Pay-as-you-go LPG: a mixed-methods pilot study in urban Rwanda

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Abstract

2.8 billion people still cook with biomass fuels, resulting in devastating impacts on health, gender equity and the environment. Pay-as-you-go (PAYG) liquid petroleum gas (LPG) is a new technology designed to make LPG affordable for urban biomass users by allowing customers to pay for fuel in small amounts. This mixed-methods study (N = 64) combined stove usage data, cooking diaries, household interviews and telephone surveys to examine a commercial PAYG LPG pilot in Kigali. It aimed to understand how households used PAYG LPG and its potential in accelerating access to clean cooking in urban Rwanda.

PAYG LPG rapidly displaced charcoal as the primary cooking fuel for the majority of participants, resulting in a mean monthly reduction in household fuel expenditure of 3,240 RWF (3.50 USD) and a mean consumption of 1.2kg/capita/month. Participants spanning all income brackets in Kigali made use of PAYG LPG. The ability to pay in smaller amounts seemed to be critical to initial adoption and sustained use during the pilot. Follow-up activities with a small subsample of participants (N = 10) found that 70% continued to use full cylinder LPG (typically 12kg) as their primary cooking fuel in the two months after the PAYG service was withdrawn. Throughout the pilot almost all participants continued to use charcoal, which accounted for 21% of cooking events. We identified a range of drivers of fuel stacking that encompassed both cultural and practical factors such as cylinder delivery delays and taste preferences for certain foods.

We conclude that PAYG LPG could contribute to the clean cooking transition in urban Rwanda, but that larger scale pilots are needed to better understand both the supply- and demand-side viability.

Highlights

- PAYG could play an important role in accelerating access to LPG in urban Rwanda
- Customers rapidly adopted PAYG LPG and continued to use it throughout the pilot
- Customers represented all five income quintiles and saved money by switching to PAYG LPG
- Most customers stacked with charcoal; PAYG LPG accounted for 79% of cooking events
- After the pilot ended, 70% of participants kept using LPG as their primary fuel

Key Words

Liquid petroleum gas; fuel stacking; clean cooking; modern energy; Rwanda; PAYG LPG; Mixed methods; Pay-as-you-go; energy transition; behaviour change; adoption; sustained use

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

1. Introduction

There are 2.8 billion people in the world who still primarily cook with biomass fuels (IEA et al. 2020). It is estimated that this results in four million deaths per year (WHO 2018) and up to 8% of total anthropogenic climate impacts (Masera et al. 2015). These problems are particularly concentrated in Sub-Saharan Africa (SSA), where around 950 million people rely on woodfuels to cook (World Bank 2016, World Bank 2019). There is therefore an urgent need for new technologies and business models to accelerate the clean cooking transition in this region.

Liquified Petroleum Gas (LPG) is widely acknowledged to be one of the most promising solutions to this problem, particularly in urban areas where biomass fuels are usually purchased rather than gathered for free (Clean Cooking Alliance 2020). LPG contributes little to the negative health and environmental impacts described above (Grieshop et al. 2011; Puzzolo 2014; Shen et al. 2018). However, barriers to its adoption include: the need to purchase new equipment upfront (Giordano et al. 2018; Gould and Urpelainen 2018); cash flow challenges with buying cylinder refills (Mani et al. 2020; Wilson et al. 2015); and supply-side factors such as local availability of fuel (Dalaba et al. 2018; Kumar et al. 2016).

Pay-as-you-go (PAYG) LPG

PAYG LPG is an emerging innovation that seeks to address some of these challenges. In a typical model, the customer is provided with the system hardware at a small upfront cost: a regulator, hose, stove and cylinder with an embedded smart meter. Credit can be purchased with mobile money services – a prerequisite for using the technology – allowing a corresponding amount of gas to be dispensed. The provider is responsible for monitoring and replenishing cylinders and thus ensuring that customers always have safe access to fuel in their homes. Home delivery is an important differentiating factor for the PAYG model as normally LPG is purchased from local shops. The additional logistical challenges of cylinder delivery in rural locations make the PAYG model more suited to urban areas. The costs of the equipment, financing, service provision and delivery are recuperated by adding a margin to the fuel price, making the levelized cost of cooking with PAYG LPG higher than that of standard LPG. The technology therefore appeals primarily to consumers who purchase biomass cooking fuels in small amounts and cannot afford to switch to standard LPG.

PAYG LPG is a nascent technology and in 2020 there were only three providers (ESMAP 2020). Whilst there has been some early optimism about PAYG LPG (Clean Cooking Alliance 2019; WLPGA 2019), some experts have been sceptical about its ability to scale (The Global LPG Partnership 2019), flagging the high costs of the meters as a critical barrier to success (Clean Cooking Alliance 2020). The only academic publication on PAYG LPG to date compared fuel consumption patterns from PayGo Energy's customer base in Kenya with a similar population using regular LPG (Shupler et al. 2021). It found that PAYG LPG can help promote clean cooking and support LPG use through periods of economic downturn. This was largely due to customers being able to pay incrementally; other advantages included the provision of double burner stoves, increased safety and home delivery. The authors recommended that more research on fuel stacking with the technology is warranted. There is also a need to understand: who are PAYG LPG consumers and what are their experiences of using the

technology? How much fuel do they use and why? The answers to these questions will help establish the potential impact of PAYG LPG in SSA.

Fuel stacking

The parallel use of clean fuels like LPG with traditional ones is known as "fuel stacking". Widespread stacking has been noted in many studies in Rwanda (Iribagiza et al. 2020; Jagger and Das 2018; Rosa et al. 2014), pointing to the fact that traditional cooking methods are rarely abandoned (Masera et al 2000). This phenomenon is problematic because it perpetuates the negative impacts of biomass cooking. Therefore the 'disadoption' of traditional stoves and fuels is equally as important as the adoption of clean ones (Ruiz-Mercado et al. 2011). The root causes of stacking can be cultural, such as the perceived need to cook with biomass to achieve the desired flavour (Troncoso et al. 2019), or practical, such as the incompatibility of traditional pots with new stoves (Burwen and Levine 2012). Recent evidence on LPG cookstoves suggests that the role of cultural factors diminishes when practical barriers are adequately addressed (Williams et al. 2020, Pillarisetti et al. 2019). PAYG LPG can add to this debate because the model addresses many of the challenges that have previously been shown to prevent consumers from adopting LPG and so offers the opportunity to study the residual barriers in a real-world environment.

The Rwandan context

This paper seeks to address the aforementioned knowledge gaps by studying a pilot of PAYG LPG customers in Rwanda's capital city, Kigali. Rwanda relies heavily on biomass cooking fuels; firewood is the primary source for most of the rural population (93%), whereas urban households are split between using charcoal (65%) and firewood (26%) (National Institute of Statistics of Rwanda 2018). LPG use is increasing but remains low. In 2018, 5% of urban Rwandan households used LPG versus 1% in 2014 (Ministry of Infrastructure 2018). This is set to change as the Government expects the annual LPG demand to increase by a factor of 24 between 2018 and 2024 (ibid.). This will be achieved through investments in infrastructure and interventions - such as PAYG schemes - to increase affordability.

Different cuisines vary in terms of their compatibility with LPG. Generally traditioned stoves are preferred for preparing "heavy" foods requiring extensive boiling, like beans and meat stews (Astuti et al. 2019; Ruiz-Mercado and Masera 2015). The ingredients of a typical Rwandan meal are rice, beans, cassava, cabbage, boiled beef, sweet potatoes, bananas and pineapple, with beans being the primary source of protein and taking many hours to cook (Global Alliance for Clean Cookstoves 2013). Little is known about the affinity between LPG and the Rwandan diet as there is limited knowledge about the relative frequencies and methods of cooking these foods.

Aims and objectives

The aim of this study was to understand how households used PAYG LPG in order to assess its potential in accelerating access to clean cooking in urban Rwanda. The specific objectives were, to: (1) establish the socio-demographic characteristics of the customer base; (2) understand the customer experience of using PAYG LPG; (3) quantify the usage of cooking fuels and explain variation between households;

(4) understand the drivers of fuel stacking; and (5) pilot the mixed-methods approach of combining fuel use data, cooking diaries, surveys and interviews.

2 Bboxx PAYG LPG Pilot in Kigali, Rwanda

This study investigated a commercial PAYG LPG pilot in Kigali that was operated by Bboxx. Bboxx are a for-profit company based in the UK who aim to transform lives through energy access (Bboxx 2021). Their focus to date has been PAYG solar devices, selling over 150,000 products across more than 35 countries; the Kigali pilot was their first venture into cooking. It launched in July 2019 with 90 PAYG LPG units and was closed in March 2020. Since then, Bboxx have launched new LPG operations in Kenya and DRC and have plans to re-enter the Rwandan market later in 2021.

The target market for the pilot was charcoal users who could not afford standard LPG. This was reflected in the marketing materials used to attract customers such as a press launch and distribution of leaflets. Units were allocated to the first 90 households that paid a downpayment over a three-month period; there were no other customer selection criteria. The Gasabo and Kicukiro districts were selected as areas of operation due to their high population density and high charcoal usage rates (National Institute of Statistics of Rwanda 2012, National Institute of Statistics of Rwanda 2018). The distribution hub was strategically located in the heart of Kigali City and five nearby sectors were targeted for customer acquisition (Figure 1).

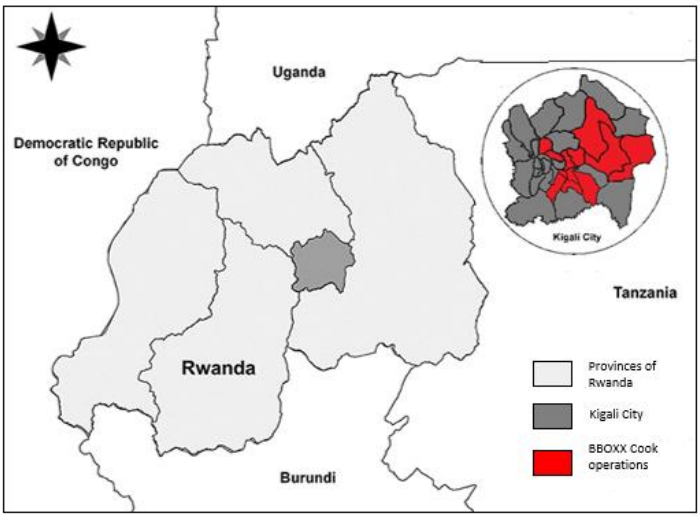

Figure 1: Locations of PAYG LPG customers in Kigali (created by author)

Bboxx technicians trained customers on how to use the equipment upon installation. Ownership of the stove and accessories (regulator and hose) were transferred to the customer after a six-month period in which monthly payments of 9,000 RWF (9.60 USD[1]) were collected. The smart meter and the cylinder continued to belong to Bboxx. Most customers paid a 13,500 RWF (14.40 USD) downpayment which included 2kg of LPG credit. The tariff varied based on monthly usage (1,900 RWF/kg for the first 3kg; 1,750 RWF/kg for the next 3kg; 1,650 RWF/kg for the next 3kg; and 1,280 RWF/kg for any subsequent use), averaging at 1,800 RWF/kg (1.90 USD). This was roughly 1.7x the market price of LPG in Kigali during this period (Rwanda Utilities Regulatory Authority 2019).

[1] : 1 RWF is the equivalent of 0.00107 USD in March 2020 (https://www.xe.com/)

Because this was a pilot project, operations were performed manually with the support of Bboxx's proprietary platform Pulse. Deliveries of new cylinders (12kg in size) and any required maintenance was triggered by customers contacting Bboxx. If customers ran out of credit or fuel during the evenings or weekends then they had to wait until the next working day for a resolution. In this sense the pilot fell short of a mature PAYG LPG offering providing a 'never run out of fuel' service.

3. Methodology

3.1 Sampling

The study started with a telephone survey (N = 62) that attempted to contact of the active PAYG LPG customers (N = 90). As well as collecting data, the survey gauged willingness to participate in other arms of the research. We wished to triangulate between different methods so it was important to have participants enrolled in several components. The triangulation process consisted of comparing single variables measured by multiple methods (e.g. self-reported stove usage and sensor-measured stove usage), thereby increasing the reliability of findings and developing a broader understanding of cooking practices (Carter et al. 2014).

The sampling for each method took into account the need for these overlaps and the different consent profiles of participants. The overall sample sizes were dictated by time and resource constraints. Table 1 and Figure 2 below show the total participants in each research element and the methodological permutations.

Group	N
TS	29
TS & INT	11
TS & INT & SUMs	8
TS & INT & SUMs & CD	5
TS & SUMs	4
TS & CD	3
TS & SUMs & CD	2

Table 1: Overlaps between research methods. TS = telephone survey, INT = household interview, CD = cooking diaries, SUM = stove use monitors

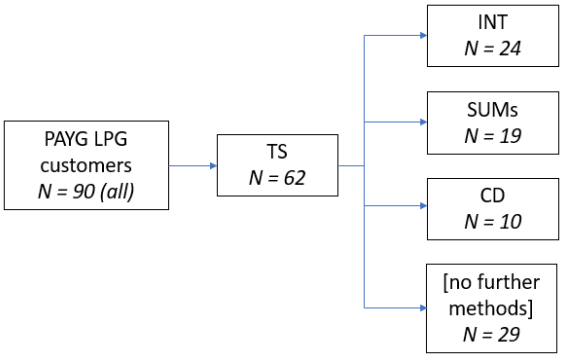

Figure 2: Sampling process

Ethical approval for this study was granted by the University College London Research Ethics Committee [17653/001] and the University of Rwanda.

3.2 Methods

Fuel consumption data

Sensor-collected fuel consumption data allowed an objective assessment of the use of different cooking fuels**.** Bboxx's SMART data was a novel secondary time-series data set collected for all of their

PAYG LPG customers. The window of analysis ran from 1st July 2019 to the 21st May 2020, when the final remaining cylinder in the field ran out of fuel. A measurement of the total volume of gas used by each unit (a 'pulse count') was recorded every ten minutes. Cooking events were identified by subtracting the pulse count at time t from time t-1. It was possible for cooking to take place in a 10-minute interval without registering a pulse, so to avoid double counting of events the data was aggregated into 20-minute intervals prior to processing. This uncertainty over cooking event classification led us to select the unit of analysis as per day rather than per cooking event.

Stove Use Monitors (SUMs) are sensors that quantify stove use by measuring temperature (Ruiz-Mercado et al. 2012). iButton DS1922L Thermochron Data loggers (Maxim Integrated Products, N = 20) monitored charcoal stoves from the 4th March to the 21st May 2020 by taking a reading every ten minutes. All participants used similar artisanal stoves that yielded clean data sets with clear temperature spikes when cooking occurred and were paid an incentive of 6,000 RWF (6.40 USD) for participating. Two households disposed of the stove with the attached SUMs so there were 18 complete sets of data**.** These were analysed with Geocene's SUMSariser tool (https://www.geocene.com/), which uses a machine learning algorithm to identify cooking events from the SUMs data. The model parameters were iteratively tuned to match the SUMSariser output to the cooking events shown in the raw data. This was then overlaid onto the SMART data set to compare the frequency and timings of charcoal and LPG cooking events.

Telephone surveys and household interviews

Telephone surveys (N = 62) were performed by two bilingual enumerators at the outset of the study. The survey focussed on sociodemographic questions and cooking practices before and after the introduction of PAYG LPG. Participants answered most questions by choosing from a fixed range of answers, but some questions were open and were later coded for analysis.

Structured household interviews (N = 24) were conducted by a single enumerator. The interviews explored the use of different cooking devices, cooking traditions, niches of different fuels and opinions on PAYG LPG. Data was also collected to calculate the Rwanda Poverty Parity Index (PPI), a country-specific poverty measurement tool that combines survey questions and observations to estimate the probability that a household is living below the national poverty line (Schreiner 2016).

Bboxx conducted a baseline survey shortly after customers signed up to the product and successfully reached 88% of the population (N = 79). This secondary data consisted of demographic information and was also used in the analysis.

The Bboxx surveys, telephone surveys and household interviews were undertaken in Kinyarwanda and recorded in English using the Kobo Toolbox survey tool. The household interviewees were paid an incentive of 2,000 RWF (2.10 USD) for participating.

Cooking diaries

Cooking diaries (CDs) generate detailed self-reported data on the food that people eat and the devices that they use to cook (Leary et al. 2019). CDs were implemented in this study using the protocols developed by Leary et al. (2019). Participants were asked to fill in a paper form every time they used a cooking device. A separate summary form completed at the end of each day gave an overview of the day's cooking activities and recorded any fuel purchases. The data was manually transferred to a spreadsheet for cleaning, translation and analysis. The summary forms were used to assess the completeness of the data sets for each customer.

A high degree of support from enumerators was planned to facilitate high quality data collection with regular household visits and frequent reviews of the forms. Therefore convenience sampling was used, prioritising those living close to the Bboxx office. Participants were paid an incentive of 4,000 RWF (4.30 USD).

4 Results & Analysis

4.1 Telephone surveys, household interviews & Bboxx surveys

Study Population

Table 2 shows the demographics of the study population along with their self-reported cooking practices. The mean monthly income (250,000 RWF) was 53% higher than the Kigali average (versus 162,500 RWF, Bower et al. 2019) but the median was lower (150,000 RWF). This is illustrated clearly in Figure 3 which shows that PAYG LPG customers were distributed across all five income quintiles and Q3 was the most common category. However, the Poverty Parity Index (PPI) found that the probability of a participant being beneath the Rwandan poverty line was far lower than the Kigali-wide statistic (2.6% versus 22%, The World Bank 2015). Each method had weaknesses; the PPI questionnaire was only performed on the interview participants (N = 24), whereas self-reported income data was drawn from a much larger sample size (N = 62) and may be prone to exaggeration.

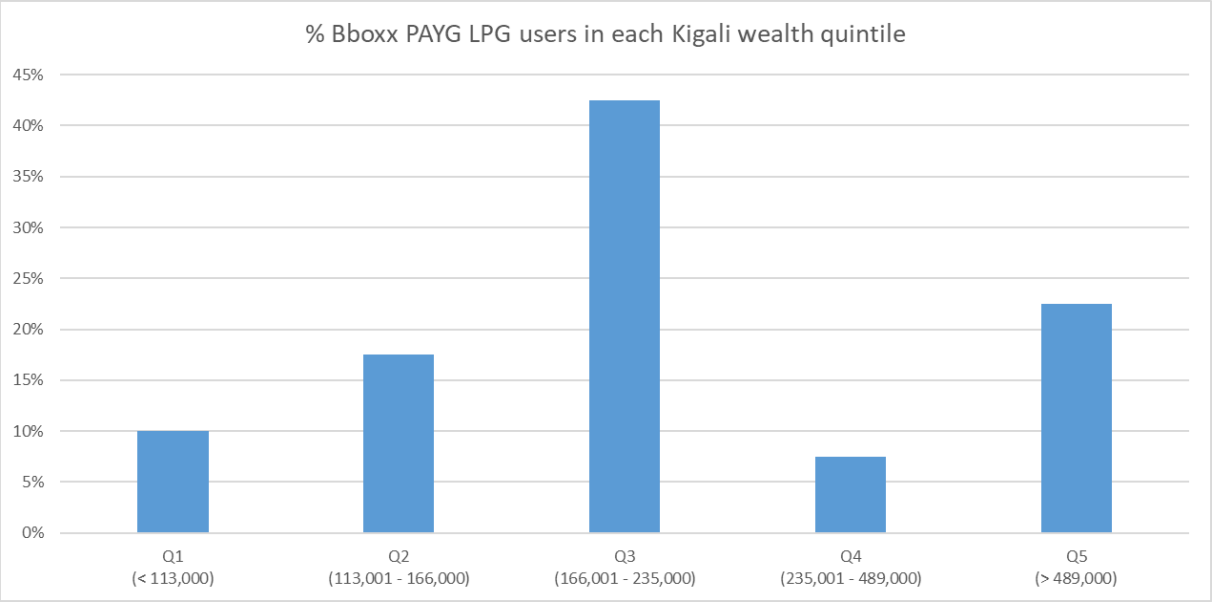

Figure 3: Distribution of Bboxx LPG users against 2019 Kigali income quintiles (source: Bower et al. 2019). Quintile boundaries are displayed in RWF / adult household member / year

Another notable difference was in education levels. The proportion of heads of household with university degrees (47%) was far greater than the Kigali-wide statistic (11%, National Institute of Statistics of Rwanda 2014). Smaller differences were found for the mean household size (3.5 versus 4.0, Bower et al. 2019) and the mean age of the head of household (33 versus 38, National Institute of Statistics of Rwanda 2019). 20% of account holders were female and 9% of households had female heads. Monthly earnings varied for 61% of respondents and all households had access to grid electricity. 83% of the household interviewees said they could afford LPG if there was no PAYG offering from Bboxx. 71% used charcoal as their primary cooking fuel before the pilot and 34% had prior experience cooking with LPG.

Experiences with PAYG LPG

The interview enumerators recorded that 91% of participants still had a working charcoal stove in their home and that 12% had a secondary LPG stove. A small number of electric cooking appliances were observed and were mostly kettles. 63% of participants reported a modest decrease in cooking fuel expenditure since they started using PAYG LPG with a mean saving of 3,240 RWF per month (3.50 USD), corresponding to 1.3% of mean income. However, 34% of participants reported an increase in fuel spend since the introduction of PAYG LPG.

Characteristic	Result	Research tool & total N
Demographics		
Income		
Mean monthly income (self-reported)	250,000 RWF (267.50 USD) *267.50 USD (SD 267.50 USD)*	TS (N = 62)
Median monthly income (self-reported)	150,000 RWF (160,50 USD)	TS (N = 62)
Monthly income IQR (self-reported)	200,000 RWF (214.00 USD)	TS (N = 62)
Probability beneath Rwandan poverty line	2.6%	INT (N = 24)
Proportion with variable incomes	61% (N = 38)	TS (N = 62)
HH characteristics		
Mean household size	3.5 (SD 2.3)	TS (N = 62)
Mean age of head of household	33 (SD 8.2)	INT (N = 24)
Proportion with access to grid electricity	100%	TS (N = 62)
Proportion of female account holders	20%	TS (N = 62)
Proportion of female heads of household	9%	TS (N = 62)
Education		
Primary	20% (N = 16)	Bboxx survey (N = 79)
Secondary	33% (N = 26)	Bboxx survey (N = 79)
Tertiary	47% (N = 37)	Bboxx survey (N = 79)
Cooking		
Primary cooking fuel before Bboxx		
Charcoal	71% (N = 56)	Bboxx survey (N = 79)
LPG	28% (N = 22)	Bboxx survey (N = 79)
Other	1% (N = 1)	Bboxx survey (N = 79)
Cooked with LPG before Bboxx		
Yes	34% (N = 21)	TS (N = 62)
No	66% (N = 41)	TS (N = 62)
Could afford LPG if no PAYG offering		
Yes	83% (N = 20)	INT (N = 24)
No	17% (N = 4)	INT (N = 24)
Observed cooking devices in home		
PAYG LPG	100% (N = 24)	INT (N = 24)
Charcoal stove	91% (N = 22)	INT (N = 24)
Kettle	21% (N = 5)	INT (N = 24)
Other LPG	12% (N = 3)	INT (N = 24)
Juice maker	4% (N = 1)	INT (N = 24)
Change in cooking fuel expenditure since PAYG		
Mean fuel saving per month	3,240 RWF (SD 13,200) *3.50 USD (SD 14.10 USD)*	TS (N = 62)
Number of households with decreased spend	63% (N = 39)	TS (N = 62)
Number of households with increased spend	37% (N = 23)	TS (N = 62)

Table 2: Results from surveys and household interviews

The survey respondents were asked whether they agreed with five statements about PAYG. Only 32% (N = 8) believed that PAYG LPG was affordable whereas 90% would recommend PAYG LPG to a friend. The following quotes illustrate the rationale behind some of the responses and highlight the range of perceptions on affordability and recommendations:

> "*The PAYG LPG is safe because everyone knows how to use it … I would recommend everyone to use PAYG LPG because it saves time,"* (customer 86).
>
> "*PAYG LPG is safe, but the price is still high that I can't recommend anyone to buy it,*" (customer 103).

Safety was an important recurring theme in the interviews and 94% of respondents believed that PAYG LPG was safe. Compared to standard LPG, the biggest advantage of PAYG was the ability to buy small amounts of a fuel at a time. The biggest disadvantage was delays in cylinder deliveries and credit top ups:

> "*Before I couldn't buy gas unless I had much money, but today I can buy [it] with whatever money I have,*" (customer 57).
>
> *"Getting Bboxx over the weekends is struggle and this makes me use charcoal again,"* (customer 11).

Experiences with LPG

A limitation of LPG was its unsuitability to cooking certain dishes:

> "*There are some kinds of foods [that are] better when cooked using traditional charcoal stove,*" (customer 19).

% of participants said that beans were best not cooked on LPG and 38% said cassava leaf. This was because these foods take a long time to cook so are too expensive to prepare on LPG.

4.2 SUMs and SMART Data

Table 3 shows that participants with SUMs placed on their stoves were representative of the larger survey population. The mean LPG consumption was 1.2kg/capita/month (SD 1.0), corresponding to a cylinder replenishment every three months.

Characteristic	Result from surveys (N = 62)	Result from SUMs (N = 19)	Significance [1] (P (Z <=z))
Mean monthly LPG use/capita	1.2 kg (SD 1.0)	1.3kg (SD 0.6)	p = 0.65
Mean monthly income	250,000 RWF (SD 306,000) *267.50 USD (SD 327.40 USD)*	250,000 RWF (SD 249,000) *267.50 USD (SD 266.40 USD)*	p = 0.96
Mean household size	3.5 (SD 2.0)	4.6 (SD 2.2)	p = 0.19
Highest education level: primary	20%	22%	p = 0.83
Highest education level: secondary	33%	17%	p = 0.17
Highest education level: tertiary	47%	61%	p = 0.28
Charcoal as primary fuel before LPG	71%	67%	p = 0.72
Variable incomes	61%	71%	p = 0.45

Table 3: Comparing results from the telephone surveys and SUMs

The SMART and interview data revealed similar purchasing patterns for the two fuels (LPG: four times per month at 2,530 RWF / 2.70 USD on average; charcoal: three times per month at 3,280 RWF / 3.50 USD on average). The modal charcoal purchase amount was 400 RWF (0.40 USD) for a small bucket weighing roughly 500g. These figures gave an estimated average monthly fuel spend during the pilot of 10,500 RWF (11.20 USD) for LPG and 8,350 RWF (8.90 USD) for charcoal. Customers with variable incomes had smaller top up amounts (2,250 RWF (2.40 USD)) than those with fixed incomes (3,300 RWF (3.50 USD)). There was good agreement between self-reported and measured cooking event frequencies as shown in Table 4. Mean cooking event durations were 1h:35m for charcoal and 45m for LPG.

On days when both SUMs and SMART data were collected both fuels were used on 34% of days, PAYG LPG only on 54% of days, charcoal only on 7% of days and neither fuel on 8% of days. The extent of stacking varied widely between households, as is shown in Table 4, with LPG being used for 23-100% of cooking events (mean: 78%; median: 87%; SD: 19%). 66% of respondents said that they used charcoal alongside LPG, despite charcoal cooking being detected by all but one deployed SUMs.

Characteristic	Result	Research tool & total N
Fuel purchasing		
Charcoal purchasing frequency	3 times / month	INT (N = 24)
Charcoal mean purchase size	3,280 RWF *(3.50 USD)*	INT (N = 24)
Charcoal mean spend per month	8,350 RWF / month *(8.90 USD / month)*	INT (N = 24)
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PAYG LPG mean purchasing frequency	4 times / month	SMART (N = 64)
PAYG LPG mean purchase size	2,530 RWF (1.4kg) *(2.70 USD)*	SMART (N = 64)
PAYG LPG mean spend per month	10,500 RWF (5.8kg) *(11.20 USD)*	SMART (N = 64)
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PAYG LPG mean purchase for fixed income custs	3,300 RWF (1.8kg) *(3.50 USD)*	SMART & TS (N = 62)
PAYG LPG mean purchase for variable income custs	2,250 RWF (1.3kg) *(2.40 USD)*	SMART & TS (N = 62)
Cooking events		
Charcoal mean cooking events per month	17.2 times / month	INT (N = 24)
Charcoal mean cooking events per month	19.6 times / month	SUMs (N = 18)
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PAYG LPG mean cooking events per month	76.8 times / month	INT (N = 24)
PAYG LPG mean cooking events per month	72.8 times / month	SMART (N = 64)
Cooking event duration		
Charcoal mean duration	01:35:08	SUMs (N = 18)
LPG mean duration	00:42:07	SMART (N = 64)
Stacking – do you use charcoal alongside PAYG LPG?		
Yes (self-reported)	66% (N = 41)	TS (N = 62)
Yes (self-reported)	100% (N = 10)	CD (N = 10)
Yes (measured)	100% (N = 18)	SUMs (N = 18)
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No (self-reported)	34% (N = 21)	TS (N = 62)
No (self-reported)	0% (N = 0)	CD (N = 10)
No (measured)	0% (N = 0)	SUMs (N = 18)
Stacking – proportion of DAYS each fuel combo used		
PAYG LPG only days	51%	SUMs & SMART (N = 18) [1]
Charcoal only days	7%	SUMs & SMART (N = 18) [1]
PAYG LPG + charcoal days	34%	SUMs & SMART (N = 18) [1]
Neither PAYG LPG nor charcoal days	8%	SUMs & SMART (N = 18) [1]
Stacking – proportion of MEALS each fuel combo used		
LPG only meals	54%	CD (N = 10) [2]
Charcoal only meals	34%	CD (N = 10) [2]
LPG + charcoal meals	12%	CD (N = 10) [2]

Table 4: Comparing stove data

[1]: Data set was filtered on days where both fuels were measured

[2]: Note that this includes both PAYG LPG and other LPG sources that were used after the pilot ended

Figure 4 and Figure 5 compare the timings of cooking events on days where only one fuel was used versus “stacked” days when both fuels were used. The graphs show that cooking was concentrated in two peaks that likely correlate with meal times. On stacked cooking days a higher proportion of LPG cooking events took place in the evening (Figure 5). This suggests that a higher ratio between the frequency of evening to daytime cooking events in the SMART data could indicate stacking.

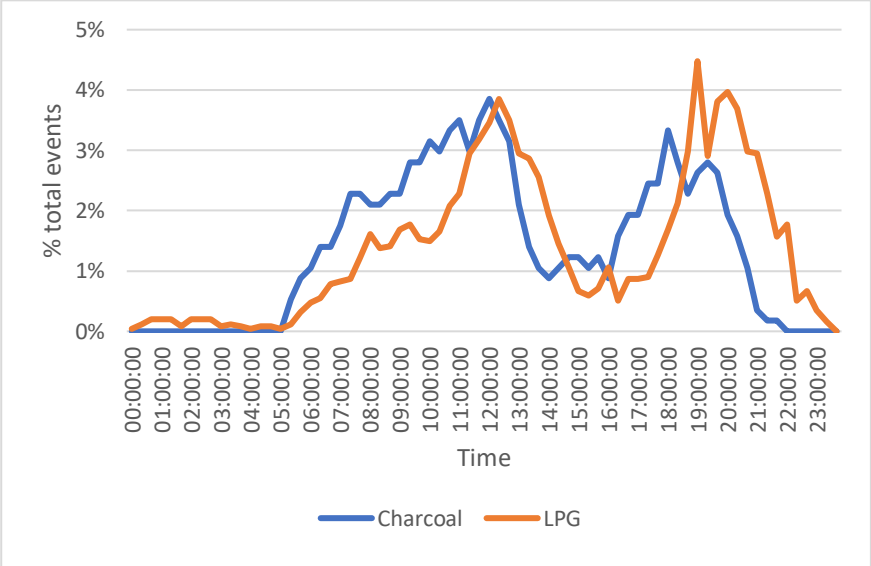

Figure 4: Timing of cooking events for days when only one fuel was used (local time)

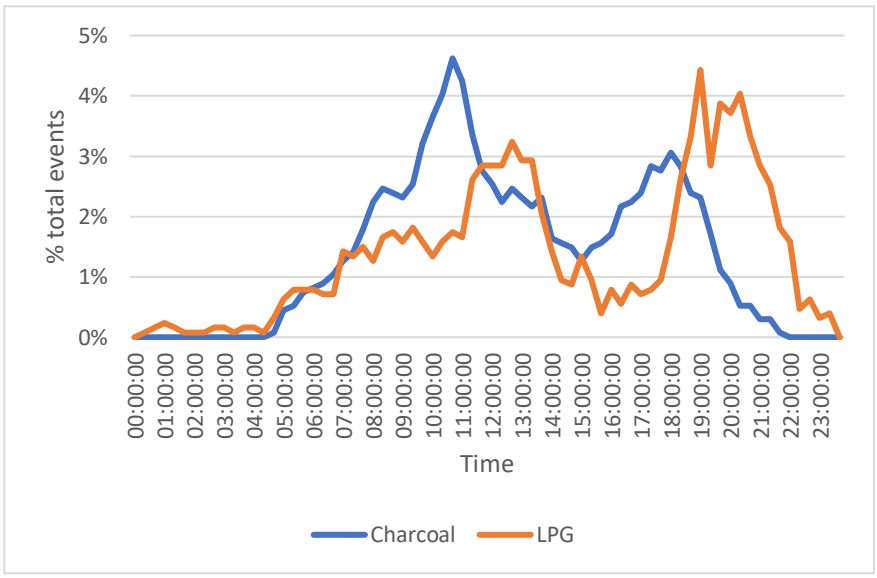

Figure 5: Timing of cooking events for days when both fuels were used (local time)

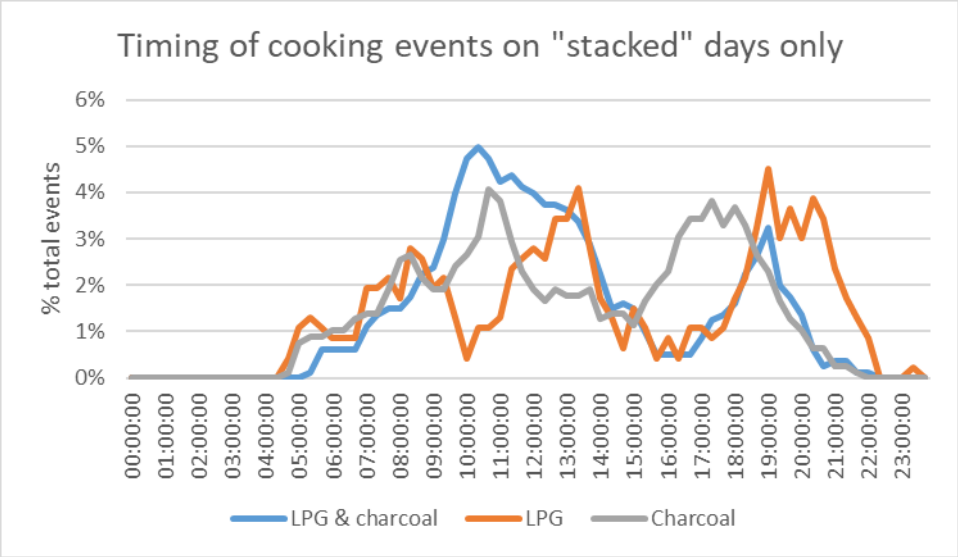

Figure 6: Timings of cooking events on "stacked" days (local time)

7% of cooking events recorded by the SUMs and smart meters involved simultaneous LPG and charcoal use ("stacked" events, N = 75). Figure 6 shows the timings of events by fuel type on stacked cooking days only. In the middle of the day stacked events coincided with charcoal only cooking, whereas in the evening stacked events took place earlier than either charcoal or LPG only cooking.

Figure 7 and Figure 8 give an overview of LPG usage throughout the pilot. Together these graphs show that PAYG LPG adoption was rapid and sustained, although some customer attrition (16%) did occur in the first three months of use. Figure 7 shows the number of active units throughout the pilot where an 'active' unit was defined as one used in the last seven days. The ramp-up between July and October reflects unit installation and the sharp fall in March was due to the pilot close-down. Customer retention was high from January to March. Figure 8 shows how the mean daily LPG consumption per household varied over time and demonstrates that after 10 days, customers had settled into stable patterns of use. Consumption was higher during the first few days, which could represent the learning curve for using gas or experimentation with a new form of cooking.

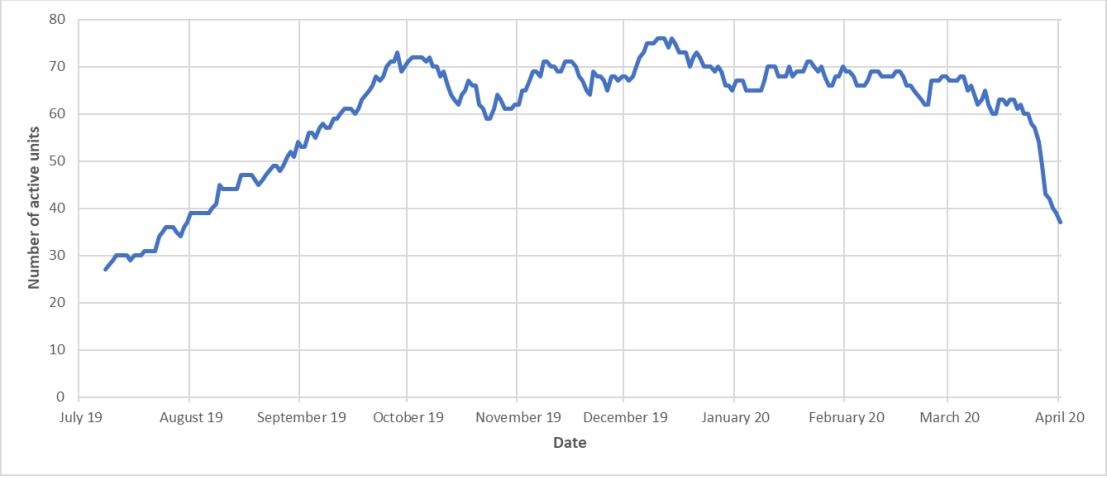

Figure 7: PAYG LPG customer retention

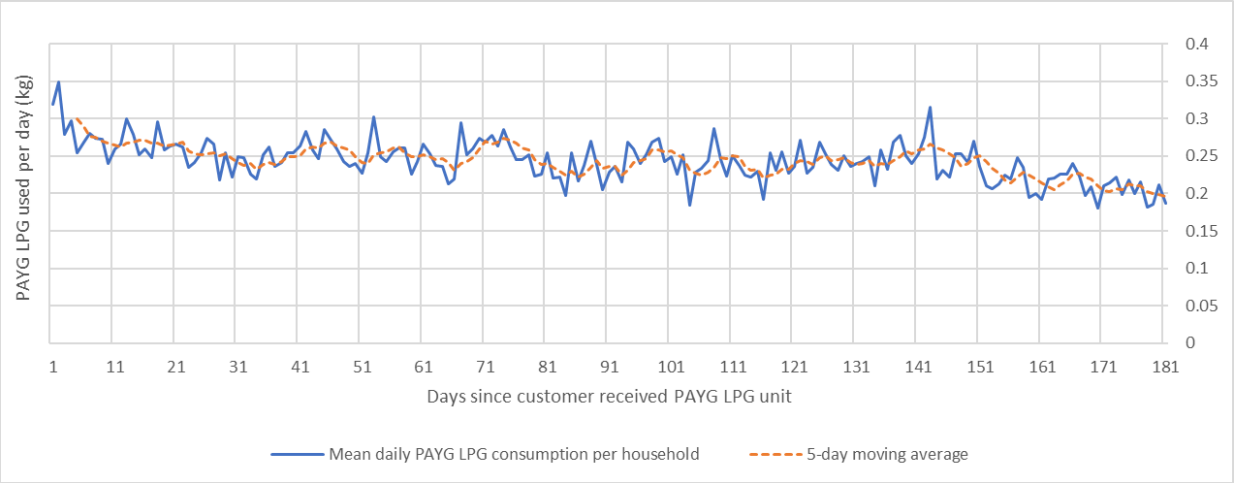

Figure 8: Mean LPG consumption per customer over time

Figure 9 compares the purchasing patterns of a PAYG LPG customer to a counterfactual of purchasing 6kg LPG cylinders. It illustrates that the cashflow allocation of PAYG LPG is very different to standard LPG.

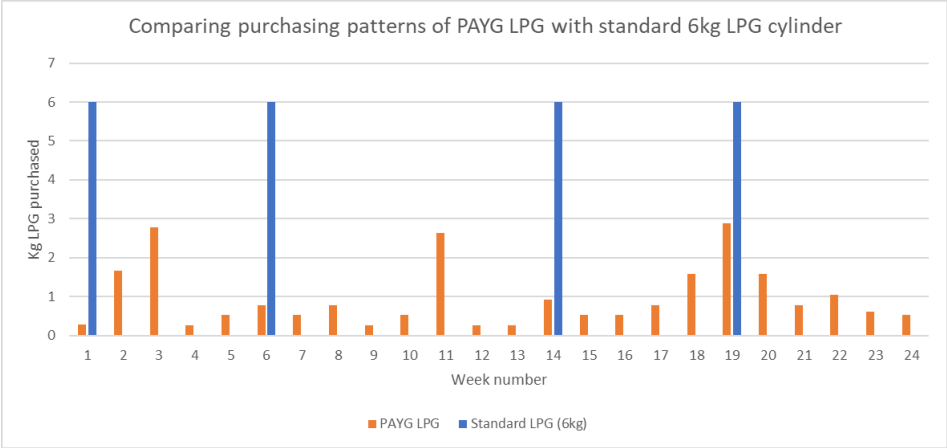

Figure 9: Comparing cash flow for PAYG LPG with standard LPG for customer 3

4.3 Cooking Diaries

The cooking diaries activity had only just commenced when the Rwandan COVID-19 lockdown was announced. This meant enumerators were unable to visit the households to collect the data or replenish the diaries. Consequently some data fields were poorly completed and had to be excluded from the analysis: the weights of charcoal used, the time of meals, the quantity of each dish cooked and the use of pan lids. 157 days' worth of data was collected and there was no participant loss. The number of meals recorded on the daily summary forms matched the number of meal forms on 70% of days. Faithfulness to meal form completion was high at 92%. The bulk of data collection was delayed until the lockdown eased in May 2020, by which time Bboxx's pilot had ended. This means any LPG use recorded would have come from a standard provider.

Analysis of the cooking events recorded in the diaries confirmed that the degree of fuel stacking varied widely between households, with LPG accounting for 13-98% of cooking events (mean: 62%; SD: 31%). Around one third of recorded cooking events were for heating water (34%) and the remainder for cooking food (66%). LPG was the dominant fuel for both categories.

The most common foods were green vegetables (usually fried), rice (usually boiled), ugali (cooked slowly whilst vigorously stirring), potatoes (boiled or fried), bananas (usually boiled) and beans (boiled or refried after boiling), which together accounted for 74% of total food cooking events. Water heating was for making hot drinks, bathing, purifying drinking water and 'other' activities such as making porridge. LPG was preferred for all foods other than beans (Table 5). The average cooking time for a dish was 42 minutes but beans took 89 minutes. A more detailed breakdown of the cooking diaries results can be found in Perros et al. (2021).

	Total cooking events [1]	**LPG cooking events [2]**	**Charcoal cooking events [2]**	**Mean cooking time across both fuels**
Food cooking events	**721**	**435 (60%)**	**286 (40%)**	**42 mins**
Green vegetables	212 (29%)	* 137 (65%)	75 (35%)	32 mins
Rice	119 (17%)	* 79 (66%)	40 (34%)	38 mins
Ugali	60 (8%)	* 33 (55%)	27 (45%)	52 mins
Potato	57 (8%)	* 29 (51%)	28 (49%)	44 mins
Bananas	57 (8%)	* 35 (61%)	22 (39%)	36 mins
Beans	54 (7%)	22 (41%)	* 32 (59%)	89 mins
Other	162 (22%)	* 100 (62%)	62 (38%)	-
Water heating events	**366**	**222 (61%)**	**144 (39%)**	
Hot drink	171 (46%)	* 101 (59%)	70 (41%)	
Bathing	77 (21%)	* 46 (60%)	31 (40%)	N/A
Drinking water	46 (13%)	23 (50%)	23 (50%)	
Other	72 (20%)	* 52 (72%)	20 (28%)	

Table 5: Cooking diaries summary

[1] : Brackets indicate % of total cooking events

[2] : Brackets indicate % of cooking events recorded for each dish

** : Indicates majority cooking fuel*

The association between different foods and choice of fuel was also investigated. There was positive correlation between average cooking time and preference for using charcoal (Figure 10).

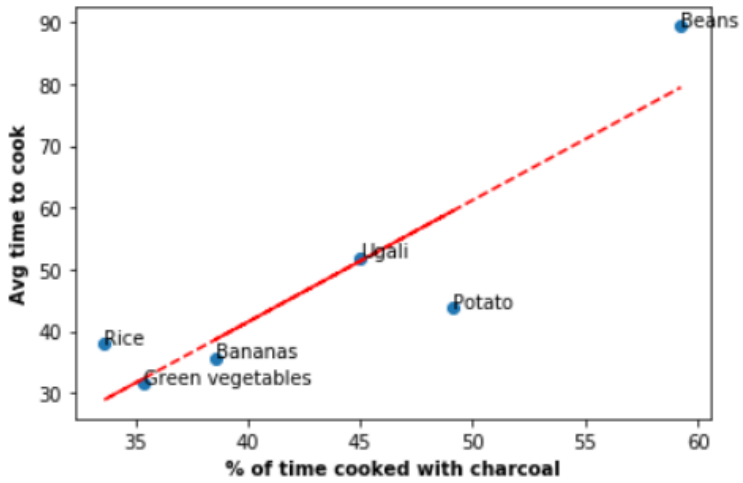

Figure 10: Cooking times versus choice of cooking fuel

Eight out of ten cooking diaries participants recorded at least one stacked meal where both charcoal and LPG were used concurrently. This happened in 12% of all meals recorded. The mean number of dishes was lower for meals involving a single cooking fuel (2.12) than those with multiple fuels (2.73). There was positive correlation between household size and the number of average dishes per meal (Figure 11).

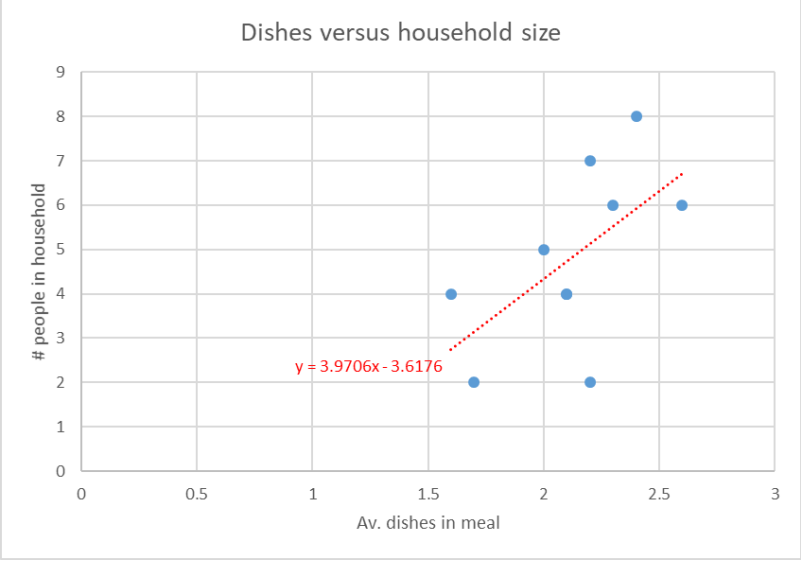

Figure 11: Dishes versus household size

4.4 Impact of COVID-19 and Pilot End

The escalation of the COVID-19 pandemic caused considerable disruption to the study. Rwanda went into total lockdown on the 21st of March 2020 (Nkurunziza 2020) and in-person data collection activities were halted. This coincided with Bboxx's closing of the pilot and forced them to pause their repossession activities, thus leaving some PAYG LPG units in customers' homes. To the best of our knowledge the availability of charcoal and standard LPG was unaffected by the lockdown.

The effects of the pandemic were far-reaching and may have diminished the study's validity with respect to 'normal' times. The extent of these impacts was measured by comparing data collected for each method at different periods in the pandemic and pilot termination process ("before pilot end", "after pilot end", "before lockdown" and "during lockdown") and the results of this analysis are shown in Table 6. The termination of the pilot resulted in an increase in charcoal cooking with families using their charcoal stove one more time per week. During lockdown, LPG cooking days reduced by 12% whereas the proportion of charcoal cooking days remained stable. On days where charcoal was used, fuel use intensified as shown by the increase in mean event duration. The proportion of days on which neither fuel was used rose from 8% to 14%.

Comparison	Data Source	Result
Impact of Bboxx pilot end [1]		
Change in mean weekly charcoal cooking events	SUM	Before pilot end: 3.9; after pilot end: 5.3
Change in proportion of days on which charcoal was used	SUM	Before pilot end: 34%; after pilot end: 42%
Impact of COVID-19 lockdown [2]		
Change in proportion of days on which LPG was used	SMART	Before lockdown: 87%; during lockdown: 75%
Change in proportion of days on which charcoal was used	SUM	Before lockdown: 41%; during lockdown: 38%
Change in proportion of days on which both charcoal and LPG were used	SMART + SUM	Before lockdown: 38%; during lockdown: 25%
Change in proportion of days on which neither charcoal or LPG were used	SMART + SUM	Before lockdown: 8%; during lockdown: 14%
Change in mean daily time spent cooking with LPG	SMART	Before lockdown: 1:50; during lockdown: 1:58
Change in mean daily time spent cooking with charcoal	SUM	Before lockdown: 1:04; during lockdown: 1:23

Table 6: Impacts of COVID-19 and pilot end

Cooking diaries collected after the lockdown eased showed that seven out of ten participants had continued to use LPG despite no longer being customers of Bboxx. A comparison to data collected on primary cooking fuels before the pilot (Figure 12) showed that six participants had upgraded their primary cooking fuel from charcoal to LPG. Only one had moved down the energy ladder by going from LPG to charcoal.

[1]: The pilot end date varied for each customer depending on when the units were retrieved)

[2]: Data set was filtered on days where both fuels were being measured)

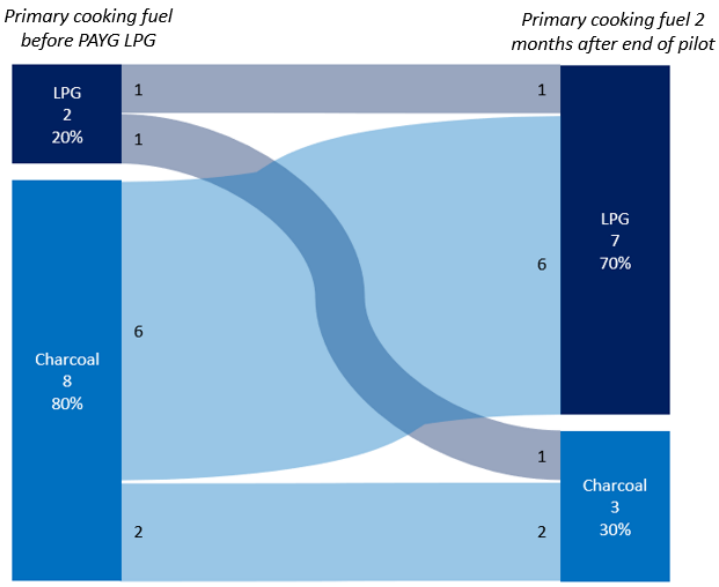

Figure 12: Impact of PAYG LPG on primary cooking fuel

5 Discussion

5.1 Socio-demographic characteristics of the customer base

PAYG LPG customers were better educated than the Kigali average and 83% said they could afford LPG if there was no PAYG service. This finding is unsurprising as it matches the characteristics of those who are predisposed to using clean cooking solutions (Lewis and Pattanayak 2012; Pye et al. 2020) and adopting new products (Rogers 2003). The vast majority of account holders were male (80%). This could demonstrate a gender power imbalance in domestic decision making, which has been identified as a constraint to the clean cooking sector (Hart and Smith 2010) and specifically to LPG adoption (Choudhuri and Desai 2020; Gould and Urpelainen 2020). There were more female account holders (20%) than heads of household (9%), suggesting women had agency over cooking fuel choice in at least some cases. More research is warranted to understand domestic decision-making in this context, but policies that foster female empowerment may aid the adoption of PAYG LPG in Rwanda.

Different methods gave contradictory findings about the wealth demographics of PAYG LPG customers so we propose that future research focusses on establishing this more reliably. However, the telephone survey (which had the largest sample size) found that participants were concentrated in the median income quintile for Kigali, and that 71% used charcoal as their primary cooking fuel prior to the pilot. This indicates that the pilot was successful in addressing existing barriers to standard LPG in urban Rwanda.

5.2 Customer experience of using PAYG LPG

Customers quickly adopted PAYG LPG and continued to use it for the duration of the pilot. This is notable as other studies have emphasised the importance of policy interventions for achieving LPG adoption and sustained use (Astuti et al 2019; Kumar et al 2016) whereas this transition was instigated by the private sector. This indicates that PAYG LPG could be an effective demand-side intervention for addressing reliance on polluting cooking fuels amongst the urban middle-classes in low and middle-income countries and echoes the conclusions of Shupler et al. (2020). Further evidence of this emerged from strong perceptions that PAYG LPG was safe, which contrasted sharply against the widespread mistrust in LPG previously observed in Rwanda (Iribagiza et al. 2020). This may explain why some customers who already used LPG switched to PAYG. However, there were instances where service constraints from Bboxx - such as operational close-downs at weekends –forced customers to periodically revert to cooking with charcoal. In this way the pilot failed to resolve the supply chain challenges associated with LPG in Rwanda (Iribagiza et al. 2020). This illustrates how important it is for service providers to have sound operations capable of supporting a complete transition to clean fuels.

PAYG LPG was purchased in small amounts with an average top up value of 2,530 RWF (2.70 USD, 1.4kg) this was the most valued aspect of PAYG LPG. While the interviews revealed perceptions that standard LPG was affordable this may not have been the reality; a typical 12kg cylinder refill in Kigali would have cost around 12,700 RWF, or 8% of the median income for the pilot customers. This suggests that small payments were made out of necessity and that the ability to pay-as-you-go was

an essential part of the product offering, mirroring findings by other cooking fuel providers in the region (Jagger and Das 2018; Shupler et al. 2020).

After the pilot ended, 70% of participants continued to use LPG from a non-PAYG retail provider, which was likely facilitated by their experiences with PAYG LPG and the equipment obtained through it. It is important to note that because participants were commercial customers they were likely more predisposed to using LPG than the average cook in Kigali. Larger-scale pilots are needed to understand the relevance of these findings to the broader population and whether customers would voluntarily transition from PAYG to standard LPG in the absence of operational closure. Shupler et al. (2020) found that PAYG LPG facilitated clean cooking during the COVID-19 pandemic by offering flexibility for fuel purchase, which may explain why some participants reverted to charcoal after the pilot closure. The proportion of days on which neither charcoal nor LPG were used almost doubled during lockdown, despite people being confined to their homes, and charcoal stoves were used once more per week on average. This suggests that the lockdown may have caused higher household air pollution exposures and increased food insecurity.

Perceptions of low affordability due to the high markup on standard LPG were a hindrance, even though most participants actually experienced decreases in expenditure since cooking with PAYG LPG. This could be because it is difficult to directly compare how much PAYG LPG would deliver the same amount of cooked food as a 500g bucket of charcoal, given that the two fuels have vastly different specific energies. It is easy, however, to contrast the cost of one kg of PAYG LPG against one kg of standard LPG and feel short-changed, particularly as few customers understood why PAYG LPG was more expensive. Educating customers about the tariff and the additional value gained through the PAYG model (e.g. cylinder delivery, ability to pay in small amount, asset financing) is critical for service providers.

Despite these complaints about affordability 90% of respondents said that they would recommend PAYG LPG. This could be because the economic shortcomings were outweighed by the other benefits or because of bias arising from customers trying to influence the service. This could have resulted in exaggerated responses, particularly around affordability (as it was customers' biggest gripe) and recommendations (as Bboxx had an incentive structure for customer referrals). Social networks are a key driver for the diffusion of new technologies (Bandiera and Rasul 2006; Conley and Udry 2010), including LPG (Srinivasan and Carattini 2020), so the high willingness to recommend the product is an indicator that is has potential to grow in the Rwandan market.

5.3 Usage of cooking fuels and explain variation between households

Stacking with charcoal (91%) and electricity (25%) was widespread but varied between households; the SUMs data showed LPG was used for 23-100% of cooking events (mean: 78%; SD: 19%). Thus, like almost all other clean cooking interventions, PAYG LPG was not successful in completely transitioning customers away from biomass fuels. The mean usage was 1.2 kg/capita/month, which is 19% higher than the pre-lockdown consumption rate of 0.97 kg/capita/month recorded by another PAYG LPG provider in Kenya (Shupler et al. 2020). This could be because the Kenyan sample used a broader range of other cooking fuels so could have been stacking more. Yet given the prevalence of fuel stacking in the Rwandan pilot and the operational limitations, there was clearly room for this to grow. A comparison can be drawn to Kenya, where people eat a similar diet, and it is estimated that urban

primary LPG users consume 1.6kg/capita/month and urban exclusive LPG users consume 2.0kg/capita/month (The Global LPG Partnership 2019).

Our analysis also identified that stacking could be detected by calculating the ratio between mealtime cooking event peaks, although more research with larger sample sizes is needed to develop this method. On days where only one fuel was used, there were two consumption peaks of equal magnitudes, whereas on stacked cooking days there was a clear preference for using charcoal in the day and LPG in the evenings. An explanation for this could be that it is better to use charcoal stoves outside because they produce smoke, which is easier during the day when there is natural light available. LPG stoves, by contrast, produce no smoke, so are likely to be the preferred device in the evenings. So if a cook actively decides to use charcoal to cook a specific dish then they are likely to do so during the day.

The proportion of cooking events with concurrent fuel use was 7% in the sensor-collected data sets, which is considerably less than the 12% recorded in the cooking diaries. Inspection of the raw SUMs and SMART data showed that LPG and charcoal were often used very close together although not at the same time; these instances would have looked like "stacked" cooking events in the diary forms. This suggests that cooks sometimes preferred to tend one stove at a time, suggesting there were labour constraints in the kitchen.

5.4 Drivers of fuel stacking and interventions to promote the adoption of clean cooking technologies

A third of recorded charcoal events were heating water for purification, bathing and making hot drinks. The introduction of specific water-heating devices such as electric kettles or solar water heaters could reduce charcoal usage but would also displace PAYG LPG. This approach is aligned with the philosophy that complete clean cooking transitions require a range of clean technology options (ESMAP 2020) and illustrates the limitation of providing LPG in isolation from other energy services.

All participants had issues with fuel availability due to operational limitations of the pilot and would have used more PAYG LPG if there was better service. Ways of addressing this include: extending the staffing hours of the service team; automating manual processes such as credit top ups; and proactively replacing cylinders. However, the relative infrequencies of top-ups and cylinder refills (once a week and once every three months respectively) mean that these supply-side issues could not have accounted for the totality of stacking recorded.

Meals prepared with two cooking fuels had more dishes (2.73) than those prepared with one fuel (2.17). This suggests that a driver of fuel stacking was the need to cook multiple components at once and that providing four-burner stoves could be an appropriate solution. Larger households cooked meals with more dishes but it took four extra family members to add an extra dish to a meal. Therefore the additional food requirement for larger households mostly came from cooking larger quantities of food rather than more dishes. Willingness to pay and culinary preferences are likely to be stronger indicators of the suitability of larger stoves than demographic variables.

It is likely that the perception of PAYG LPG as an expensive fuel led to lower use. This could be resolved by educating customers about how to make cost comparisons between fuels, by tracking savings made

through using PAYG or by amending the tariffs to separate out a regular servicing charge from the on-demand LPG price.

Cooking diaries and telephone surveys found that beans and 'hard' foods were a driver of fuel stacking as people preferred to cook them on charcoal than on LPG. This was due to the practice of cooking beans from a dried state by boiling them for several hours; it was likely seen as 'wasteful' to use 'expensive' PAYG LPG on such a long task. Interventions that could have addressed this include promoting practices that accelerate cooking of hard foods such as using pressure cookers or pre-soaking beans. These hard foods only accounted for 5% of the cooking events recorded in the diaries, showing that LPG had a high degree of compatibility with participants' diets.

5.5 Reflection on the mixed-methods approach of combining stove use data, cooking diaries, surveys and interviews

Only 66% of telephone survey participants said they used charcoal alongside LPG yet almost everyone who participated in the cooking diaries and SUMs used charcoal regularly. This could be attributed to social desirability bias in the surveys and echoes Wilson et al. (2018) in finding that self-reported user behaviour does not correlate well to measured stove use, highlighting the importance of using sensor-collected data. On the other hand, in the interviews we observed excellent agreement between self-reported and measured monthly frequency of charcoal cooking events (interview: 17.2; SUMs: 19.6) and PAYG LPG cooking events (interview: 76.8; SMART data: 72.8). Participants underreporting charcoal use and overreporting PAYG LPG use also points to social desirability bias. It could additionally indicate measurement errors in the SMART data, as the processing methods used gave a loss in sensitivity to short but distinct cooking events. This means that the 72.8 LPG events/month is likely to be a lower bound figure. A key difference between the methods was that the interviews were conducted with women (usually the main cooks), whereas the telephone surveys were conducted with Bboxx account holders (usually the male head of household).

The cooking diaries and sensor-collected data agreed that stacking with charcoal was widespread. An advantage of the diaries was that they could also capture the use of other devices, such as kettles; their major disadvantage was their heavy reliance on the engagement of participants, who had to fill in onerous paperwork each time they cooked. We ultimately had to exclude some of the data fields from our analysis due to poor or incorrect completion but found the recording of dishes cooked, fuel used and fuel purchases were of excellent quality. We suggest that such "simplified" cooking diaries could reduce the costs of collecting granular stove-use data whilst not being overly burdensome on participants.

Lastly, we observe that the multi-method approach vastly increased the study's resilience against adversity. Our lack of reliance on a single method of data collection allowed us to adapt to the escalating COVID-19 pandemic and we were able to triangulate between data collected at different times to assess the impact that the lockdown had on our findings (section 4.4).

6 Conclusions

This study aimed to understand how households used PAYG LPG in order to assess its potential in accelerating access to clean cooking in urban Rwanda. The majority of customers transitioned rapidly from using charcoal as their primary fuel to using PAYG LPG and continued to use the service for the duration of the pilot. After Bboxx's operations closed, some people continued to use LPG from a standard retailer. This suggests that PAYG LPG could help transition biomass users to clean fuels by providing a low-risk way of trialling the technology and a route to equipment ownership, although the sample was small and it is unclear whether this pathway would have been chosen had it not been forced.

The pilot highlighted the challenges of providing a never-run-out-of-fuel cooking service at a satisfactory price. Yet there was cause for cautious optimism. Firstly, payment data revealed that the 'pay-as-you-go' facility was critical to the adoption and sustained use of PAYG LPG. This shows that PAYG business models offer an important and unique advantage over other means of asset financing. Secondly, we found that in the eyes of customers PAYG LPG was good value for money compared to charcoal, but bad value for money compared to standard LPG. As the target market currently cooks predominantly with charcoal rather than with LPG, the comparison with charcoal is the most important. We propose that demand-side feasibility for PAYG LPG should be evaluated against the fuel it is displacing rather than standard LPG. Larger-scale pilots are needed to understand both the supply- and demand-side viability of the technology as it filters down to the mass market, and whether this will reach the lower income customers that PAYG LPG is suited to.

Overcoming the cash flow, affordability and equipment access barriers were not sufficient to eradicate cooking with charcoal completely, as was demonstrated by the ubiquity of fuel stacking. We identified a range of drivers of stacking and support other studies in advocating the need for both technical and behavioural interventions to facilitate a complete transition to clean cooking. In doing so, we add to the growing body of evidence about the inertia of traditional fuel use.

7 Acknowledgements

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