Enhancing clean cooking options in peri-urban Kenya: a pilot study of advanced gasifier stove adoption

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Abstract

Kenya has experienced a decade of relative prosperity with consistent economic growth and minimal political tension. GDP is growing by 3% annually and poverty rates are declining. Despite these gains, Kenya still has a lot of ground to cover to achieve the Sustainable Development Goals (SDGs) by 2030. SDG7, which aims to ‘Ensure access to affordable, reliable, sustainable and modern energy for all’, exemplifies both Kenya’s achievements and the challenges that remain. Access to grid-based electricity and LPG have grown rapidly. However, over 90% of Kenyans still rely on polluting fuels like wood, charcoal and/or kerosene for some or all of their cooking needs. Substantial effort is needed to ensure all Kenyans have access to clean cooking options by 2030. We present the results of a pilot study in which gasifier-based pellet stoves were introduced in 150 peri-urban households. The stoves include an internal fan that improves combustion efficiency and reduces emissions by 90%–99% relative to charcoal and fuelwood in traditional devices. A subset of participants received stoves with ‘Pay-as-You-Cook’ (PAYC) hardware, which relies on pre-paid RFID card to activate the stove’s internal fan, allowing vendors to sell the stove below cost and recoup losses through pellet sales. We find that people were willing to include pellet stoves in their cooking routines and, in many cases, pellets displaced polluting fuels. We also find that PAYC hardware did not negatively impact adoption: PAYC users had higher daily rates of fuel consumption and reported higher willingness to pay for the stove than non-PAYC users. However, stoves were not used exclusively. Instead, people stacked pellets in combination with other cooking options, with pellets contributing to 12%–40% of their cooking needs (inter-quartile range).

Though the project did not successfully overcome all of the barriers necessary to achieve long-term adoption of advanced pellet stoves, the results demonstrate that pellets could contribute to a portfolio of cleaner options.

Social media abstract:

In a pilot project, clean-burning ‘pay-as-you-cook’ pellet stoves were stacked with LPG and polluting fuels.

1. Introduction

Kenya has experienced a decade of relative prosperity with consistent economic growth and minimal political tension. During this period, per capita GDP grew by 3% annually, poverty rates declined by 5%–10% points between 2005/6 and 2015/16, and the country shifted from lower to lower-middle-income status [1, 2]. Despite these gains, Kenya’s still has a lot ground to cover to achieve the Sustainable Development Goals (SDGs) by 2030. SDG7 aims to ‘Ensure access to affordable, reliable, sustainable and modern energy for all’. Looking at Kenya’s progress toward this goal reveals some achievements but
also highlights the challenges that the nation still faces.

The targets specified in SDG7 include access to both electricity and clean cooking. Kenya has made progress in both areas. For example, between 50% and 64% of the country’s population currently has grid access and hundreds of thousands use solar lighting products [3, 4]. Additionally, access to cooking gas (LPG) increased by roughly 10% annually between 2014 and 2018 [4]. However, more than 90% of Kenyan families still rely on polluting fuels like wood, charcoal and kerosene as their primary or secondary cooking option [4]. Substantial effort is needed for Kenyans to achieve universal access to clean cooking options by 2030.

Polluting fuels are associated with a range of negative impacts that link the achievement of SDG7 to progress toward other goals like improving health (SDG3) and mitigating climate change (SDG13) [5, 6]. In Kenya, cooking is commonly done indoors [7]. Roughly 5% of premature mortality is attributable to exposure to household air pollution [8]. Many of the same pollutants that harm human health also contribute to climate change, which is exacerbated if woodfuels are harvested unsustainably leading to a reduction of forest carbon [9]. Reducing unsustainable wood harvesting also reduces land degradation (SDG15). Other SDGs support increased access to cleaner cooking options. For example, several studies have found that education (SDG4) and gender equality (SDG5) are both associated with the use of improved stoves and/or clean fuels [10–14].

For decades, cleaner cooking options have been promoted to reduce the health and environmental impacts associated with polluting fuels. Millions of stoves have been disseminated, many of which have been shown to reduce emissions in both lab and field conditions [15–17]. However, health improvements and reduced environmental impacts are elusive and difficult to measure. Sometimes, new technologies are quickly discarded and people revert to their old practices. Other times, new stoves are enthusiastically embraced, but people ‘stack’ them with their older, ‘baseline’ technologies. Stacking can persist for years, limiting the benefits of cleaner options [18]. Many in the research community now seek to understand whether a combination of suitable options could create a ‘clean stack’ for households to eliminate their reliance on polluting fuels.

Advanced gasifier pellet stoves could contribute to a ‘clean stack’; emissions reductions of 90%–99% relative to charcoal and fuelwood have been measured in field conditions, which is nearly as low as LPG [17]. However, numerous challenges need to be overcome to achieve widespread use. First, the stoves are costly, and few families can pay the full price upfront. Second, the stove and fuel both differ from the stove/fuel combinations commonly in use, so that users must adapt their cooking behavior. Third, new fuel sales and distribution systems must be created to ensure that users have access to a consistent and affordable fuel supply.

Here we present the results of a pilot study in which an advanced gasifier pellet stove was introduced in 150 households across two peri-urban communities outside Nairobi, where the household fuel mix includes a combination of clean and polluting options. The timing of the study is particularly interesting because it occurred soon after the Kenyan government implemented a ban on charcoal production [19]. The ban went into effect in February 2018, and the intervention phase of this project began in November of the same year. The ban has not been fully enforced and charcoal is still widely available, but prices increased roughly 75% [20]. When our pilot project was implemented, people had already started substituting charcoal with LPG or kerosene. This complicated our study, which was initially designed to test whether pellets would displace charcoal. Nevertheless, the price shock provided an opportunity to see how pellets fit into a fuel mix in which charcoal has already been sidelined.

We find that participants were willing to use advanced gasifier stoves and, in many cases, displace polluting fuels. However, the pilot project did not successfully overcome all of the barriers necessary to achieve long-term adoption. In the sections that follow, we provide some background on advanced pellet stoves and describe the residential energy mix in urban and peri-urban Kenya. We then explain the pilot study design and examine the results of the study. We then close with a discussion of policy implications.

1.1. Pellet stoves and fuels in Kenya and elsewhere

Advanced gasifier stoves for household use were first introduced in the mid-2000s [21]. Several types of gasifiers have been developed and disseminated either in pilot projects like this one or in limited commercial markets. One design is side fed like a common ‘rocket’ style stove and can burn typical fuelwood, but most models are batch-fed and require small wood pieces, pellets, or similarly sized solid fuels like nutshells. The characteristic feature that they all have is an internal fan that blows air into the combustion chamber. The ‘forced-draft’ improves combustion efficiency and reduces emissions. Additionally, pellets are uniform in size and moisture content, which further improves combustion.

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1Two recent nationally representative surveys resulted in different estimates of electricity access; we present the two estimates as upper and lower bounds.
2WHO classifies wood, charcoal and kerosene as polluting fuels because they present a risk to public health. Though it is a fossil fuel, LPG is considered non-polluting because there are very few emissions at the point of use.
This pilot project was conducted in collaboration with Burn Manufacturing, a Nairobi-based cook-stove manufacturer, and Mimi-Moto, a Netherlands-based stove design company. Mimi-Moto recently developed a forced-draft pellet stove (hereafter the MM), which is available in select markets. The MM achieved Tier-4 status in energy efficiency, indoor emissions, and overall emissions and was selected for this study precisely because of its emission reduction potential.

1.2. Overcoming barriers to scaling advanced gasifier pellet stoves

There are three main barriers to achieving scale dissemination of advanced gasifier pellet stoves: affordability, adoptability, and access to affordable fuel. This pilot project explored options to directly address affordability and adoptability. However, the project only implemented short-term measures to make fuel accessible for participating households. To truly make pellet fuels affordable and accessible at a large-scale, substantial investment will be required, which is beyond the scope of this project.

1.3. Making advanced gasifier stoves affordable for poor urban households

The main objective of this pilot project was to understand how people use the MM stove, so the implementers needed to ensure uptake in sufficient numbers to observe a range of user behaviors. To promote uptake, the stoves were sold at roughly one-fourth of their retail cost. While this degree of subsidy is suitable for a pilot project supported by external funds, it is not a sustainable approach to achieve commercial scale-up, unless the initial losses can be recovered. Other commercial projects using the same stove model either provide the stove for free, or for a steep discount and recover the loss through profits on pellet sales. To simulate a commercial project, this pilot project adopted a similar approach. There is a risk that stove users will not purchase fuel from the stove provider unless they take steps to ‘lock-in’ their customers. For example, one company promoting the MM stove in Rwanda gives stoves for free on the condition that their customers sign a contract obligating them to buy pellets for 12 months [22]. The firm also offered pellet delivery. A company in Zambia adopts a similar approach by selling the MM for a 10%–20% down-payment and signing users up for a monthly pellet purchase plan for 12–18 months [23].

The commercial projects in Rwanda and Zambia have both dealt with defaults in payments. To reduce the risk of default, this project tested a ‘pay-as-you-cook’ (PAYC) approach in a subset of households. The concept is similar to ‘pay-as-you-go’ delivery models for off-grid solar home systems, which are already common in many developing markets [24, 25]. The past year has also seen rapid growth of pay-as-you-go LPG services, such as Envirotik’s ‘Smart-Gas’, PayGo Energy, and M-gas, which was recently acquired by Safaricom, Kenya’s largest mobile phone provider [26, 27]. To our knowledge, this is the first study of adoption of a PAYC cooking solution.

The PAYC system adds about USD 5 to the production cost of the stove. It functions by adding an RFID reader linked to a timer integrated into the stove’s controller (figure 1). When the user purchases pellets from an authorized vendor, they receive an RFID card with sufficient credit to burn the entire bag. They activate the stove by waving the card in

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3The international community uses four indicators to categorize stove performance: efficiency, total emissions, indoor emissions and safety (IWA-ISO 2012). The indicators are scaled in five tiers ranging from zero (worst) to four (best) (GACC 2017).

4RFID or radio-frequency identification is a prolific technology used in applications ranging from retail theft prevention, to so-called smart passports and key-less entry systems.

5In the pilot project, fuel was available in either 2 kg or 10 kg bags.
front of the controller. An indicator verifies activation is successful and also flashes when the credit is running low, which occurs when the pellets are nearly used up. When the fuel is finished, the user returns to the authorized vendor to obtain more fuel and another RFID card, ensuring the stove provider recoups their loss from the initial stove sale.

2. Methods

2.1. Study design

MM stoves were marketed in Gachie and Githunguri, peri-urban communities in Kiambu County outside Nairobi (figure 2). The communities were selected based on their proximity to the stove and fuel providers. 30 PAYC stoves were sold in Gachie and 120 MM stoves without PAYC hardware were sold in Githunguri. In both communities, stoves were sold for KES 2000 (~USD 20), well below the stove's projected retail price of KES 8000. For comparison, stoves commonly in use in these communities cost between KES 400 for a simple charcoal stove and 4500 for a single-burner LPG stove (4 and see supplemental materials for stove-specific prices).

Stoves were promoted during a series of sales events held on market days when potential customers have the cash on hand. Buyers signed-up, paid a small deposit, and the stove was delivered to their home. The home visit allowed vendors to provide ‘hands-on’ training to ensure users understood how to operate the stove. It also allowed the team to implement a short baseline survey. Follow-up surveys were also conducted roughly 3 months after stoves were delivered. Pellets were sold from kiosks located close to the households through vendors recruited by Burn, who tracked sales and periodically reported back to the research team.

The project tested two types of fuel: wood pellets produced from sawdust and macadamia shells. Participants received one free 2 kg bag of each, so they could try both and decide which they prefer. Later, participants purchased their preferred fuel in either 2 kg or 10 kg bags. Macadamia shells cost KES 15 kg⁻¹ and pellets cost 25 kg⁻¹. For comparison, during the project, charcoal was selling for roughly KES 35 kg⁻¹, kerosene cost 100 KES kg⁻¹, and LPG cost KES 160 kg⁻¹. However, comparing cost per unit mass fails to account for different calorific values and stove efficiencies. Taking these factors into account, we can estimate the costs of obtaining ‘useful energy’ for each stove/fuel combination. Here, we find that charcoal is the cheapest option at 3–4

Figure 2. Map showing the location of the communities.

6The number was dictated by the limited production of PAYC hardware.

7Macadamia shells were purchased from a nut processor for KES 8 kg⁻¹, then packaged and sold through vendors for a small profit. Kenya’s pellet industry is at a very early stage and costs are still quite high. We purchased pellets wholesale for KES 47 kg⁻¹. After packaging, distributing and adding a small markup, the retail cost would have been KES 75 kg⁻¹, which is more than charcoal. To ensure users could participate, pellets were sold for KES 25 kg⁻¹, which is similar to US prices heating pellets (USD 250/ton).

8These prices are national averages among urban Kenyans and may not reflect the prices that participants paid during the pilot study. The charcoal price is taken from then National Bureau of Statistics monthly consumer price index data from the start of the study [20] and other fuel prices are from urban responses given in a national household energy survey collected between October and November 2018, which directly overlaps with the start of the pilot project [4].
KES (MJ\text{del})^{-1}. Kerosene is slightly more expensive at \approx 5 KES (MJ\text{del})^{-1}, LPG costs around 6 KES (MJ\text{del})^{-1}, and wood costs \approx 9 KES (MJ\text{del})^{-1} depending on the efficiency of the device. Interestingly, the cost of useful energy from the MM at the fuel prices offered in this study is just 2–3 KES (MJ\text{del})^{-1}, which is lower than all of the current options (see table S1 and accompanying discussion in Supplemental Material for an explanation of the underlying data and assumptions used for these calculations).

In Gachie, where PAYC stoves were marketed, buyers were studied in more detail. Stove use was measured by installing stove use monitors (SUMs) on all baseline stoves. In addition, two rounds of in-depth interviews and focus group discussions were implemented to understand users’ daily practices and motivations. The results of the interviews and focus groups are detailed elsewhere [28]. Here we focus on data collected from surveys, fuel sales, and SUMs data.

3. Data collection and analysis

3.1. Surveys

Surveys collected basic socio-demographic data as well as information about baseline cooking behavior and respondents’ experiences using the MM stove.

3.2. Stove use monitors

Stove use monitors (SUMs) have been described in several previous publications [29–32]. The system consists of a data-logging temperature sensor to collect temperature measurements, a data management program, customized signal-processing software, and reporting tools to quantify and graphically illustrate cookstove use and adoption. This study used Labjack Digit-TLH data loggers (Labjack Corp., Lakewood, CO), which log temperature pre-set intervals. Data are downloaded through a USB connector. Digits measure between \(-35\) and \(+85\) °C with \(\pm 0.5\) °C accuracy and store up to 260 000 readings with timestamps recorded for each data point.

SUMs were deployed on baseline stoves in early November 2018, two weeks before MM deployment. Roughly 2 weeks later, MM stoves were distributed with SUMs attached. SUMs were checked periodically to download data and replace depleted batteries or malfunctioning sensors and remained in place until the close of the study in May 2019. Data was coded with household ID, SUM ID, stove type, and download date and field staff tracked household details, including issues that would affect the analysis (e.g. the participant removed the sensor or obtained a new stove).

SUMS data was analyzed with custom Python scripts to determine the number and duration of cooking events. Plots of device signals with event counts and event duration were illustrated through a graphical user interface, also coded in Python (see supplemental materials for examples of these outputs). Outputs from the SUMS software were further processed in SQLite and Microsoft Excel. Scripts performed five main steps (figure 3). We briefly describe each step here (see supplemental materials for details).

(a) Signal smoothing

In this first step, a smoothing algorithm is applied to the dataset to remove noise. This process is applied to all stove types.

(b) Ambient temperature profile

The SUMS software generates an ambient temperature profile by removing large peaks in the temperature profile. This distinguishes background temperatures and diurnal peaks from

\footnote{The code will be made available upon request.}
Table 1. Basic characteristics of households in the sample, the county and country-wide.

|                               | Households in this study | Urban and peri-urban households |
|-------------------------------|--------------------------|---------------------------------|
|                               | Gachie (n = 30)          | Githunguri (n = 120)           | Kiambu (n = 830) | Nationwide (n = 9484) |
| Average HH size               | 3.9                      | —                               | 3.0             | 3.3                      |
| % who own their home          | 7%                       | —                               | 32%             | 26%                      |
| Mean no. of rooms occupied    | 2.3                      | —                               | 2.1             | 1.8                      |
| Electricity                   | 90%                      | 97%                             | 87%             | 74%                      |
| Primary cooking fuel (prior to intervention) |                        |                                 |                 |
| LPG                           | 73%                      | 37%                             | 46%             | 28%                      |
| Charcoal                      | 23%                      | 34%                             | 17%             | 23%                      |
| Fuelwood                      | 0%                       | 27%                             | 6%              | 16%                      |
| Kerosene                      | 4%                       | 1%                              | 28%             | 29%                      |
| Electric                      | 0%                       | 1%                              | 0%              | 1%                       |
| Other/Did not cook            | 0%                       | 1%                              | 3%              | 4%                       |
| Stove/fuel stacking (prior to intervention) |                        |                                 |                 |
| Percentage of HHs using more than one stove/fuel | 80%                      | 75%                             | 49%             | 52%                      |

*First three questions were not asked in Githunguri*  
*County and national-level data are from the 2015/16 Kenya Integrated Household Budget Survey [33]*

cooking events and helps define the threshold temperature used in subsequent steps.

(c) Signal peak detection
Temperature peaks are identified by an increasing rate of temperature change that is too high to be explained by changes in ambient conditions. A cut-off rate determines when the stove is activated and a possible cooking event [29, 30].

(d) Cooking event detection:
The start of a cooking event is identified with the smoothed temperature exceeds a user-defined threshold temperature. To define the threshold, the SUMS software applies three different algorithms based on previous SUMS analyses. The algorithm with the highest event capture rate and lowest rate of false events is used for further analysis (see supplemental materials for details).

(e) Cleanup:
Sometimes stoves cool below the threshold temperature and then heat up again during a single event. This step merges separate events that occur within a preset time (e.g. 30 min). It also removes short-duration events and events that do not reach a sufficiently high temperature.

4. Results

Surveys provide an overview of each household and allow a comparison with Kenya's broader urban and peri-urban population. The families who purchased MM stoves were typical of Kenyan families living in small towns and peri-urban areas (table 1). Most households have 3–4 members, the majority rent their homes, which consist of 2–3 rooms. Nearly all homes are connected to the main grid although none of the families in the sample and very few country-wide, use electricity to prepare meals.

Participants noted that they use a variety of primary cooking fuels including LPG, charcoal, and kerosene, which also matches the broader urban and peri-urban population. One difference between communities is the use of fuelwood in Githunguri, but not Gachie. For participants and throughout Kiambu county, LPG is the most common primary fuel. However, the ‘primary’ label is misleading. We observe a stacking pattern among participants in this study which is similar to the rest of the Kenyan population: at the outset, 69% stacked LPG with polluting fuels (specific stove/fuel combinations are shown in figure 4), 15% used LPG exclusively, and the balance used only polluting fuels.

Baseline fuel mix is an important indicator because it provides an indication of the emissions reductions that the MM stove could achieve. It also provides some information about users’ starting points and their potential motivation for trying this new technology. These themes are beyond the scope of this analysis and are explored in a companion paper [17].

Follow up surveys asked participants about use, types of meals cooked, and overall satisfaction with the introduced stove. Here, participants gave mixed
responses. In surveys administered roughly three months after receiving the MM stove, participants were asked how often they used the stove in the past week. Two thirds of those who responded claimed that they used the MM stove daily, 20% claimed that they used it 3–5 d/week, and 7% said they had not used it at all (see figure S3). This distribution of MM usage does not agree completely with SUMS data, which indicated lower levels us use (see below and supplemental materials). In addition, the majority of users claimed that they found the MM suitable for all types of dishes, particularly staple grains like rice or maize meal, which constitute the main caloric content of most meals (figure S4). The only limitation that emerged was that some users felt that the MM was not good for quick tasks like boiling water for tea, because it is batch-lit, cannot be easily extinguished, and they did not want to waste fuel.\textsuperscript{11}

Participants were also asked about things they found challenging and things they would change about the stove. Nearly half of those responding (45 out of 110) did not mention any challenges. For those who did, the most common issues they raised were the stove’s power control (20/110) and the smokiness (24/110). Notably, most users who were bothered by the MM’s smokiness reported that LPG was their primary fuel prior to our intervention, so they were

\textsuperscript{11} MM designers informed us that short tasks can be accommodated without waste by using a smaller charge of pellets, but it requires some trial and error to get the quantity correct.
acustomed to smoke-free cooking. In addition, the survey focused mainly on technical aspects of the MM. In more detailed interviews, and focus-groups, the research team probed more deeply into the users’ experiences acquiring and learning to use the stove, as well as after-sales support, which we explore in the companion paper [28].

114 participants responded to a question asking what they would change about the stove. Multiple responses were permitted, with 135 suggestions collected overall. Nearly one in four respondents said they would not change anything. The remaining responses were coded into three categories: stove design; fuel characteristics; and cost. Most suggestions focused on stove design (57%) with 26% of respondents suggesting that the stove should be larger. 30% of responses focused on various fuel issues and 9% of respondents made suggestions related to cost (see supplemental materials for details stacks.iop.org/ERL/15/084017).

In addition, follow-up surveys asked participants about their willingness to pay (WTP) for the stove. They originally paid KES 2000 and were aware that this price was subsidized. The subsidized price of KES 2000 was the median response. It is possible that the price was subsidized. The subsidized price of KES 2000 they payed in the pilot. In addition, responses differed between the two communities: in Githunguri the median was KES 2000 and in Gachie it was KES 3000 (p < 0.01).

The survey data reflect some satisfaction with the stove among MM users. Many noted that they encountered challenges and suggested improvements, but people used the stoves for a wide range of cooking tasks. This indicates that stoves met their expectations, and many stated that they would be willing to pay more than the subsidized price they originally paid. In addition, PAYC users reported higher WTP than non-PAYC users, indicating that the PAYC feature may not be a major barrier to adoption (however, see 28 for a deeper examination of users’ experiences with PAYC).

4.1. Fuel sales
Fuel vendors reported pellet sales between October 2018 and March 2019. Users had a strong preference for macadamia shells, which outsold wood pellets by nearly a factor of four (figure S5). This was also evident from the surveys; 80% of users stated a preference for macadamia shells. Respondents explained their preference because macadamia cost less and, according to some, burned more slowly than pellets, although others reported that pellets lasted longer.

Fuel sales data also allow us to examine per capita consumption in the two communities. We found average daily pellet and macadamia shell consumption was ~0.4 kg/household in Gachie (the PAYC community) and ~0.2 kg/household in Githunguri, which supports the assertion that PAYC was not a barrier to MM use.

4.2. SUMS data
In total, we monitored 83 stoves in 29 households between November 2018 and May 2019 (one household recruited from Gachie dropped out soon after the study began). Over the six-month monitoring period, we recorded 11 700 complete ‘stove-days’ (some days were missed because of malfunctioning sensors). To observe household-level stacking and changes in stove use, we need valid measurements from every stove in the household. If one sensor fails for a number of days, we cannot draw conclusions about those days of stove use. After filtering out days during which one or more SUMS failed, we were left with 3263 valid ‘household-days’ of data: 339 before MMs were distributed, and 2924 after. We review cooking patterns among MM users prior to the intervention, MM usage during the monitoring period, and the extent of stove/fuel stacking both before and after participants received the MM stoves (an example of processed SUMs data is shown in figure S6).

Sensors failed in five households during baseline data collection, before the introduction of the MM stove, limiting our baseline sample to 24 households. Among these, LPG was used for nearly 75% of cooking time before the MM stoves arrived. Disaggregating into different baseline fuel users, we find 11 households used LPG exclusively, nine households stacked LPG with kerosene and/or charcoal, and four households used a mix of kerosene and charcoal with no LPG.

At a community scale, MM use fluctuated over time (figure 6(a)). For the first month, about half of the participants used the MM frequently: 20% used it daily, and ~30% used it three or more days per week. After that, use declined and by the 10th week (early-January), fewer than half of the households used the stove at all. We later discovered that the two pellet retailers were inaccessible at the point where we identified a sudden and significant drop in usage, and users could not obtain fuel. Usage rebounded and increased steadily through February, before dropping off in early March. MM use peaked again in mid-March immediately after the research team visited the community to collect data but fell soon after and fluctuated between 15% and 30% of users through the end of the monitoring period in early May.

SUMS also measure the duration of cooking events. This indicates whether stoves are used for short tasks like making tea or reheating leftovers, or for longer tasks like preparing full meals. Most people used the MM for just over 2 h per cooking task; 90% of events fell between 1.2 and 4.1 h (figure 6(b)), indicating that most people used the MM for substantial
**Figure 6.** (a) Percentage of households using the MM stove at least once each day between mid-November and early May; (b) Distribution of MM-stove event-times over the entire monitoring period (using all algorithms).

**Figure 7.** Contribution to total cooking by stove and fuel during the two weeks before (left) and 24 weeks after adoption of the MM (right). Plots show the full sample (a), HHs that used only LPG at baseline (b), HHs that stacked LPG with charcoal and/or kerosene (c), and HHs that used only charcoal or kerosene with no LPG (d).
cooking tasks. For comparison, cooking events with LPG and kerosene generally ranged between one and two hours, and tasks utilizing charcoal lasted between 2 and 6 h (table S3).

SUMS data also allows us to examine contributions of different stove and fuel options to overall cooking time. During the post-adoption monitoring period, participating HHs used the MM for 27% of observed cooking time, with considerable variation across households. The full sample is shown in figure 7(a). We grouped the sample by the mix of fuels used prior to MM adoption, to see whether groups behaved differently. The sample sizes are small, and we cannot generalize from these results; however, we see patterns that might be worth further investigation. The 11 households that were exclusive LPG users during baseline used the MM for roughly 26% of their cooking activity during the monitoring period (figure 7(b)). The households that used LPG in combination with kerosene and/or charcoal used the MM for 18% of their observed cooking activity, while households that used only charcoal or kerosene during baseline used the MM for over 40% of monitored cooking activity (figures 7(c) and (d)).

Last, we examine absolute changes in baseline cooking activity. Across the community, we observe a 12% reduction in time spent cooking with baseline fuels (figure 8), but this was not uniform. Among the 23 households with valid data from before and after MMs were delivered, 16 households reduced baseline stove use by an average of ~24%, but the remaining seven households used baseline stoves as much or more after obtaining the MM stove. For these users, the MM was a complementary technology that expanded their cooking options but did not reduce baseline fuel.

4.3. Limitationsof the study
This pilot study faces several limitations. Our household survey sample covers all 150 participants, and we collected over 11 000 ‘stove-days’ of SUMS data, the latter covered a relatively small number of households, particularly to compare pre-and post-MM behaviors. In addition, the sample was self-selected and not necessarily representative of the two communities or peri-urban Kenyans more generally. Thus, while the results are instructive, we cannot make generalizations to the broader population.

In addition, the study was originally intended to test whether the MM could reduce negative impacts associated with charcoal. However, the Kenyan government’s charcoal ‘ban’, which was announced months before this pilot project was implemented, created an unprecedented charcoal price shock, shifting study participants toward more kerosene and/or LPG usage already before the MM introduction. As a result, our baseline showed lower charcoal dependence than existed prior to the ban.

5. Discussion and conclusions
The MM made modest a contribution to families’ cooking needs. People were generally satisfied with the stove’s cooking performance, though they suggest several changes to improve users’ experience (table S2). In addition, there were shortcomings in fuel provision that likely resulted in lower usage than would have occurred if fuel was more available.

Participants showed a preference for macadamia shells over pellets, both because of lower cost and longer burn times. This raises questions about scalability. Kenya produces 14 000 tons of macadamia shells per year.12 Families in Gachie used roughly 0.4 kg day$^{-1}$, which accounted for just over a quarter of their cooking time. Shell production could satisfy similar demand in 96 000 households: a tiny fraction of the population using polluting fuels in urban and peri-urban areas. However, as the country’s pellet industry matures, quality and affordability should improve, making pellets a more attractive option.

Whether the MM or similar stove models play a role in Kenya’s future mix of clean cooking options remains to be seen. This small pilot project has demonstrated that people using a variety of baseline fuels were willing to use a gasifying pellet stove over an extended period of time for a fraction of their cooking needs. Based on pellet sales, surveys and WTP data, the PAYC hardware did not result in lower use rates or create a substantial barrier to adoption and may be a viable option for vendors to sell expensive stoves below cost and recoup their losses over time.

These lessons could also be pertinent for the emerging players in PAYC LPG, which has seen a lot of recent investment in Kenya. Displacing modest amounts of polluting fuels with MM stoves, while unlikely to result in health improvements (SDG3), will reduce emissions (SDG13) and potentially relieve pressure on forest resources (SDG15), particularly in markets where charcoal demand has not been affected by a government ban.

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12Kenya produces 7000 tons of processed macadamia kernels per year and the shell-to-kernel ratio is about 2:1 [34, 35].
errors or omissions are the sole responsibility of the authors.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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