the final regression, figure 12. Education is again statistically significant and positive. Having a secondary education is associated with an increase in the percentage of cooking done with LPG by 4.17% and a university education is associated with an 8.31% increase, compared to those with a primary education or less ($p <0.01$). If the household cooks outside of their primary dwelling the share of LPG drops on average 4.93% ($p <0.01$). Similarly to other models, as household size increases, the share of LPG used in a month drops by 0.58% per member added. Households with older cooks tend to use LPG at a greater rate, as the age of the cook increases by 1 year the cooking share with LPG increases by 0.13% ($p < 0.01$). Once again, water and sanitation indicators move with LPG usage. Using a flush toilet in the home is associated with greater share of cooking done with LPG by 5.29% and drinking piped or bottled water is associated with an 8.53% increase in cooking with LPG ($p < 0.01$). Owning, as opposed to renting, the home is associated with an increase of 2.15% of the cooking share done with LPG ($p < 0.10$). Each additional asset owned by the household is associated with a 1.78% increase in LPG cooking share and each additional dollar spent on food per household member is associated with a 0.07% decrease ($p < 0.05$). Each additional dollar spent on cooking fuel per household member is associated with a 0.97% increase in cooking share with LPG ($p < 0.01$).

Coefficients plots

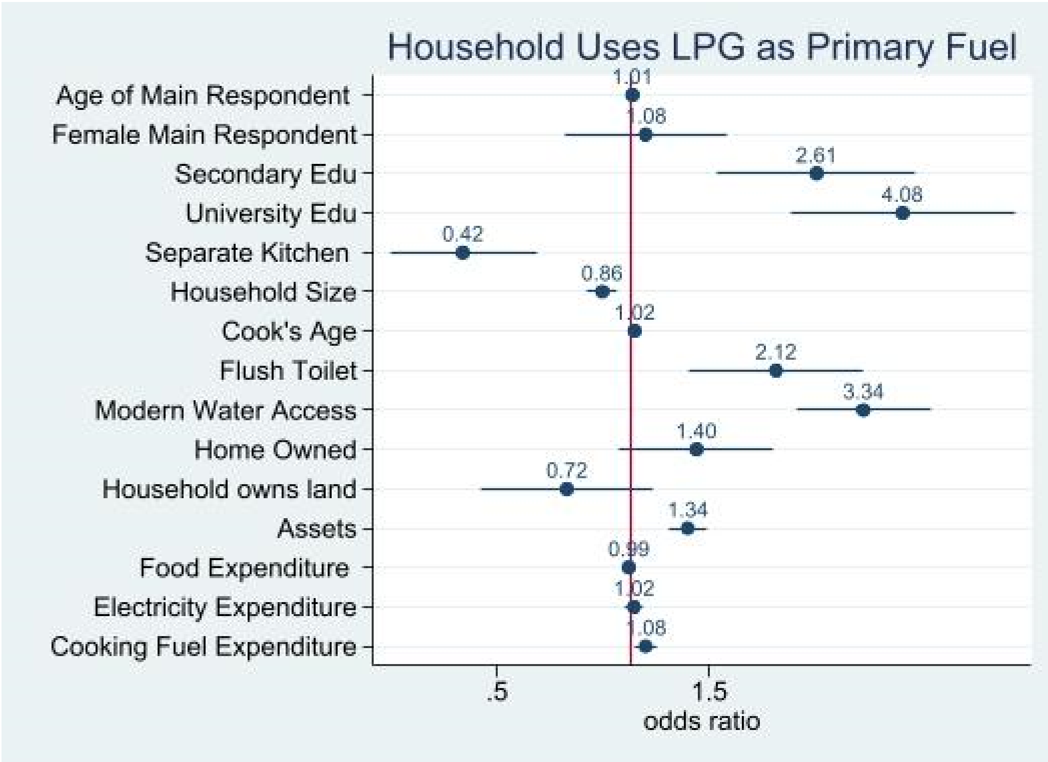


Figure 8. Logistic regression of LPG as household's primary fuel

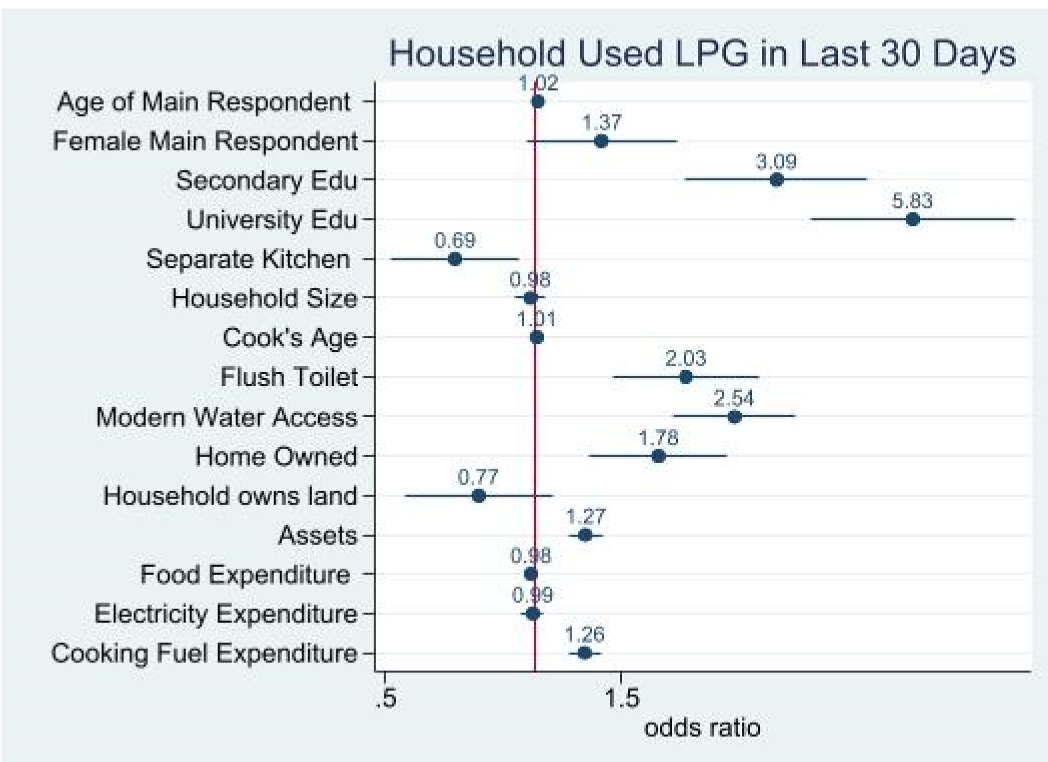


Figure 9. Logistic regression of LPG use at any level over the last 30 days

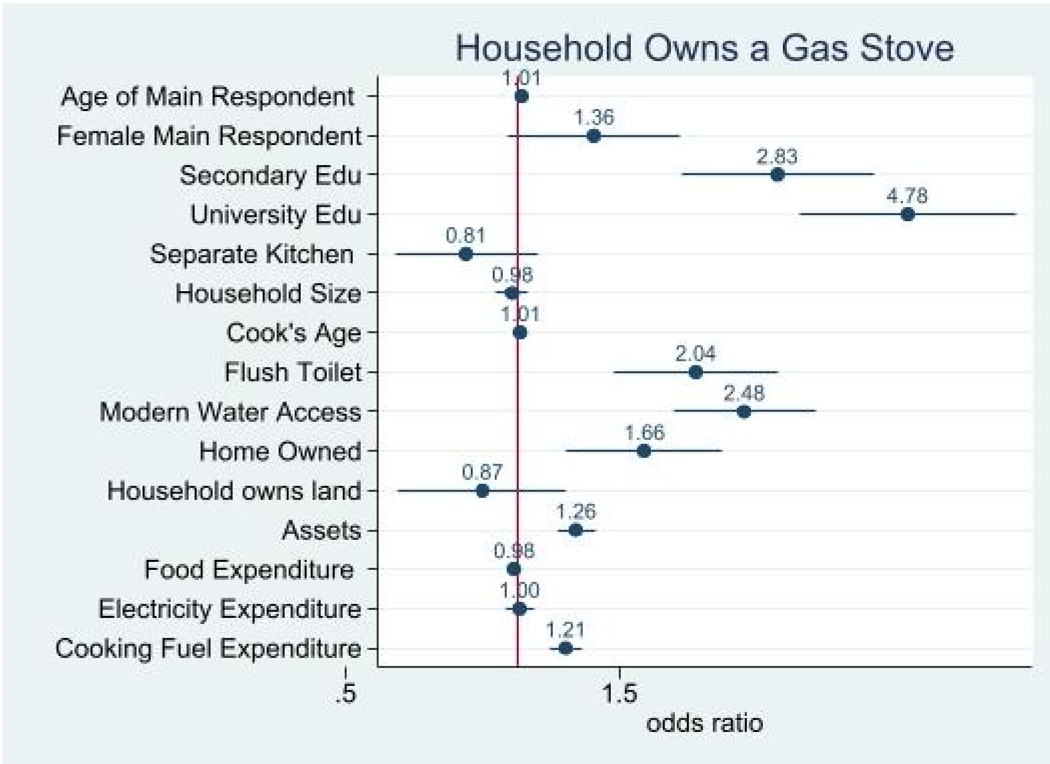


Figure 10. Logistic regression of gas stove ownership

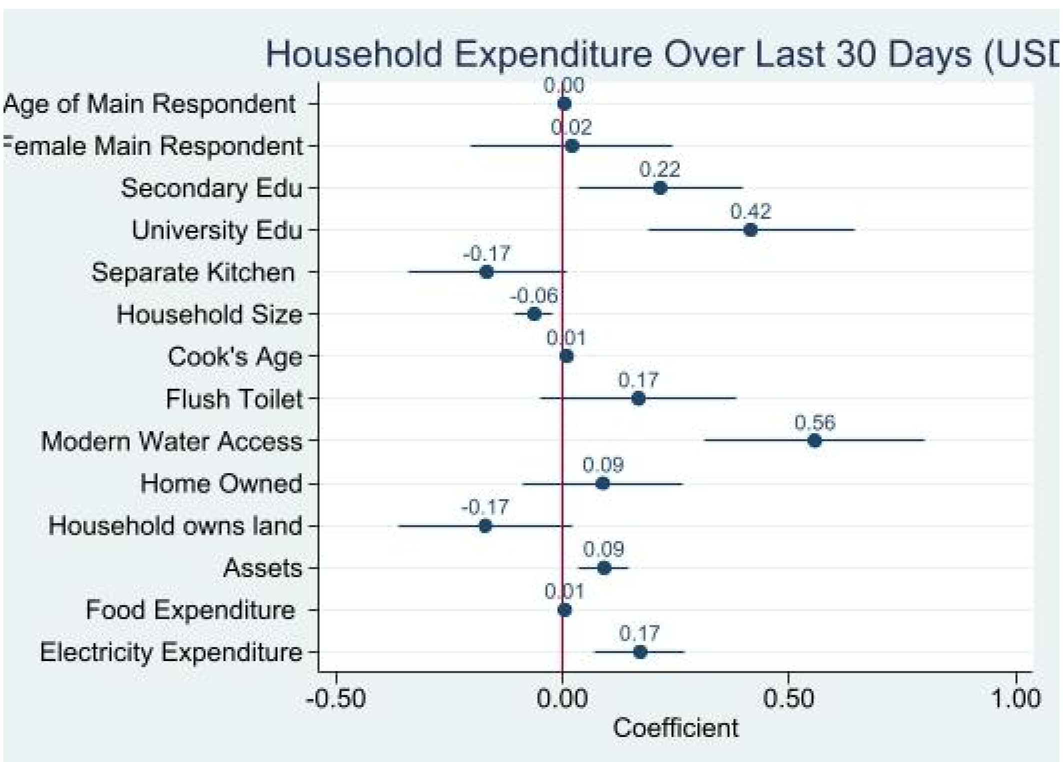


Figure 11. Linear regression of expenditure on LPG in USD

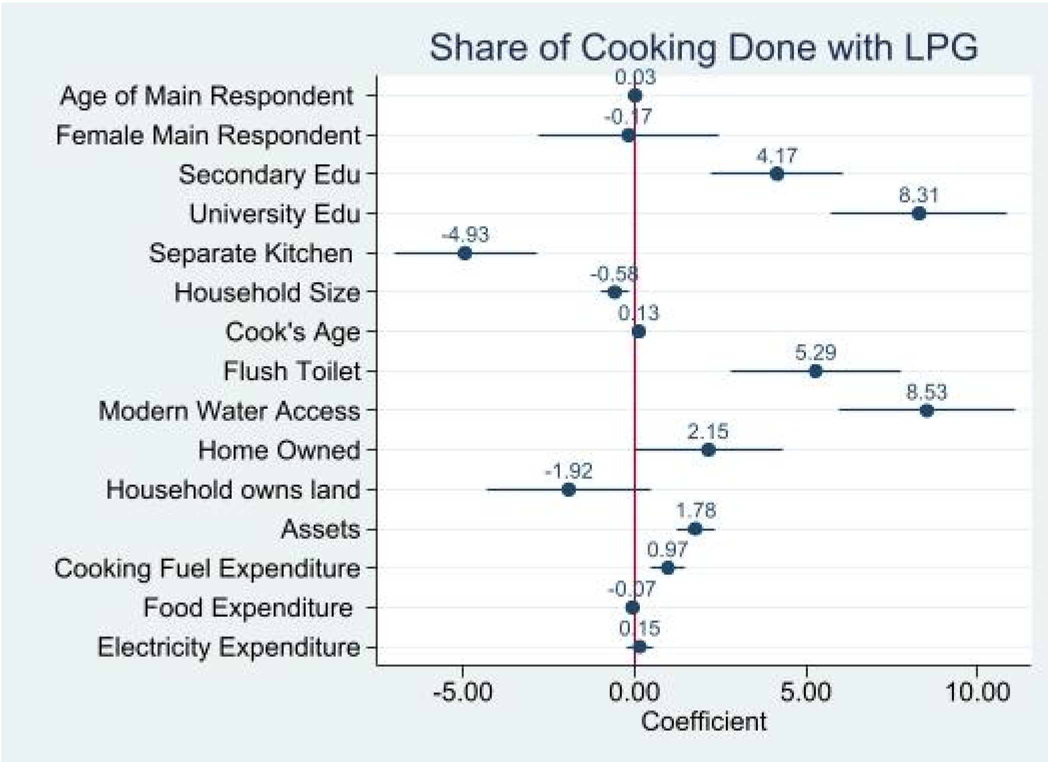


Figure 12. linear regression on the share of cooking done with LPG in a month

Are biomass pellets a step toward LPG adoption?

In late 2019 the pellet company and sole distributor of the biomass pellets and gasifying stoves went out of business in Rwanda. This unexpected event provides an interesting opportunity to explore if biomass pellets are a steppingstone to cleaner fuels. It helps us test the hypothesis that making a first step up the energy ladder catalyzes transitions to clean energy. Those who adopted pellet stoves in the last few years and were using pellets as their primary fuel as late as 2019 were forced to change their cooking behavior when their preferred fuel vanished. A plausible hypothesis is that adopting and using a clean stove and fuel combination could encourage movement further up the energy ladder to LPG when forced to move on from pellets allowing us to test whether pellets are a transition fuel between charcoal and LPG in this setting. Figure 13 provides a visualization of energy transitions between 2019 and 2020, with the closure of Inyenyeri happening in late 2019. Most pellet users moved “down the energy ladder” between 2019 and 2020 to charcoal instead of switching to LPG or another clean fuel 186 households used pellets as their primary fuel in 2019 and, by 2020, 150 of them had moved on to charcoal, 11 remained with pellets (perhaps these households had reserves), 23 moved up the energy ladder to LPG, and two households reverted to fuelwood.

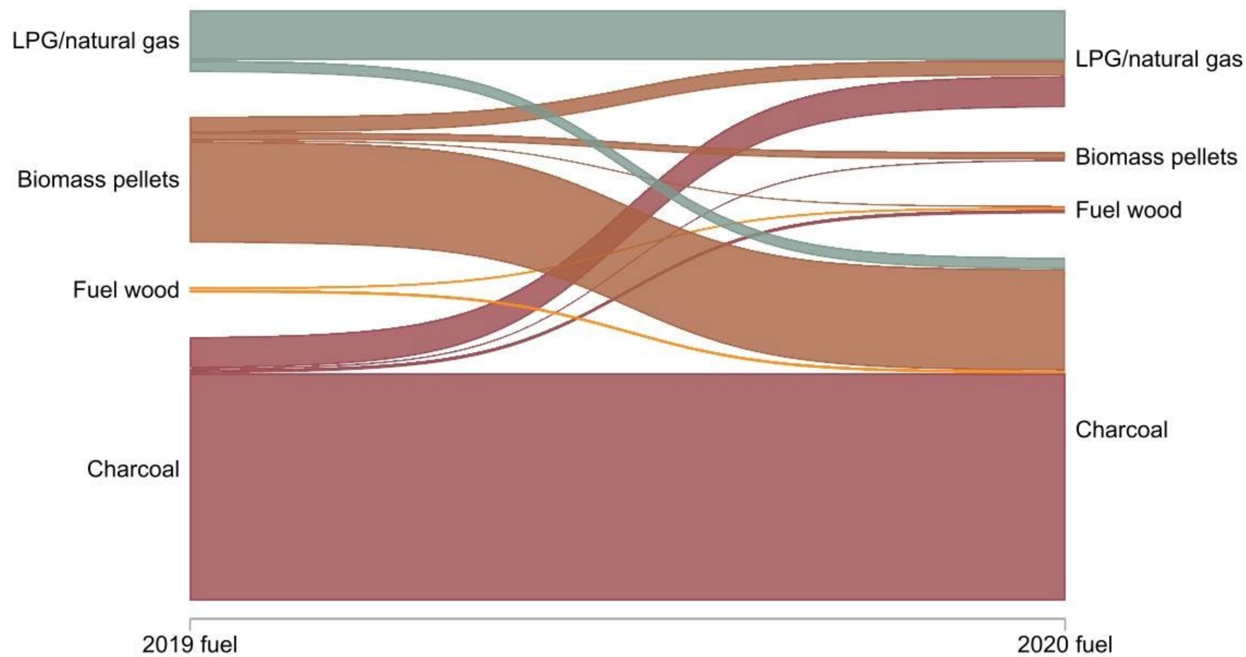


Figure 13. adoption and disadoption from 2019 to 2020 (primary fuel use)

4. Discussion

This study uses data from a randomized controlled trial studying the adoption and impact of biomass pellets and microgasification stoves for household cooking in Rwanda. Over the course of the five-year impact evaluation, LPG was introduced through market mechanisms in Rwanda leading to considerable adoption within the study population, both within the treatment and control groups in the experiment. The dynamic process of adoption observed here highlights the importance of using longitudinal data to study household energy transitions from polluting fuels to clean fuels. The aim of this analysis was to understand what factors were driving the rapid adoption of LPG in this urban sub-Saharan African setting. We consider a range of household level factors (asset wealth, size, home ownership, etc.), characteristics of the main respondent (age, sex, education), and characteristics of the person doing most of the cooking (age). We find compelling evidence, that is robust across sub-samples and across different operational definitions of adoption, of household factors influencing adoption and use of LPG and LPG stoves.

We find some evidence that the age of the main respondent has influence on the uptake of LPG and gas stoves, as in some models, older main respondents were more likely to adopt. This does not contradict previous literature, as studies have shown both positive and negative associations with adoption of various clean cooking technologies and the age of household head. Education, however, is often shown to positively influence the adoption of clean cooking technologies, and we report strong supporting evidence for that narrative. Compared to attaining only primary school education, attaining secondary or a technical education undoubtedly increases the likelihood of adoption – and attaining a university education increases the likelihood significantly more. Age of the primary cook had positive associations with the likelihood to use LPG and adopt a gas stove, expenditure on LPG, and the share of cooking done with LPG. Our results suggest that the household member or hired cook that is doing most of the cooking has influence over which technology is used, and older cooks tend to use LPG more often than younger ones. More attention is usually paid to the characteristics of the household head in studies of adoption patterns of clean cooking, but our results suggest that the cook may have significant influence on adoption.

Our study adds strong evidence to the existing literature that wealth, defined here by ownership of assets, influences adoption of LPG. One likely explanation for the wealth association is that LPG is typically more expensive than other fuels, and is often cost-prohibitive (Karimu, 2015; Karimu et al., 2016; Stanistreet et al., 2019; Troncoso et al., 2019). Our results show that those households spending more on cooking fuel also tend to use more LPG, which supports the notion that it is expensive in this setting. We corroborate findings in other literature that suggest households with larger families are less likely to use LPG. Household size is both negatively associated with consumption and primary use of LPG, suggesting that it may not be the preferred method for preparing large meals for households with many members (Nuño Martínez et al., 2020; Shupler et al., 2021). In a setting where adoption of LPG is driven by market forces, it is likely that poorer households and bigger families will be left out of the transition. It will be most challenging for LPG interventions to reach these households, so policymakers should give special attention to these situations, through subsidies and other targeted policies.

While the share of meals cooked with LPG increased steadily with asset wealth, the inverse is true about the biomass pellet solution. Households in the lower quintiles of wealth were using pellets for a greater share of their cooking, and wealthier households were using pellets to a lesser extent [see figure 7]. Also, pellets were acting as households' exclusive fuel at a greater rate than LPG [see figure 5]. This means that households using pellets as their primary fuel were more often using it exclusively (i.e., suspending the use of other, dirty fuels) than LPG users. There are two, suggestive, conclusions we derive from these finding. First, a pellet solution may be able to reach poorer households with greater success than more expensive fuels like LPG. Second, pellets may be a better substitute for charcoal than LPG, as it was displacing charcoal more effectively within households. However, the business sustainability was the core challenge in this setting, and more attention should be paid to understanding how to make the business model sustainable, as it may be better suited for reaching those that are hardest to reach. Similar pay-as-you-go or stove leasing mechanisms may be better suited for reaching the poorest households with clean cooking solutions in SSA, but business scalability should be studied.

Interesting results that have few parallels in the literature are the water, sanitation, and hygiene (WASH) variables included in the analysis. Having a flush toilet and modern drinking water access report the highest increased odds of adopting LPG, only rivaled by having a university education. Both variables are strongly significant across all models and report high magnitudes of association compared to other indicators that are frequently included in adoption studies. Our results strongly suggest that adoption of WASH technologies and practices and LPG adoption and of use move hand in hand. A recent study from (Zhu & Wu, 2020) in China find that uptake of clean fuels alongside WASH facilities collectively reduced health risks and improved welfare of households. They find that prevention of stunting in adolescent girls is not achieved solely by access to WASH facilities or clean cooking access, but that the two interplay to reduce the risk. Our results reinforce the connection they have made between WASH and clean cooking and indicate adoption of one may lead to the other. There have also been efforts in Rwanda to promote improved cooking alongside drinking water filters through a collaboration between the Rwandan Government and DelAgua, a social enterprise (Barstow et al., 2018). Policy makers may find it easier to increase adoption in clean cooking by coupling their efforts with WASH initiatives, or vice-versa.

Finally, our analysis adds depth the energy ladder discussion. First, we find that wealthier households are more likely to adopt and use LPG, supporting the hypothesis that as socioeconomic status increases, households move towards modern fuels. However, like others (Choumert-Nkolo et al., 2019; Hiemstra-van der Horst & Hovorka, 2008; O. R. Masera et al., 2000), we find that exclusive use of clean fuels without supplemental use of solid fuels is quite rare (regardless of how we define adoption). Stacking of fuels is much more common among those higher up the energy ladder. Out of those who use charcoal as their primary fuel, nearly 80% use it exclusively. Of pellet users, around 45% use it exclusively and less than 20% of LPG users use it exclusively. Thus, in this case moving up the energy ladder does not coincide with fuel switching from higher polluting fuels to less polluting fuels exclusively. We also add some descriptive evidence of non-linearity of the energy ladder to the discussion (refer to figure 13). Between wave two and wave three of data collection, the improved biomass pellet factory closed its doors in Rwanda. Those households that had made the switch from primarily charcoal to a clean burning pellet fuel were forced to move on to a new fuel. As shown above, most of the households reverted to charcoal or "down" the energy ladder after making a step up. Of course, this scenario is highly context-specific, as there was an external supply shock and there was abruptly little to no availability of pellets.

Limitations

Our study focuses on the household determinants of LPG adoption and use but pays little attention to supply side factors that could be important in a household's decision to adopt. In peri-urban Ghana, Shupler et al. (2021) show that supply-related issues like inconsistent fuel supply and high costs associated with cylinder refill are barriers to sustained use of LPG. News stories from Rwanda suggest that charcoal prices were increasing over this period and taxes were scrapped from LPG, making refills of the gas cheaper. Charcoal and LPG prices are likely crucial factors in a household's decision-making process. Unfortunately, we were not able to find data on charcoal prices in the study area over the period of our study. A final caveat is that though we similar rates of LPG take-up in both treatment and control groups, we are not able to conclude that our study did not have an impact on overall LPG take-up in our sample. By virtue of participating in our study (whether in the treatment or control group), study respondents are likely to have an above average understanding of household air pollution health burden and other negative externalities associated with cooking with biomass fuels. Thus, while our study has high internal validity, the external validity or generalizability of our study to the broader population should be interpreted with care.

5. Conclusion

To achieve Sustainable Development Goal 7 (Access to Modern Energy Services) we need to see great reductions in the share of people using solid fuels for cooking, especially in Africa where the rate of cooking with solid fuels is the highest. Gains made in clean cooking can contribute to many other sustainable development goals (Fuso Nerini et al., 2018), as well as improve welfare and well-being. This paper contributes to the understanding of drivers of adoption of clean cooking technologies and, perhaps more policy-relevant, which demographic groups are least likely to adopt. Cleaner household air could prevent premature deaths in sub-Saharan Africa, but to achieve low enough levels of pollutants there needs to be suspension of solid fuel use, which we rarely see in these data. Households that adopt LPG or electricity for cooking, but still regularly burn charcoal or fuelwood indoors for some of the cooking, are not experiencing the full health benefits these fuels can provide. In this sample we see evidence that the biomass pellet solution was reaching the poorest households, something that has been a struggle in the push for clean cooking. Pellets were also displacing charcoal and meeting total household cooking needs at greater rates than LPG, but clearly there were business sustainability challenges.

For policymakers and practitioners, LPG programs should target the households that are most likely to be left out of the energy transition – the poorest. Even if subsidies make LPG cost-competitive with charcoal, attention should be paid to how well LPG displaces charcoal or other woodfuels, even if there is “adoption” of LPG. Future analyses of adoption should study suspension of solid fuels alongside adoption of cleaner fuels. Clean fuel adoption is often operationally defined as primary use or use at all in the literature. However, researchers should be careful not to conflate adoption of clean fuel with suspension of biomass fuels and should not consider adoption alone as a means to adequate reductions in HAP. The pellet model that was reaching poor households here employed something like a pay-as-you-go model, and this should continue to be studied in the clean cooking field. A major limitation of this study is the lack of supply-side information and policies surrounding cooking in Rwanda. Future research should continue to study cooking in Rwanda, as cleaner fuels are being adopted rapidly in urban areas. Further, the Rwandan government is pushing LPG while also restricting the use of charcoal. Attention should be paid to how these policies affect health, forests, and emissions.

Appendix

Full Sample Regression Models

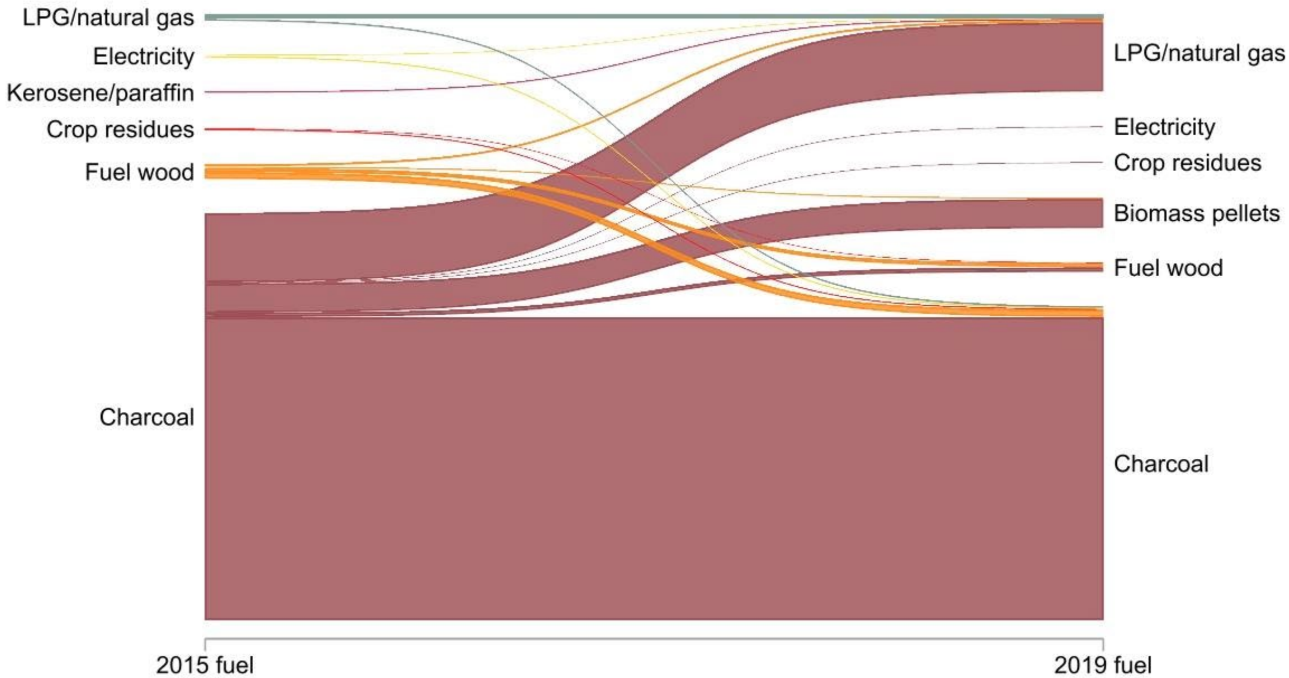
	(1)	(2)	(3)	(4)	(5)
	Full Sample Primary Fuel (Odds Ratios)	Gas Stove Ownership (Odds Ratios)	Full Sample LPG USE 30d (Odds Ratios)	Full Sample LPG Expenditure (Coefficients)	Full Sample LPG Share (Coefficients)
Age of Main Respondent	1.007	1.014**	1.016**	0.00383	0.0305
	(0.00762)	(0.00614)	(0.00624)	(0.00355)	(0.0399)
Female Main Respondent	1.080	1.355*	1.368*	0.0201	-0.174
	(0.232)	(0.237)	(0.244)	(0.115)	(1.349)
Secondary or Technical Edu	2.615***	2.831***	3.089***	0.215**	4.165***
	(0.683)	(0.555)	(0.666)	(0.0929)	(0.979)
University Education	4.081***	4.776***	5.830***	0.416***	8.309***
	(1.205)	(1.053)	(1.409)	(0.116)	(1.313)
Kitchen Outside of Dwelling	0.419***	0.812	0.690**	-0.167*	-4.934***
	(0.0807)	(0.119)	(0.105)	(0.0893)	(1.064)
Total Household Members	0.862***	0.978	0.980	-0.0624***	-0.577***
	(0.0350)	(0.0319)	(0.0335)	(0.0213)	(0.218)
Cook's Age	1.019***	1.009*	1.009	0.00973**	0.127***
	(0.00692)	(0.00550)	(0.00567)	(0.00407)	(0.0375)
Household has a Flush Toilet	2.120***	2.042***	2.026***	0.168	5.287***
	(0.487)	(0.343)	(0.351)	(0.110)	(1.276)
Modern Drinking Water Access	3.340***	2.479***	2.539***	0.557***	8.527***
	(0.588)	(0.363)	(0.372)	(0.124)	(1.297)
Home is Owned (vs. Rented)	1.403*	1.659***	1.779***	0.0898	2.147*
	(0.284)	(0.264)	(0.293)	(0.0902)	(1.098)
Household Owns Land	0.718	0.867	0.770	-0.170*	-1.916
	(0.162)	(0.149)	(0.137)	(0.0980)	(1.209)
Assets Owned	1.343***	1.260***	1.269***	0.0914***	1.783***

	(0.0652)	(0.0491)	(0.0507)	(0.0277)	(0.271)
Per Capita Expenditure on Food (USD)	0.990**	0.984***	0.984***	0.00554	-0.0664**
	(0.00411)	(0.00397)	(0.00409)	(0.00386)	(0.0300)
Per Capita Expenditure on Electricity (USD)	1.016	1.005	0.992	0.171***	0.152
	(0.0260)	(0.0287)	(0.0257)	(0.0509)	(0.195)
Per Capita Expenditure on Cooking Fuel (USD)	1.080***	1.209***	1.261***		0.973***
	(0.0300)	(0.0399)	(0.0475)		(0.257)
lnsig2u	1.960***	1.593**	1.466		
	(0.485)	(0.335)	(0.345)		
Constant	0.00324***	0.00299***	0.00177***	-0.539**	-6.614***
	(0.00193)	(0.00150)	(0.000961)	(0.220)	(2.413)
Observations	3,148	3,148	3,148	3,148	3,148
Number of hh_id	1,852	1,852	1,852	1,852	1,852
Robust seeform in parentheses					
*** p<0.01, ** p<0.05, * p<0.1					

Panel Regression Results

	(1)	(2)	(3)	(4)	(5)
	Full Panel Primary Fuel	Full Panel Gas Stove Ownership	Full Panel LPG Use 30d	Full Panel LPG Expenditure	Full Panel LPG Share
Age of Main Respondent	0.995	1.007	1.006	0.000934	-0.0748
	(0.0120)	(0.0104)	(0.0106)	(0.00630)	(0.0785)
Female Main Respondent	0.681	1.044	0.952	-0.353	-4.608
	(0.227)	(0.316)	(0.290)	(0.250)	(3.038)
Secondary or Technical Edu	2.830***	2.602***	2.651***	0.133	4.864***
	(0.998)	(0.721)	(0.789)	(0.162)	(1.790)
University Education	5.353***	5.216***	6.728***	0.525**	11.63***
	(2.328)	(1.766)	(2.448)	(0.205)	(2.624)
Kitchen Outside of Dwelling	0.392***	0.862	0.793	-0.159	-6.317***
	(0.109)	(0.197)	(0.187)	(0.160)	(1.998)
Total Household Members	0.841***	0.913*	0.934	-0.120***	-0.790**
	(0.0496)	(0.0452)	(0.0463)	(0.0302)	(0.383)
Cook's Age	1.025**	1.014*	1.016*	0.00760	0.198***
	(0.0102)	(0.00811)	(0.00841)	(0.00603)	(0.0600)
Household has a Flush Toilet	2.227**	2.211***	2.193***	0.124	6.216***
	(0.756)	(0.576)	(0.576)	(0.176)	(2.264)
Modern Drinking Water Access	3.140***	3.000***	2.885***	0.691***	10.06***
	(0.786)	(0.687)	(0.628)	(0.208)	(2.101)
Home is Owned (vs. Rented)	1.565	2.317***	2.481***	0.232	4.416**
	(0.531)	(0.647)	(0.702)	(0.151)	(2.045)
Household Owns Land	0.652	0.642	0.616	-0.262	-2.657
	(0.226)	(0.183)	(0.182)	(0.165)	(2.285)
Assets Owned	1.360***	1.233***	1.227***	0.145***	2.047***
	(0.102)	(0.0797)	(0.0811)	(0.0449)	(0.541)

Per Capita Expenditure on Food (USD)	0.989	0.980***	0.980***	0.0116	-0.0985
	(0.00689)	(0.00697)	(0.00666)	(0.00819)	(0.0656)
Per Capita Expenditure on Electricity (USD)	1.041	1.035	0.986	0.0537	0.299
	(0.0629)	(0.0702)	(0.0548)	(0.0567)	(0.487)
Per Capita Expenditure on Cooking Fuel (USD)	1.080*	1.186***	1.254***		1.331***
	(0.0481)	(0.0531)	(0.0633)		(0.447)
lnsig2u	1.722*	1.584	1.582		
	(0.537)	(0.448)	(0.441)		
Constant	0.0110***	0.00991***	0.00589***	0.261	-0.0551
	(0.0100)	(0.00843)	(0.00510)	(0.362)	(5.613)
Observations	1,212	1,212	1,212	1,212	1,212
Number of hh_id	452	452	452	452	452
Robust seeform in parentheses					
*** p<0.01, ** p<0.05, * p<0.1					


LPG/natural gas
Electricity
Kerosene/paraffin
Crop residues
Fuel wood
Charcoal
LPG/natural gas
Electricity
Crop residues
Biomass pellets
Fuel wood
Charcoal
2015 fuel
2019 fuel

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