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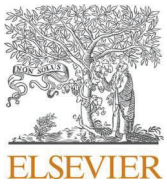

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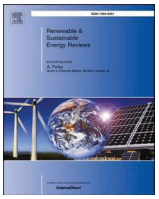

Cleaning up the stack: Evaluating a clean cooking fuel stacking intervention in urban Kenya

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ABSTRACT

There are a growing number of market-based providers of clean cooking solutions in sub-Saharan Africa that rely on use customer fuel sales to subsidise upfront cost of equipment. These business models can widen access to clean cooking but are undermined by the continued use of polluting fuels, known as "fuel stacking", which limits provider revenues whilst perpetuating the negative impacts of cooking with traditional fuels.

This study aimed to design and test a fuel stacking intervention with commercial pay-as-you-go LPG customers in Kisumu, Kenya. It consisted of three main phases: developing and testing a survey tool for diagnosing drivers of stacking (n = 99); using an intervention design framework (the Behaviour Change Wheel) to design an intervention consisting of the bundled provision of a pressure cooker, chapati pan and training; and testing the intervention in a small (n = 19) pre-post study.

There was high uptake of the intervention, with the pans being used by all participants on roughly two-fifths of days. Target foods were cooked more frequently on LPG in the intervention phase, resulting in a significant increase in PAYG LPG use and an insignificant decrease in charcoal use. A third of participants stopped cooking with charcoal altogether, but some residual charcoal usage continued amongst the remainder.

The results show that targeted stacking interventions can simultaneously promote sustained use of clean fuels and dis-adoption of polluting ones, resulting in commercial gains for clean cooking fuel providers. This could address the wicked problem of fuel stacking and accelerate progress towards Sustainable Development Goal 7.

1. Introduction

Approximately 2.4 billion people still lack access to clean, modern and affordable cooking fuels [1]. They instead rely on polluting alternatives like dung, charcoal and firewood, producing household air pollution (HAP) that causes lung cancer, pneumonia and other diseases, accounting for 3.6 % of the years lost globally to ill-health, disability and death [2]. Polluting cooking is responsible for 2 % of annual CO_2 emissions and drives unsustainable deforestation [3]. Women and children bear a disproportionate heath and time burden as cooking and fuel gathering are tasks that usually fall within their domain [4,5].

These problems are especially concentrated in sub-Saharan Africa (SSA), where 950 million people still rely on wood fuels to cook – a third of the global total [6,7]. To date, significant changes in country-level clean cooking access in Latin America and Asia have been driven by heavily subsidised government programmes and policies [8–10], but such approaches are rarely economically viable in the SSA context. There is a mounting expectation that market-based solutions provided by the private sector will drive clean cooking progress in SSA over the coming decades and a corresponding urgency for new technologies and financing mechanisms that can address traditional barriers to clean fuel adoption [11,12].

This has spurred the development of so-called "razor-and-blade" business models in the cookstove sector that sell both stoves and fuel to consumers, often providing the stove at a loss with the expectation that future fuel sales will generate profits [13]. These businesses generate value by creating lasting relationships between customers and fuel

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Abbreviations

AFF	Affordability
APEASE	Acceptability, Practicability, Effectiveness, Affordability, Side-effects, Equity
BCT	Behaviour Change Technique
BCW	Behaviour Change Wheel
COM-B	Capability-Opportunity-Motivation-Behaviour
CUK	Cultural Compatibility
END	End Uses of Traditional Stoves
EQU	Equipment Compatibility
ESMAP	Energy Sector Management Assistance Programme
FUN	Stove Functionality
HAP	Household Air Pollution
HHD	Household Dynamics
IRENA	International Renewable Energy Agency
KES	Kenyan Shillings
KNO	Knowledge and Training
LPG	Liquefied Petroleum Gas
MININFRA	Rwanda Ministry of Infrastructure
PAYG	Pay as You Go
SAF	Safety Issues
SDG	Sustainable Development Goal
SHS	Solar Home Systems
SSA	Sub-Saharan Africa
TEC	Technical Characteristics
TIM	Time Aspects
UNSD	United Nations Statistics Division
USD	United States Dollars

providers, combating the patterns of stove abandonment that have rendered past clean cooking interventions unsuccessful [14]. The more fuel that customers use, the more money that providers make, which enables their businesses to scale and bring clean cooking to wider audiences. However, these models can also incur additional costs (e.g. financing, hardware, software) that increase costs to the end-user. Razor-and-blade models have so far been trialled with liquefied petroleum gas (LPG), biomass pellets and electric cooking technologies [15–18]. A critical feature of these systems is that they use the internet of things (IoT) to track fuel sales, allowing providers to remotely gauge stove adoption at the household level.

However, when consumers adopt new cookstoves they rarely stop using their old ones one and instead tend to continue to use multiple fuels and stoves in parallel. This is known as stove or fuel stacking and, as concluded by a 2020 review of stove studies, "everybody stacks" [19] and can negate the health and environmental benefits of clean cooking [9,20,21]. Profit and impact therefore converge at the need for razor-and-blade stove providers to actively reduce polluting stacking.

However, little is understood about how this can be done. Research about cooking fuel stacking has increased exponentially over the past decade [22], but this body of literature tends to stop short of attempting to actively influence clean fuel adoption [23–26]. A notable attempt to reduce stacking was an intervention to encourage exclusive LPG use amongst pregnant women cooking with LPG and firewood in Guatemala [27]. Study participants were provided with a free LPG stove, free refills, and education about the benefits of cooking with LPG, which limits the real-world generalisability of the study. Daily wood fuel use across the sample consequently dropped from 6.4 h to 1.9 h. Similarly high levels of clean fuel adoption have been achieved in other health-focussed randomised controlled trials designed to address affordability and supply barriers from the outset [20,28,29]. The results of these studies collectively suggest that it is possible to actively limit fuel stacking, although it is unclear how effective such efforts would be if people were paying for their own fuel. Razor-and-blade stove providers are uniquely positioned to develop and implement transition pathways from polluting stacking to the complete adoption of clean fuels by using their consumption datasets to target interventions at relevant consumers. This study is the first attempt to test such an approach, which could enhance the efficacy of market-based clean cooking interventions, thus realising the full benefits of clean cooking transitions in line with the energy access targets defined in the Sustainable Development Goals.

Like any attempt to change behaviour, effective stacking interventions first require an understanding of why polluting cooking perpetuates. However, stacking occurs for a diverse and complex range of reasons that are difficult to quantify. Efforts to understand patterns of stacking typically consist of pairing stove usage data with qualitative interviews to try and discern motivations for using different cooking fuels [23,30,31]. Such studies are resource intensive and unstandardized, meaning that their quality varies and they are likely to only identify the most prominent stacking drivers.

The behavioural sciences offer a range of tools and methods to understand why behaviour occurs and how to change it. One example is an integrative behaviour change intervention development framework called the Behaviour Change Wheel (BCW) [32,33]. The COM-B model (Capability-Opportunity-Motivation-Behaviour, Fig. 1) is part of this framework and stipulates that for behaviour to occur, people must have a combination of capability, opportunity and motivation to enact the desired behaviour. Capability can refer to people's physical or psychological capability such as their physique or intellectual capacity. Opportunity can refer to social or physical opportunity such as the social norms or the physical objects with which people interact. Motivation can be automatic or reflective motivation and refers to the intentions, desires and habits that direct human behaviour. The BCW provides a structured approach to designing behaviour change interventions centred around identifying what needs to change in terms of capability, opportunity and motivation.

Informed by the COM-B model, Perros et al. (2022) developed a taxonomy for understanding the drivers of fuel stacking via a review of grey and peer-reviewed scientific literature. The taxonomy thematically aggregates the diverse set of reasons why people stack across multiple countries, contexts and technologies and categorises them according to the COM-B model. It consists of 61 distinct drivers grouped into 11 broad categories depicting potential influences on behaviour (Table 1) and offers a framework that can be used to systematically examine drivers of stacking and identify those most prominent within a given population.

This research aims to understand the extent to which fuel stacking interventions can facilitate a complete transition to clean cooking. The first part of this study applies Perros et al.'s (2022) stacking taxonomy to design a survey aimed at understanding why people stack. This was

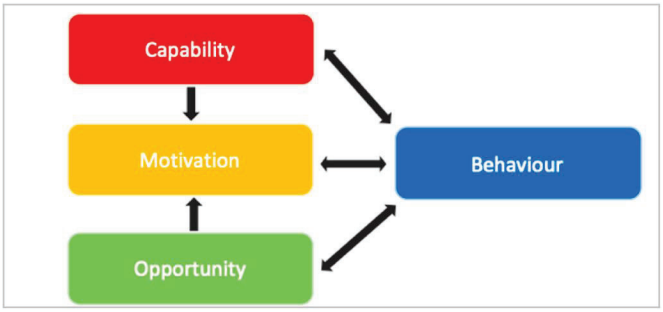

Fig. 1. COM-B model (Michie et al., 2011; 2014).

Table 1
Taxonomy of stacking drivers mapped to the COM-B model. Phy_Cap = Physical Capability; Psy-Cap = Psychological Capability; Soc_Opp = Social Opportunity; Phy_Opp = Physical Opportunity; Ref_Mot = Reflective Motivation; Aut_Mot = Automatic Motivation.

Category	Code	Description	COM-B
AFFORDABILITY (AFF)	AFF_1	Fuel price too high	Phy_Opp
	AFF_2	Income constraints	Phy_Opp
	AFF_3	Can't afford to buy fuel in the quantities it is sold in	Phy_Opp
	AFF_4	Fuel price changes	Phy_Opp
	AFF_5	Availability of cheaper alternative fuels	Phy_Opp
	AFF_6	Too expensive to cook certain foods on clean stove	Phy_Opp
	AFF_7	Distortions in affordability caused by subsidies	Phy_Opp
CULTURAL COMPATIBILITY (CUL)	CUL_1	Traditional stove preferred for taste	Aut_Mot
	CUL_2	Belief that it is healthier to cook on traditional stove	Ref_Mot
	CUL_3	Traditional stove necessary for ceremonial rituals	Ref_Mot
	CUL_4	Importance attached to cooking the traditional way	Ref_Mot
	CUL_5	Culturally inappropriate to remove a pot from flame whilst cooking	Ref_Mot
	CUL_6	Belief that wood smoke solidifies walls of buildings	Ref_Mot
	CUL_7	Social aspects of cooking with traditional stoves	Soc_Opp
	CUL_8	Traditional stoves preferred during festivals	Ref_Mot
END USES OF TRADITIONAL STOVES (END)	END_1	Wood smoke is used to preserve meat and fish	Phy_Opp
	END_2	Space heating	Phy_Opp
	END_3	Space lighting	Phy_Opp
	END_4	Wood collection is an important source of income	Phy_Opp
	END_5	Wood smoke keeps insects away	Phy_Opp
	END_6	Embers and ashes from traditional stove are used in cooking	Phy_Opp
EQUIPMENT COMPATIBILITY (EQU)	EQU_1	Clean cooking device cannot be used with large pots	Phy_Opp
	EQU_2	Clean cooking device damages traditional pots	Phy_Opp
STOVE FUNCTIONALITY (FUN)	FUN_1	Broken equipment	Phy_Opp
	FUN_2	Customers do not know how to fix and maintain equipment	Psy_Cap
	FUN_3	Lack of local technicians to fix and maintain equipment	Phy_Opp
	FUN_4	Lack of access to spare parts	Phy_Opp
	FUN_5	Stove use minimised to avoid damaging stove	Phy_Opp
HOUSEHOLD DYNAMICS (HHD)	HHD_1	Person who cooks is usually different to the one paying for fuel	Soc_Opp
	HHD_2	Gender norms around use of cooking fuels	Soc_Opp
	HHD_3	Not all members of the household know how to use stove	Psy_Cap
	HHD_4	Safety concerns from other members of the household	Ref_Mot
	HHD_5	High labour requirement for feeding biogas digester	Phy_Opp
KNOWLEDGE AND TRAINING (KNO)	KNO_1	Low awareness of how to use stove correctly	Psy_Cap
	KNO_2	Belief certain foods cannot be cooked on stove	Ref_Mot
	KNO_3	Lack of motivation to use clean cook device	Ref_Mot
SAFETY ISSUES (SAF)	SAF_1	Fear of short-circuiting electricity in the house	Aut_Mot
	SAF_2	Fuel perceived as dangerous	Aut_Mot
	SAF_3	Fear of gas explosions	Aut_Mot
	SAF_4	Fear of burns	Aut_Mot
FUEL SUPPLY ISSUES (SUP)	SUP_1	Fuel shortages at retail points	Phy_Opp
	SUP_2	Inadequate voltage supply	Phy_Opp
	SUP_3	Lack of raw materials to produce fuel	Phy_Opp
	SUP_4	Travel cost or distance to purchase fuel	Phy_Opp
	SUP_5	Weather impacts on fuel supply	Phy_Opp
	SUP_6	Distrust in local fuel retailers	Ref_Mot
TECHNICAL CHARACTERISTICS (TEC)	TEC_1	Stove doesn't get hot enough	Phy_Opp
	TEC_2	Stove is physically unable to perform certain cooking tasks	Phy_Opp
	TEC_3	Difficulties controlling temperature	Phy_Opp
	TEC_4	Difficulties lighting stove	Phy_Opp
	TEC_5	Stove too small	Phy_Opp
	TEC_6	Stove produces unpleasant smell whilst cooking	Aut_Mot
	TEC_7	Stove is smoky	Phy_Opp
	TEC_8	Can't track fuel use and therefore expenditure	Phy_Opp
	TEC_9	Stove not portable	Phy_Opp
	TEC_10	Inconvenience of fuel preparation for clean stove	Phy_Opp
	TEC_11	Difficulties reloading fuel for clean stove	Phy_Opp
TIME ASPECTS (TIM)	TIM_1	Need to cook multiple items at once	Phy_Opp
	TIM_2	Cannot multi-task whilst using stove	Phy_Opp
	TIM_3	Seasonal variation in fuel usage	Phy_Opp
	TIM_4	Stove takes too long to cook	Phy_Opp

tested on n = 99 paying customers of a razor-and-blade LPG provider in urban Kenya. Informed by the findings of the survey, the second section documents the application of the BCW method to design an intervention aimed at reducing stacking. The final section evaluates the intervention to assess its effectiveness at reducing stacking. The scientific contributions and value of this work are therefore three-fold; 1) it is the first application of a theoretically-derived taxonomy of stacking drivers thereby validating its use within stacking research; 2) it explicitly documents an intervention development process thereby providing an adaptable template with guidance for other researchers and practitioners working in this area; 3) it presents the first attempt to reduce polluting fuel stacking within the context of a market-based clean cooking technology thereby advancing the boundaries of knowledge within clean cooking science.

2. Case study

This study focusses on pay-as-you-go (PAYG) LPG in Kisumu, Kenya, where the research partner, Bboxx, were operating a pilot with this technology. PAYG LPG is a new technology and business model consisting of an internet-connected meter (known as a SMART meter) that is mounted to an LPG cylinder. Credit is purchased from the provider via mobile money, allowing the corresponding amount of gas to be dispensed from the cylinder whenever the customer wishes to use it. Once the credit has been spent, the meter shuts off until another payment is made. As well as enabling LPG to be bought in micropayments, the meter also collects detailed LPG consumption data (known as SMART data) that provides insights into customer cooking behaviour. Although there are different configurations of the PAYG LPG business model, equipment financing is usually incorporated into the gas tariff

and the provider is usually responsible for delivering fuel to customer households. PAYG LPG therefore inherently addresses many of the affordability and supply barriers that constrain full-cylinder LPG use [16,17].

The pilot was operated by Bboxx, a for-profit enterprise who design, manufacture, distribute and finance products to improve access to energy across the developing world [34]. Over the past decade, Bboxx have provided hundreds of thousands of PAYG solar home systems (SHS) across SSA and are now applying their technology to LPG cookstoves. They launched their Kisumu operations in 2020 with support from Power Africa and targeted low-income consumers living in informal settlements who primarily cooked with kerosene, charcoal or firewood. Customers initially paid a 23 USD downpayment to access the service and receive a double burner cooker, 13 kg cylinder, 3 kg gas credit, hose and regulator. Payments were split into two different components: a daily charge of 0.25 USD to repay the equipment over a three-year period, and gas purchases, which were made via mobile money as and when customers required at a price of 1.78 USD/kg. This structure allowed Bboxx to price LPG at the standard local market rate whilst simultaneously providing and financing the equipment. Cylinder delivery was also part of the service and was triggered by customers refill requests.

3. Methodology

This research consisted of three phases: a quantitative survey to understand the drivers of stacking in the PAYG LPG customer base, the development of an intervention based on the survey results and a pre-post study to evaluate the effectiveness of a fuel stacking intervention. Ethical approval for this study was granted by University College London [17653/002] and Strathmore University [SU-IERC1048/21].

3.1. Survey

The survey sought to understand patterns of stacking in PAYG LPG customers in Kisumu, and was designed so that each participant response mapped to one of the stacking drivers identified in the stacking taxonomy [22]. It was administered via telephone and was performed on n = 99 participants who were randomly sampled from Bboxx's population of n = 400 PAYG LPG customers. The scale of the survey was determined by resource constraints but followed Pearson et al.'s recommendation of a minimum sample size of n = 100 participants for exploratory surveys [35]. A secondary survey of n = 16 was subsequently performed to understand why participants in the first survey preferred to use charcoal stoves to cook chapatis, an unexpected finding that emerged through the first survey.

The main survey consisted of three different sections. The first contained sociodemographic questions about the household size and the roles of different household members in cooking and making fuel purchasing decisions. The second section focussed on the frequency of use of different cooking fuels. The final and main section drew upon the taxonomy to ask about drivers of fuel stacking. To prevent the survey from becoming too long, it did not ask about stacking drivers that were deemed irrelevant to PAYG LPG customers from the stacking taxonomy, for example SUP_2: inadequate voltage supply and SUP_3: lack of raw materials to produce fuel, which are specifically relevant to electric and biogas cooking respectively.

As well as undergoing the usual survey analysis process, which consists of considering the responses to each question in turn, the survey was also analysed against the stacking taxonomy. Each potential response mapped onto one of the taxonomy drivers so that each survey collected could be tested for the presence of each individual stacking driver. Summing the results showed the prevalence of each stacking driver across the sample.

3.2. Intervention development

The intervention was developed using the Behaviour Change Wheel (BCW) approach outlined by Michie et al. [32,33]. This research also adapted the methods of others researchers who have applied this framework to intervention development [36,37]. Fig. 2 shows how the BCW consists of three parts: (1) An inner hub which depicts behavioural influences as capability, opportunity and/or motivation; (2) A middle layer of broad strategies or "intervention types" to target underlying influences to enact behaviour change, and; (3) An outer layer of policy options for supporting delivery of the intervention types.

After intervention types and policy options have been selected, there is an additional step which involves systematically mapping intervention types to specific Behaviour Change Techniques (BCTs) from the Behaviour Change Technique Taxonomy [38] −93 hierarchically clustered techniques identified as being able to change behaviour (e.g., action planning and goal setting). Also not depicted in Fig. 2 is the additional APEASE framework (Acceptability, Practicability, Effectiveness, Affordability, Side-effects, Equity) (Table 2), which was developed as part of the wider BCW intervention development process. APEASE is a set of judgement and decision-making criteria for intervention designers to consider throughout the whole intervention development process to ensure the intervention is context-appropriate, sustainable and socially just.

In line with the BCW, first the identified behavioural influences were mapped from the survey onto COM-B, which enabled a better understanding of what needed to change. Next, there was a secondary mapping exercise which involved selecting intervention types from the BCW guide that are suggested to most likely to be effective for changing the behavioural targets identified in the previous step. Since changing policy is beyond the scope of this work, our research skipped the selection of policy options. The BCW also offers guidance on the BCTs most commonly used per intervention type and so this was used to support intervention selection. The final mapping exercise involved selecting BCTs from the BCT Taxonomy for the selected intervention types in the previous step. APEASE criteria were applied throughout the whole process to guide selection of intervention content.

3.3. Intervention evaluation

The survey results suggested that a bundled intervention consisting of the provision of a pressure cooker, chapati pan and training on how to use these devices could reduce polluting stacking with charcoal in PAYG LPG consumers in Kisumu. This was tested through a pre/post study design consisting of monitoring cooking practices for three weeks prior to the interventions and three weeks after, amongst a small (n = 19) sample of PAYG LPG customers. The sample size was determined by budgetary constraints, which limited the number of pans that could be purchased, and the study was knowingly underpowered because of a combination of budgetary constraints and the lack of available data to estimate the effect size in advance.

The intervention efficacy was measured by comparing changes in fuel use captured through simplified cooking diaries and SMART data before the intervention (phase 1) and after the intervention (phase 2). Cooking diaries consist of self-reported, high-frequency data about a household's cooking practices. The cooking diaries used in this study were simplified versions of Leary et al.'s original methodology [39] and consisted of a one-sided form that was completed daily. The diaries were designed to only collect data relevant to the analysis and to be easy to transcribe, thus minimising the burden on both the participants and the researcher. The first part of the form asked questions about fuel use and purchases and the second part of the form consisted of a table listing the foods being targeted by the interventions. Participants stated whether each of the foods had been cooked fresh or reheated that day, and the fuel that had been used to do so. The phase 2 forms also asked additional questions relating to the interventions, namely whether the pans had

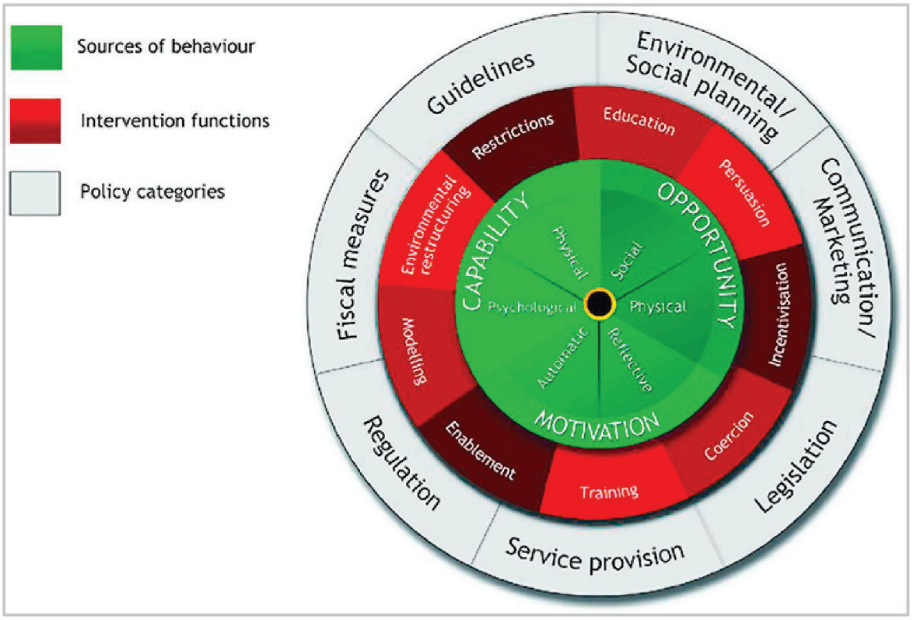

Fig. 2. The Behaviour Change Wheel (Michie et al. 2011, 2014).

Table 2
APEASE criteria for designing interventions (Michie et al., 2014; 2011).

Decision-making criteria	Definition
Acceptability	How far is it acceptable to key stakeholders? This includes the target group, potential funders, practitioners delivering the interventions and relevant community and commercial groups.
Practicability	Can it be implemented at scale within the intended context, material and human resources? What would need to be done to ensure that the resources and personnel were in place, and is the intervention sustainable?
Effectiveness	How effective is the intervention in achieving the policy objective(s)? How far will it reach the intended target group and how large an effect will it have on those who are reached?
Affordability	How far can it be afforded when delivered at the scale intended? Can the necessary budget be found for it? Will it provide a good return on investment?
Side-effects	What are the chances that it will lead to unintended adverse or beneficial outcomes?
Equity	How far will it increase or decrease differences between advantaged and disadvantaged sectors of society?

been used to cook each of the relevant dishes, and whether any other foods had been cooked with the pans that day.

The intervention was provided free of charge and the pans were later gifted to the participants as a thank you for taking part in the study. Fig. 3 shows how each phase lasted for three weeks and at the end of the study, household interviews were conducted with the participants. These were designed to collate feedback on experiences of using the intervention pans and willingness to pay for them. The latter was measured using a Vickrey auction, where each participant submitted hypothetical secret and separate bids for the pressure cooker and chapati pan. The rules of the auction dictate that the highest bidder wins, but that they pay the second-highest price [40]. This incentivises bidders to reveal their true willingness to pay.

To be eligible for the intervention, participants needed to have partaken in the telephone survey and shown through their responses that both of the pans would be relevant to them (n = 79). Prospective participants needed to reside in the Obunga, Manyatta and Kondele districts (n = 55) in order to limit the travel burden of visiting households. These three areas are informal settlements typical of the areas that Bboxx operated in. Once these filters had been applied, participants (n = 20) were sampled evenly across categories of PAYG LPG consumption, which was assumed to be a proxy of the extent of stacking in each household (low: <300 g/capita/month n = 7, medium: 300–360 g/capita/month n = 7, high: >360 g/capita/month n = 6). There was one dropout during the study giving a final sample size of n = 19. Table 3 shows that the nineteen intervention participants were comparable to the rest of the survey group (n = 80, excluding the n = 19 interventions participants) in terms of their LPG consumption, household size and proportion of female account holders, suggesting that the results from intervention component of the study are generalisable to Bboxx's wider customer base.

A local woman who had received culinary training at catering college

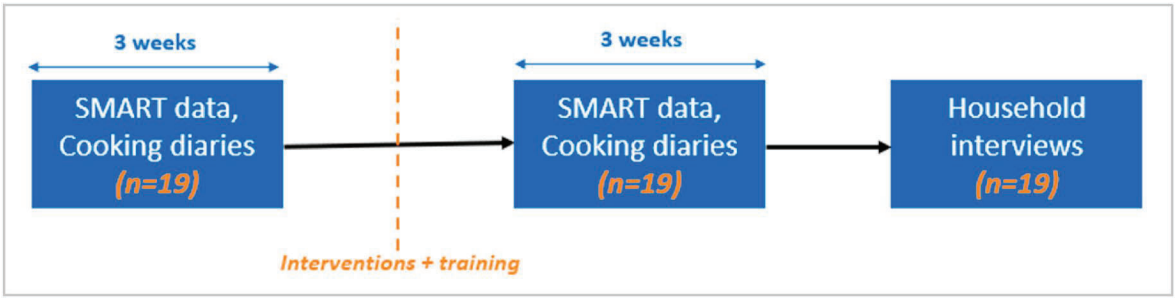

Fig. 3. Structure of interventions study.

Table 3
Comparing characteristics between sub-samples. All statistical tests found insignificant differences at a 5 % significance level. Mann-Whitney U-tests were used for PAYG LPG consumption and HH size, whereas z-tests were used to compare the proportion of female account holders. SD = standard deviation.

Characteristic	Intervention study group (n = 19)	Rest of stacking survey group (n = 80)	Significance (P (Z ≤ z))
Mean PAYG LPG consumption (g/week)	1153 (SD 589)	1138 (SD 629)	p = 0.83
Median HH size	4	4	p = 0.68
% female account holder	79 %	69 %	p = 0.39

was hired as an enumerator for this study. She focussed on building social relationships with the participants to gain their trust. This gave her credibility when teaching them new cooking practices. Training took place in the household with the main cook and consisted of teaching them about the benefits of the pressure cooker and chapati pan, also providing a leaflet of recipes and instructions, and performing a demonstration where the enumerator and participant cooked four chapatis and two tins of beans together.

4. Results and discussion

4.1. Survey

In the survey, respondents reported cooking with PAYG LPG (98 % of participants), charcoal (63 %), firewood (16 %), full-cylinder LPG from other providers (9 %) and kerosene (4 %). Full-cylinder LPG was used in emergencies (n = 4) and as a substitute for PAYG LPG (n = 1). Firewood tended to be purchased rather than gathered. The most common fuel combination was PAYG LPG and charcoal (50 %).

Participants stacked for reasons that spanned all of the stacking taxonomy's categories, indicating the difficulty of eliminating polluting fuel stacking in the PAYG LPG customer population. All participants stacked due to reasons falling into the Affordability (AFF), Technical Characteristics (TEC) and Time Aspects (TIM) categories (Fig. 4a). Stacking due to Cultural Compatibility (CUL), Stove Functionality (FUN), Knowledge and Training (KNO) and End Uses of Traditional Stoves (END) was also common. There was very little stacking due to Household Dynamics (HHD) or Safety Issues (SAF). The former could be due to the high proportion of female account holders, who by definition had the agency to select their cooking fuel. The latter could reflect that the majority of Bboxx's PAYG LPG population previously cooked with single-burner LPG *meko* stoves that screw directly onto the cylinder, which are often believed to be less safe than the two-burner PAYG LPG stove.

Fig. 4b shows that the Affordability category contained the most stacking drivers across the survey sample and yet PAYG LPG was considered to be one of the most affordable fuels in the stack (AFF_5), equal to firewood and full-cylinder LPG. This was often attributed to the way that PAYG LPG could be purchased in any amount (AFF_3, n = 21). However, a quarter of households struggled to afford PAYG LPG at certain times of year due to seasonal income fluctuations (AFF_2, n = 23). The majority of customers reported stacking in order to save PAYG LPG fuel (n = 69); it is unclear whether this was for affordability reasons (AFF_1, AFF_2) or to avoid damaging equipment (FUN_5).

These affordability constraints could be addressed by reducing the PAYG LPG tariff. However, this is unlikely to be feasible without support from other actors, such as through the Rwandan results-based financing

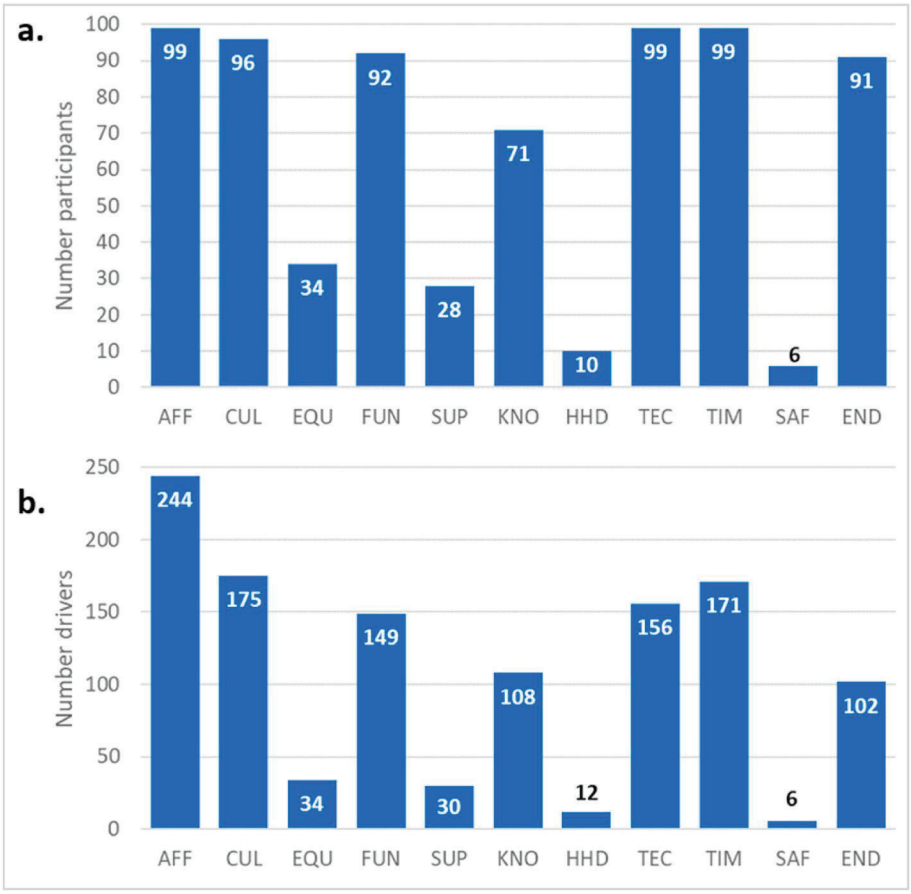

Fig. 4. Bar charts showing (a) the number of participants experiencing each stacking category and (b) the total number of stacking drivers in each category.

programme that provides tiered levels of support for different income groups [41]. Alternatively, PAYG LPG providers could implement flexible tariffs that extend credit to customers in times of financial hardship. This approach has been proposed in the PAYG solar sector [42] but appears unexplored in the less mature realm of clean cooking.

PAYG LPG was widely considered to be compatible with steaming, quick boiling, grilling and frying (Fig. 5) but was perceived by almost everyone to be incapable of performing tasks that involve long boiling (TEC_2, n = 94), such as preparing githeri and beans. This was because it was considered too expensive to cook these foods on LPG (AFF_6, n = 89). However, only about half of participants who reported this had actually tried cooking long-boiling foods on LPG (KNO_2, n = 63, Fig. 5). This suggests that customers had already decided how they would use PAYG LPG before receiving their unit and that these preconceptions hindered adoption. Providers may be required to actively educate their customer base about LPG's versatility and ways of cost-effectively cooking energy-intensive foods on the fuel, such as using pan lids and regulating the flame properly. Such practices could also help address wider affordability issues of cooking with clean fuels.

More specifically, all respondents said that there were certain foods they preferred not to cook on PAYG LPG, most commonly githeri (n = 85), chapatis (n = 74), beans (n = 68) and peas (n = 60). For githeri, beans and peas, this was because of the aforementioned high costs of cooking long boiling foods on PAYG LPG (AFF_6). The introduction of pressure cookers with accompanying training was therefore identified as a high-potential intervention for reducing stacking in the Kisumu customer base. There is a nascent and growing interest in the potential for pressure cookers in the SSA context, although the focus to date has been on electric pressure cookers (EPCs) rather than LPG ones [43–45]. LPG pressure cookers have the advantage of being cheaper and non-reliant on electricity supply, but they have higher knowledge barriers to use [46] and can cause accidents, especially if they lack safety pins [47]. Compatibility of long-boiling foods with LPG can also be enhanced by soaking beans, which shortens their cooking time [48,49], or by providing pre-cooked beans that simply need warming [17,50].

The aversion to cooking chapatis on PAYG LPG was less clear given that the fuel was perceived to be generally well-suited to frying tasks (Fig. 5). A small sample of n = 16 participants were asked further questions about the reasons behind this. Three-quarters reported always using charcoal to cook chapatis; just under a half (n = 7, KNO_2) had never tried cooking chapatis on LPG. They preferred to use charcoal because they believed cooking chapatis on PAYG LPG would use too much gas (n = 5, AFF_6), would burn the chapatis (n = 4, KNO_1) or that LPG is incompatible with a certain type of heavy frying pan that is often used to cook chapatis in Kenya (n = 4). These barriers could be addressed through the provision of modern, lightweight frying pans along with training on how to regulate the LPG flame in order to use them. The burning of chapatis further suggests the presence of a knowledge gap in regulating the LPG flame that was not picked up directly in the survey, which found that only a handful of participants did not feel confident using PAYG LPG (KNO_1, n = 15). Future iterations of the survey should find an improved way of investigating this stacking driver, such as asking the participant to describe how they would cook a food that requires regulation of the flame.

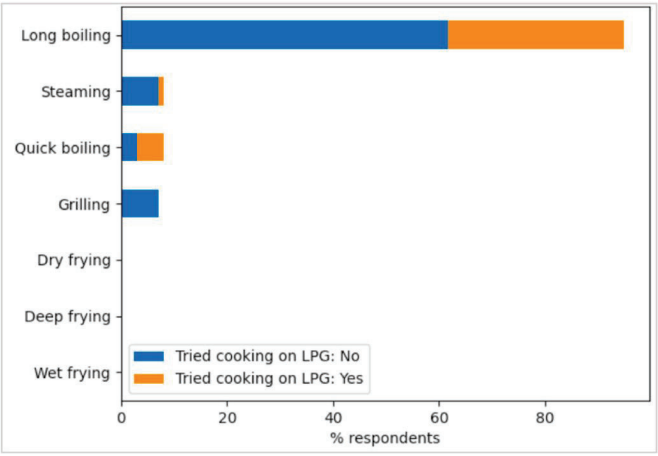

Fig. 5. Bar chart showing cooking processes that participants preferred to use other fuels to perform.

Other studies have found that polluting fuel use increases during cultural events [26,51,52] and this was also the case for PAYG LPG. The majority of respondents stacked PAYG LPG alongside other fuels during cultural events or special occasions (CUL_8, n = 89). This was usually to cook several things at once (TIM_1, n = 62), because of the social aspects of cooking with wood or charcoal (CUL_7, n = 24), or because of the need to cook large quantities of food. The latter was not possible on LPG because the stove was too small (TEC_5, n = 19) or unable to support large pots (EQU_1, n = 19). However, cultural events were occurred rarely and were seasonally clustered. Outside of these occasions, few respondents required more than two burners to cook exclusively with PAYG LPG (TIM_1, n = 17).

Biomass use was also perpetuated by the need to produce embers and ashes that were subsequently used for other purposes (END_6, n = 84). The literature review showed a variety of uses for embers, such as keeping food warm after cooking [52–54] and toasting meat and fish [55]. The reasons behind this practice in the Kisumu context are unclear and further research is needed to understand it. Few participants used traditional fires for space heating (END_2, n = 16), likely due to Kisumu's consistently warm climate.

Most participants had at some point cooked with a different fuel because of malfunctioning equipment (FUN_1, n = 78) due to technical issues processing credit top ups (n = 62), broken stoves (n = 14) and broken meters (n = 10). The most common technical issue with the stove was that it produced soot and smoke (TEC_7, n = 22), and participants had been unable to cook with PAYG LPG for a median of one day in the past month due to technical issues. The high prevalence of equipment problems differed from the findings of Perros et al.'s literature review (2022), which did not find technical issues to be a common driver of full-cylinder LPG stacking in the underlying studies. This reveals a disadvantage of PAYG LPG: it is a more complex technology with higher potential for breakages. Companies are there recommended to provide the highest-quality equipment that is feasible. The fuel delivery service did not completely solve the fuel supply issue; a third of participants reported having cooked with alternative fuels because they had run out of PAYG LPG (SUP_1, n = 27). This is a clear area of improvement for Bboxx and more mature PAYG LPG offerings should work towards eliminating these issues.

The survey found that PAYG LPG consumption is highly seasonal, with all participants expecting to use less fuel at certain times of year (TIM_3, n = 99). This most frequently occurred in October–December (n = 48) due to cultural events and cheaper firewood prices during this time (Fig. 6). A substantial number of participants also expected to use less PAYG LPG use in January–March (n = 33) because of other spending priorities. These months coincide with school fees payments in Kisumu, which other studies have identified as being the root cause of temporary backsliding to polluting fuels [56,57]. This seasonal nature of PAYG LPG consumption should be of interest to PAYG LPG providers, who use fuel sales as a critical performance metric, as it reveals that there are expected time-based variations in fuel consumption. More research is needed to understand whether the suppression in PAYG LPG use corresponds to increased cooking with other fuels or simply less domestic cooking in total.

The incompatibility of cooking pots and fuels can also drive stacking. A minority of respondents (n = 15) said that some of their pots were incompatible with PAYG LPG, either because the pot was too large (EQU_1, n = 12) or was made of a material that might break on LPG

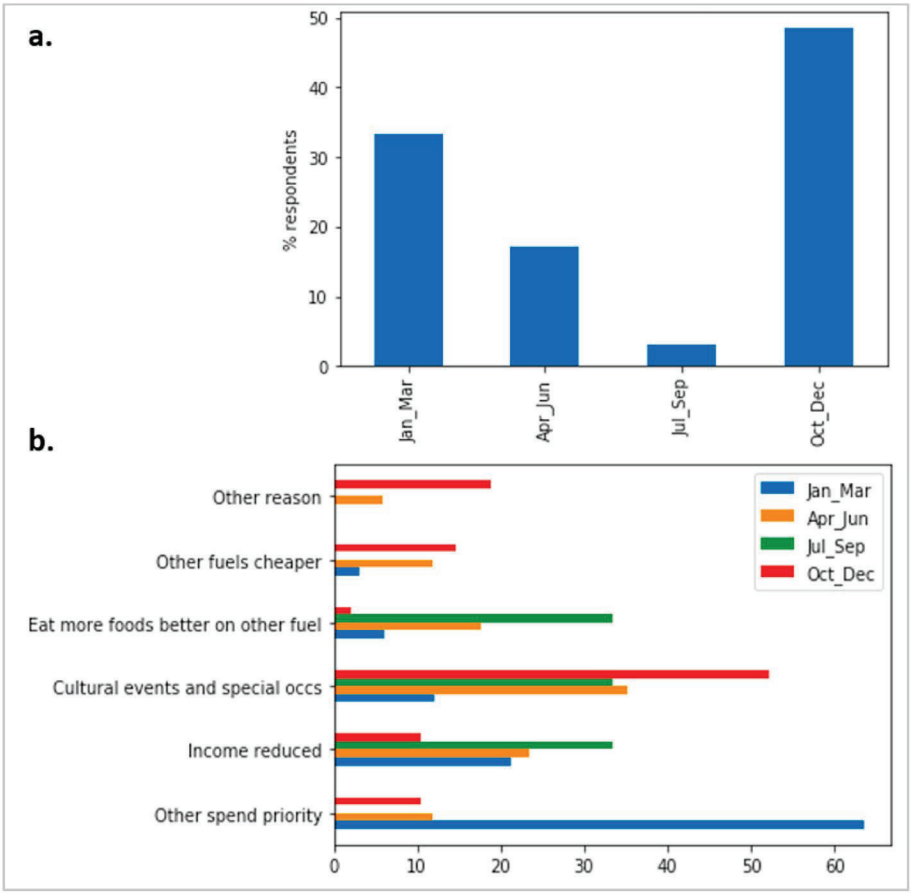

Fig. 6. Bar charts showing (a) seasons during which respondents anticipated using less PAYG LPG and (b) the reasons why.

(EQU_2, n = 3. However, not all had high levels of motivation to cook with clean devices, as around a third ranked the importance of cooking with clean fuels as less than four on the Likert scale (KNO_3, n = 30). This suggests that households were primarily attracted to PAYG LPG because of the co-benefits of cooking with a clean fuel, such as time and financial savings, as has been found in other studies [58–60].

Respondents generally liked the taste of food cooked on LPG, with the median Likert score of 4 = "satisfied", and only a handful (CUL_1, n = 11) avoided using LPG for certain dishes because of taste. This high level of satisfaction with the taste of food cooked on LPG contradicts the findings of other studies [27,53,61] and could be because the majority of Bboxx's customers were not first time LPG users who were probably already accustomed to the taste of food cooked on LPG.

This survey tool could help promote a more rigorous and standardised approach to researching fuel stacking. Comparing results between different samples could generate new insights about the contextual specificity of stacking patterns. To do this, the survey tool should be tested and refined across a broad range of technologies location types, geographies and business models.

4.2. Intervention development

A a range of potential intervention types (Table 3) and BCTs (Table 4) were considered based on intervention strategies likely to be effective at addressing the stacking drivers identified by the survey. The use of APEASE criteria, along with consideration of intervention context, assisted in narrowing down potentially appropriate intervention types and BCTs. The intervention types selected were 'education' and 'environmental restructuring'. The BCTs selected were 'adding objects to the environment', 'restructuring the physical environment' and 'providing instruction on how to perform the behaviour'.

implementation options for the selected BCTs were then devised in terms of potential intervention specifications. These were subsequently further narrowed down and selected based on consultation with the Bboxx staff and technicians who work closely with their PAYG LPG customers. The implementation options were assessed in terms of their likelihood for impact and ease of implementation in the PAYG LPG business model. This final mapping exercise to select the final intervention specification is shown in Table 5. The selected intervention was the co-provision of pressure cookers and chapati pans along with training on how to use them (see Table 6).

4.3. Intervention evaluation

4.3.1. Theory of change

A theory of change provides a structured way of mapping the causal pathway between an intervention's inputs and its desired outcome [62]. The theory of change for this study is based on results derived through the stacking survey and is outlined in Fig. 7 below. The pressure cookers were anticipated to increase the affordability of cooking long-boiling foods such as beans, peas and githeri on LPG, thus allowing participants to switch from using charcoal to LPG for these tasks. Similarly, the chapati pans were expected to increase the compatibility of cooking chapatis on LPG, thus displacing charcoal.

The pans used in the study are shown in Fig. 8 alongside the traditional ones they were intended to displace. It proved difficult to source a sufficient quantity of modern LPG-compatible chapati pans, so participants were provided with high quality non-stick frying pans instead (henceforth referred to as the "frying pan"). Each participant received both devices as they were expected to be mutually exclusive; it is impossible to long boil foods in a shallow frying pan or to fry chapatis in a high-walled pressure cooker. Through using cooking diaries to track

Table 4
Intervention types appropriate for targeting the most commonly identified underlying stacking drivers.

Stacking driver	COM-B	Potential Intervention type	Definition	APEASE consideration	Inclusion/ Exclusion
TEC_2 (n = 99) **TIM_3** (n = 99) **AFF_6** (n = 97) **END_6** (n = 84) **FUN_1** (n = 79)	Physical opportunity (i.e., affordability/income constraints and issues relating to the cookstove design/functionality not meeting user needs)	Environmental restructuring	Changing the physical or social context	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	**Included**
AFF_1 (n = 45) **AFF_5** (n = 44) **EQU_1** (n = 31) **AFF_2** (n = 23) **TIM_1** (n = 68)		Enablement	Increasing means/reducing barriers to increase capability (beyond education/training) or opportunity (beyond environmental restructuring)	Not applicable because a strategy going beyond both education and environmental restructuring unlikely in this context	Excluded
CUL_8 (n = 95)	Reflective Motivation (i.e., beliefs and preferences for traditional foods and cooking methods)	Education	Increasing knowledge or understanding	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable**, should have limited **side effects** and shouldn't create significant issues of **equity**	**Included**
KNO_2 (n = 63)		Persuasion	Using communication to induce positive or negative feelings to stimulate action	Considered **practical**, potentially **acceptable,** should have limited **side-effects**, shouldn't create significant issues of **equity** but not considered **affordable** (e.g., high cost of advertising/media campaign) or likely to be **effective** as stacking drivers were not found to be issues with emotions or other automatic motivational processes	Excluded
		Modelling	Providing an example for people to aspire to or imitate	Considered **practical**, potentially **acceptable,** should have limited **side-effects**, potentially **effective**, shouldn't create significant issues of **equity** but not considered **affordable** (e.g., high cost of advertising/media campaign)	Excluded
CUL_7 (n = 50)	Social opportunity (i.e., social aspects of cooking with cookstoves)	Modelling	Providing an example for people to aspire to or imitate	Considered **practical**, potentially **acceptable,** should have limited **side-effects**, potentially **effective**, shouldn't create significant issues of **equity** but not considered **affordable** (e.g., high cost of advertising/media campaign)	Excluded
		Enablement	Increasing means/reducing barriers to increase capability (beyond education/training) or opportunity (beyond environmental restructuring)	Not considered **practical** because a strategy going beyond both education and environmental restructuring e.g., community cadres to create positive social norms/motivate clean cooking not implementable in this context	Excluded

the frequency of cooking the target foods, it was therefore possible to conduct both interventions simultaneously and to disaggregate their respective fuel use and dietary impacts.

4.3.2. Understanding user acceptability of cooking with non-stick frying pans and pressure cookers

The household interviews revealed that 21 % of participants had used a pressure cooker before the study and 95 % a non-stick frying pan. Opinions of pressure cookers before the study were largely negative, specifically because participants felt that they were difficult to use (n = 10), scary to use (n = 3), expensive (n = 1) and fuel intensive (n = 1). However, some participants said that they were easy to use (n = 2), desirable to use them (n = 1) and energy saving (n = 1). Views on non-stick frying pans before the study were more positive, with participants perceiving them as easy to use (n = 12), useable by everyone (n = 1) and desirable to use (n = 1). Some respondents said that chapati pans could not be used with LPG (n = 5), presumably referring to the traditional, heavy chapati pans that study aimed to displace (Fig. 8c).

During the intervention phase of the study (phase 2), all participants recorded using both pans, although the frequency of use varied (Fig. 9). The pressure cooker experienced heavier use, despite having more negative perceptions beforehand; its median proportion of recorded usage days was 43 % versus 38 % for the frying pan. This could be because of the high dietary compatibility between pressurised cooking and the East Africa diet that has been observed with electric pressure cookers [63–65]. The pressure cooker was most commonly used to cook beans (n = 102 recorded instances), githeri (n = 58), peas (n = 29), meat (n = 13) and tripe (n = 9). The frying pan was most commonly used to cook chapatis (n = 128 recorded instances), eggs (n = 38), pancakes (n = 11) and vegetables (n = 8).

Table 5
Table outlining BCTs selection process for the selected intervention types.

Selected intervention type	Potential BCT	APEASE	Inclusion/ Exclusion
Environmental restructuring Education	Self-monitoring of behaviour	Not considered likely to be **effective** as drivers of stacking were mostly related to physical opportunity not issues of behavioural regulation	Excluded
	Adding objects to the environment	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable** (for citizens, policy makers and companies), should have limited **side effects** and shouldn't create significant issues of **equity**	**Included**
	Restructuring the physical environment	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable** (for citizens, policy makers and companies), should have limited **side effects** and shouldn't create significant issues of **equity**	**Included**
	Instruction on how to perform the behaviour	Considered **affordable**, **practical**, potentially **effective**, potentially **acceptable** (for citizens, policy makers and companies), should have limited **side effects** and shouldn't create significant issues of **equity**	**Included**
	Information about social and environmental consequences	Not considered likely to be **effective** as drivers of stacking were mostly related to physical opportunity not issues of knowledge relating to negative health or environmental impacts	Excluded
	Information about health consequences	Not considered likely to be **effective** as drivers of stacking were mostly related to physical opportunity not issues of knowledge relating to negative health or environmental impacts	Excluded
	Feedback on behaviour	Not considered **practical** for this context as behaviour is happening in the privacy of homes or likely to be very **effective** as drivers of stacking were mostly related to physical opportunity not issues of behavioural regulation	Excluded
	Feedback on outcome of behaviour	Not considered **practical** for this context as behaviour is happening in the privacy of homes or likely to be very **effective** as drivers of stacking were mostly related to physical opportunity not issues of behavioural regulation	Excluded
	Prompts/cues	Not considered **practical** for this context as behaviour is happening in the privacy of homes or likely to be **effective** as key drivers were not related to issues of memory/attention	Excluded

The main benefits of using the pressure cooker were that it saved time (n = 19) and energy (n = 13). The main disadvantages were that it required training before using (n = 6) and that it is scary to use first time (n = 2). Nine participants said there were no disadvantages at all.

The main benefits of the frying pan were that it saved energy (n = 8), that it had a handle (n = 6) and that it cooked soft chapatis (n = 5). The only disadvantage was the need to know how to regulate LPG in order to use it (n = 14). Five participants cited no disadvantages. These findings suggest that there could be latent demand for more ergonomic cooking equipment in Kenya and that baseline knowledge of how to adjust the LPG flame was poor, in accordance with the stacking survey. Bboxx were already following published best practice [66] by providing comprehensive training on stove operation when PAYG LPG was first installed. However, the results of this study suggest that this one-off approach is insufficient and that periodic top-up training may also necessary for ensuring optimum utilisation of the fuel.

Participants were unanimously willing to recommend the pans to their friends and family. They were very positive about the taste of food cooked in both pans and the experience of using them, showing the intervention had a high degree of cultural compatibility and perceived utility. The Likert scale revealed a slight preference for the pressure cooker, which more frequently obtained the highest ratings, reflecting its higher rate of use. The training and handouts provided were exclusively reported as good or very good.

4.3.3. Measure the impact of providing non-stick frying pans and pressure cookers on the consumption of cooking fuels

The cooking diaries found that the only fuels used by participants during both phases of the study were LPG and charcoal. Phase 2 marked a range of changes in fuel use (Fig. 10a). Overall, the cooking diaries showed a statistically significant 9 % increase in the days on which PAYG LPG was used (paired *t*-test p = 0.0072 at 5 % significance level), but a statistically insignificant decrease in charcoal use of 4 % (paired *t*-test p = 0.745 at 5 % significance level). Six participants completely stopped cooking with charcoal in phase 2. There was one outlier participant who increased the proportion of days they used charcoal by 82 % once they received the pans. Examination of the cooking diaries shows this was driven by a corresponding increase in regularity with which they cooked beans, and that they preferred not to use the pressure cooker for this task.

There was also a distributed change in fuel spend (Fig. 10b). According to the cooking diaries, the median daily increase in PAYG LPG expenditure was 5 KES (*0.05 USD*, SMART data), which was less than the median decrease in charcoal spend of 7 KES (*0.06 USD*, cooking diaries). Participants therefore spent less money on cooking fuel in phase 1 than in phase 2. The SMART data set verified the increase in PAYG LPG consumption, with the median daily LPG use changing from 161 g per day in phase 1–186 g per day in phase 2 (16 % change).

Table 7 shows a breakdown of how the target foods were cooked throughout the study. Githeri was cooked with a similar frequency in phase 1 (n = 92) and phase 2 (n = 83) and usually with LPG in both phases (64 % of cooking events in phase 1 versus 70 % of cooking events in phase 2). Githeri was cooked more often from fresh in phase 2 (n = 46 in phase 1 versus n = 58 in phase 2) and LPG was used for this task three times more often in phase 2 than phase 1 (Fig. 11).

LPG was the dominant fuel for cooking chapatis throughout the study (91 % in phase 1 and 97 % in phase 2). There was a large (1.5×) increase in frequency of cooking chapatis in phase 2 and a shift towards cooking them from fresh instead of reheating (59 % of cooking events in phase 1 versus 92 % in phase 2). Reheating foods was almost always done on LPG in both phases. There was little change in the cooking practices of peas, with LPG being used nine times out of ten in both phases. Beans were cooked more frequently in phase 2 (n = 116) compared to phase 1 (n = 88), and more often with LPG (91 % of cooking events in phase 2 versus 75 % of cooking events in phase 1). Beans were twice as likely to be cooked from fresh in phase 2 (Fig. 11), and LPG was almost twice as likely to be used for this purpose in phase 2 (49 % in phase 1 versus 89 % in phase 2).

The observed changes in frequency of cooking certain dishes suggest that the intervention altered participants' diets as well as causing a fuel transition. This could be a positive change; for instance, the higher frequency of cooking beans indicates an increased intake of protein, agreeing with a study in India which found that pressure cookers can positively impact nutrition [67]. However, it also undermines the like-for-like comparison between the phases that is needed for a pre-post study design [68]. Future studies should use randomised controlled trials to study stacking interventions, as randomisation ensures that the participants in each group are similar and can produce definitive answers about the impacts of the intervention [69].

The intervention pans were used for the majority of target food

Table 6
Potential implementation options for the intervention based on selected BCTs and assessed according to their likelihood of impact and ease of implementation in the intervention context.

Behaviour Change Technique	Potential implementation option for the intervention	Likelihood of impact	Ease of implementation
Instruction on how to perform the behaviour	**Encourage customers to soak pulses overnight so they have a shorter cooking time and are thus more affordable to prepare on PAYG LPG**	Low – soaking can reduce cooking times, but these foods will still take a relatively long time to cook. Soaking is not a common practice in Kenya and it is likely to be difficult to persuade people to adopt it	High – education exercise requiring demonstrations with no cost to the customer
Adding objects to the environment **Restructuring the physical environment**	**Provision of pre-cooked pulses that simply need warming through rather than cooking**	High – eliminates the need for long boiling foods completely	Low – these products are currently not mainstream in Kenya. Bboxx would need to partner with a new market entrant in order to supply beans to customers. They are likely to cost more money than dried alternatives, presenting another affordability challenge
Adding objects to the environment **Restructuring the physical environment**	**Provision of pressure cookers to cook long boiling foods on LPG**	High – pressure cookers can cook dried pulses in minutes, effectively eliminating long boiling foods	Medium – pressure cookers are not commonly used in Kenya so they will be a new device for most customers. They can be scary and even dangerous to use so there need to be provision of adequate training to use the appliance. They may not be culturally acceptable. Customers may not be willing to pay for these devices.
Adding objects to the environment **Restructuring the physical environment**	**Provision of modern chapati pans to cook chapatis on LPG**	Medium – it is unclear whether providing chapati pans will help transition customers to cooking chapatis on LPG	Medium – also requires provision of training as part of the issue with cooking chapatis may be knowing how to regulate the LPG stove. Customers may not be willing to pay for these devices
Restructuring the physical environment	**Flexible tariffs to allow customers to continue to use LPG despite seasonal fluctuations. For example, a promotional lower tariff in January when school fees are due, or in December when firewood is cheaper**	Medium – should help customers cook with LPG during these periods. However, there is a chance that it could backfire and turn them away from LPG when the tariff returns to full rate	Low – requires reconsideration of pricing and some mechanism to subsidise at certain times of year
Adding objects to the environment **Restructuring the physical environment**	**Provision of four-burner stoves**	Low – because this is intervention is largely relevant to cultural events and special occasions, which happen irregularly	High – Four burner stoves are easy to source but they are expensive. No additional training required. Customers may not be willing to pay for these devices
Restructuring the physical environment	**Provision of higher quality equipment**	Medium – Higher quality equipment should reduce the amount of downtime due to broken equipment. However, downtime was reported to be relatively low (1 day per month)	Low – requires considerable effort and expense to source, test and distribute new equipment
Restructuring the physical environment	**Reduce tariff for all**	Medium – this may make PAYG LPG more affordable for some people stack for affordability reasons, but it will disproportionately benefit heavy users who can afford the current tariff	Low – Likely to be financially unfeasible to implement
Restructuring the physical environment	**Means-tested tariffs that are lower for customers who need additional support to switch completely to clean fuels**	High – this intervention could really help support low-income households to transition to cooking with clean fuels	Low – Financially unfeasible to implement without the support of a partner who is concerned in funding the impacts of clean cooking, such as the government or the World Bank through one of their RBFs

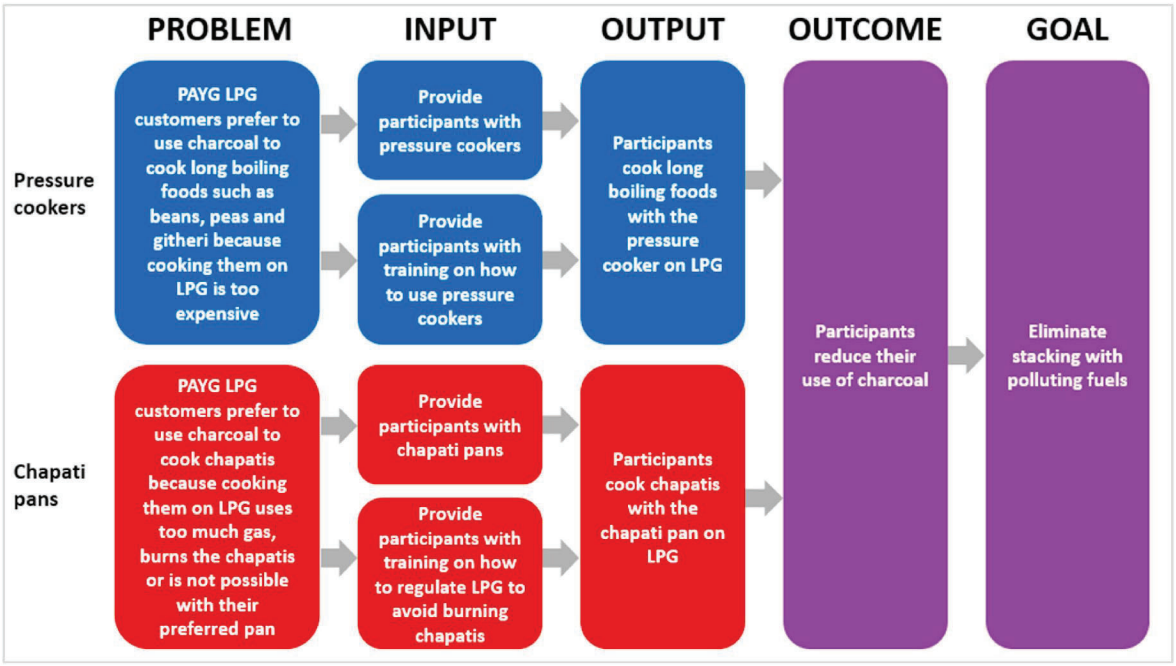

Fig. 7. Theory of change presented in the format outlined by Krishan (2017).

Fig. 8. Pans used in the Kenya Interventions study. (a): traditional sufuria boiling beans on a charcoal stove. (b) pressure cooker preparing beans on an LPG stove. (c) traditional frying pan preparing chapatis on a charcoal stove and (d) frying pan preparing chapatis on LPG stove. Photo credit: Paulah Okoth

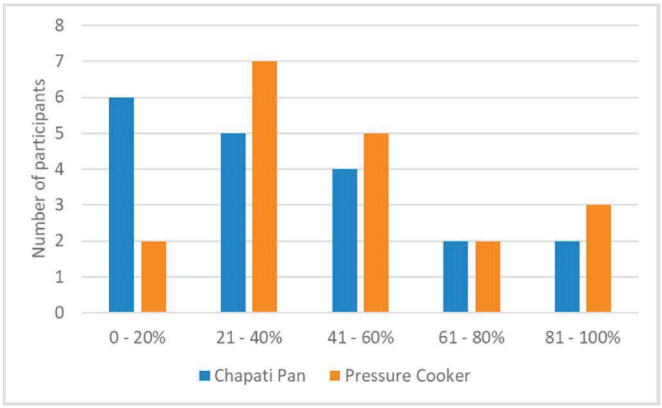

Fig. 9. Histogram showing proportion of days that the intervention pans were used.

cooking events in phase 2, namely chapatis (intervention pan used for 90 % of cooking events), beans (88 %), peas (73 %) and githeri (70 %). However, for each target food there were instances of the pans being paired with charcoal stoves instead of the PAYG LPG stove as intended. This phenomenon peaked for the pressure cooker, with 19 % of pressure cooker events occurring on charcoal. Although this was an unintended consequence of the intervention, it was not necessarily a negative one, as the efficiency gains of the pressure cooker would have decreased the amount of charcoal being burned and therefore reduced the associated health and climatic impacts. The food most anchored to charcoal was githeri (43 % of phase 2 cooking events), implying particularly strong cultural linkages between githeri and polluting fuels. This has also been observed in multiple other studies [63,70–72]. More research is needed to understand the inertia behind githeri fuel transitions and how it can be overcome.

The results presented in this section point towards high intervention uptake. However, there was a wide range of measured impacts, with some participants even experiencing sharp increases in charcoal use in

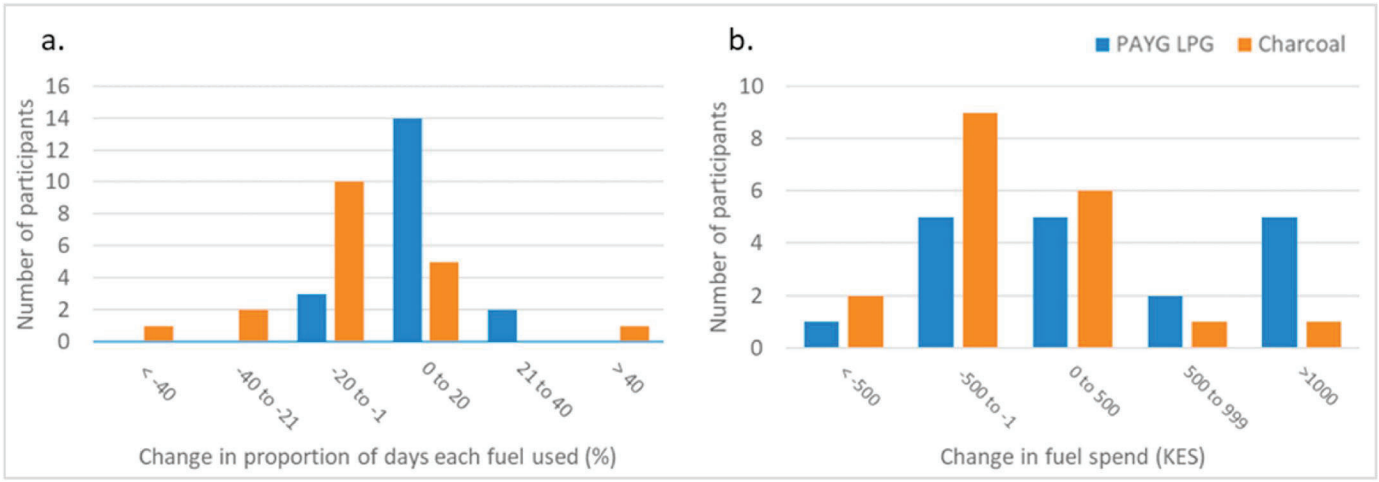

Fig. 10. Bar charts showing the change in (a) proportion of days each fuel used and (b) fuel spend.

Table 7
Comparing the cooking of target foods in phase 1 and phase 2.

	Githeri		Beans		Peas		Chapatis	
	Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2
Number of customers cooked each food	18	17	19	19	17	14	19	19
Median % days cooked	25 %	22 %	27 %	22 %	18 %	8 %	25 %	30 %
Total number of times each food cooked	92	83	88	116	65	40	94	143
Number of times each food cooked on PAYG LPG	59 (64 %)	58 (70 %)	66 (75 %)	105 (91 %)	58 (89 %)	36 (90 %)	86 (91 %)	139 (97 %)
Number of times each food cooked on charcoal	33 (36 %)	25 (30 %)	22 (25 %)	11 (9 %)	7 (11 %)	4 (10 %)	8 (9 %)	4 (3)
Number of instances cooked from fresh	**46** (50 %)	**58** (70 %)	**43** (49 %)	**102** (88 %)	**33** (51 %)	**32** (80 %)	**51** (54 %)	**128** (90 %)
% PAYG LPG	28 %	57 %	51 %	89 %	79 %	88 %	82 %	97 %
% Charcoal	72 %	43 %	49 %	11 %	21 %	13 %	18 %	3 %
Number of instances reheated	**46** (50 %)	**25** (30 %)	**45** (51 %)	**14** (12 %)	**32** (49 %)	**8** (20 %)	**43** (46 %)	**15** (10 %)
% PAYG LPG	100 %	100 %	98 %	100 %	100 %	100 %	100 %	100 %
% Charcoal	0 %	0 %	2 %	0 %	0 %	0 %	0 %	0 %
Number of instances used pressure cooker	–	**58** (70 %)	–	**102** (88 %)	–	**29** (73 %)	–	**0**
% PAYG LPG	–	64 %	–	89 %	–	90 %	–	–
% Charcoal	–	36 %	–	11 %	–	10 %	–	–
Number of instances used frying pan	–	**0**	–	**0**	–	**0**	–	**128** (90 %)
% PAYG LPG	–	–	–	–	–		–	95 %
% Charcoal	–	–	–	–	–		–	5 %
Number of instances used no intervention pan	–	**25** (30 %)	–	**0**	–	**11** 27 %	–	**20**
% PAYG LPG	–	84 %	–	–	–	92 %	–	100 %
% Charcoal	–	19 %	–	–	–	9 %	–	0 %

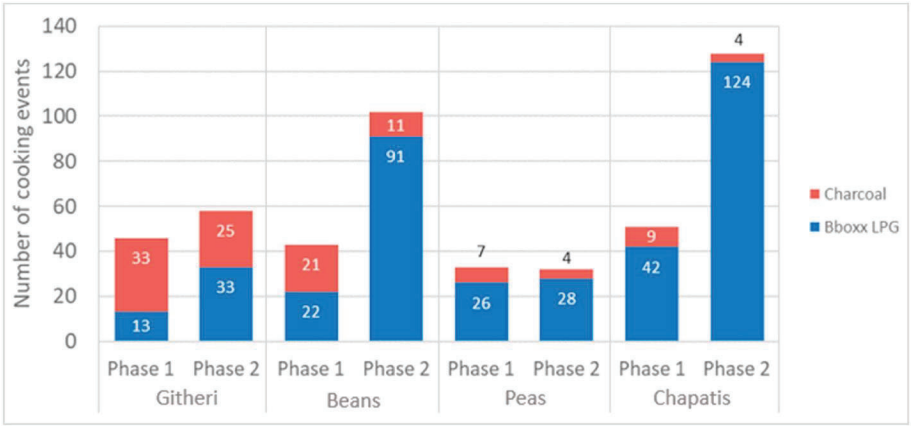

Fig. 11. Comparing the fuels used to cook foods from fresh in phase 1 and phase 2.

phase 2. This shows the theory of change was flawed for some households. Explanations for this include: changes in cooking practices in phase 2 that distorted the results, either due to natural variation in diet or due to the intervention pans facilitating cooking of certain foods; the efficiency gains of the intervention pans, which could result in a decrease of PAYG LPG consumption for foods prepared on LPG in both

phases; and inadvertent incentivisation of cooking on charcoal, as the pans also offered affordability improvements with other fuels. Table 8 highlights how these dynamics related to the original theory of change presented in Fig. 7. These learnings could help improve the implementation future research studies on fuel stacking interventions.

The household interviews also asked about which cooking fuels were used in phase 2. Everyone said they had used PAYG LPG and 37 % (n = 7) said they had used charcoal, whereas 68 % (n = 13) recorded use of charcoal in phase 2 in the cooking diaries, which suggests bias in the interviews. More generally, charcoal was used when guests were visiting (n = 2), there was a need to cook many foods at once (n = 1), PAYG LPG had run out (n = 1), there was no money to buy PAYG LPG (n = 1), to warm the house (n = 1) and because participants liked to use both fuels (n = 1).

Participants were also asked to suggest further interventions that would allow them to exclusively use PAYG LPG. The most common response was to reduce the fuel price (n = 15). This finding is likely to be biased; after all, most participants were already using PAYG LPG for the vast majority of their cooking, suggesting it was not so unaffordable. However, they support the stacking survey in suggesting that PAYG LPG is a significant expenditure that households struggle to budget for.

4.3.4. *Investigate the financial feasibility of the interventions at scale*

The Vickrey auction responses varied, with a median willingness to pay of 2000 KES *(18.54 USD)* for the pressure cooker and 1000 KES *(9.27 USD)* for the frying pan. In both cases, the cost of the pans (2900 KES/*26.88 USD* for the pressure cooker and 1900 KES/*17.61 USD* for the frying pan) was higher than the median bid. However, the pans were bought from a local supermarket at retail prices. Bulk sourcing could improve both product quality and price; Bboxx estimated a 30 % cost reduction as a reasonable estimate. This would bring the pressure cooker, but not the frying pan, in line with median willingness to pay.

It took 30 min for the enumerator to train each customer on how to use the pans. In a non-pilot setting, training could be managed in two ways: delivered individually by a technician or through community demonstrations to many households at once. Given the effectiveness of the approach adopted by this study, individual training is recommended. This could be incorporated into regular technician visits to install equipment or replenish empty cylinders. Bboxx paid their technicians through a commission for each activity completed; 100 KES *(0.92USD)* is a reasonable estimate for a pan training fee in Kisumu. Based on these figures, Table 9 considers the financial viability of providing pressure cookers and frying pans through different business models: upfront sales, a three-year equipment loan, upfront sales with a 50 % subsidy and a 100 % subsidy. It assumes there is a 30 % reduction in unit cost to Bboxx and adds a 10 % profit margin to the customer price. It does not include the costs of financing the equipment. Because the pans were associated with a net increase in LPG use, all four models show net gains to Bboxx after three years, ranging from 1940 KES *(17.98 USD)* for the 100 % subsidy model to 5636 KES *(52.35 USD)* for the upfront sale model. Based on these results, the recommended mode of delivery is to provide the pans with a 50 % subsidy and 50 % upfront sale to the customer. This reduces the risk to Bboxx whilst maintaining a high level of affordability for customers that falls below their median willingness to pay.

4.3.5. *Quantify the fuel and time savings from cooking with frying pans and pressure cookers*

Tests were conducted to measure the time and fuel savings from cooking with the intervention pans versus the standard ones. The tests consisted of cooking beans and chapatis in a two-fold comparison that looked at using the relevant intervention pan versus a traditional one, and cooking on LPG versus charcoal. Most tests had three repeats and the results are shown in Fig. 12 below.

In all of the tests, the intervention pans saved money and time compared to the traditional ones. The bean cooking tests showed that it was cheaper to cook 1 kg of beans on LPG (100 KES/*0.92 USD*) than on charcoal (133 KES/*1.23 USD*) with normal pans (Fig. 12a). Using the pressure cookers resulted in lower costs for both fuels (50 KES/*0.46 USD* for LPG and 100 KES/*0.92 USD* for charcoal, with a larger reduction for LPG. It was also quicker to cook 1 kg of beans in a standard pan with LPG (1 h) than with charcoal (2 h 10 min), probably because LPG burns with a hotter flame (Fig. 12b). Using a pressure cooker resulted in considerably quicker cooking times for both LPG (30 min) and charcoal (40 min). Pressure cooker related energy and time savings have also been observed in a recent pilot run by the United Nations in Cox's Bazaar, a displacement camp in Bangladesh, although the full results are not yet available [73].

Similar patterns were observed with the chapati cooking tests, which found that it was cheaper and quicker to cook 1 kg of chapatis on LPG with both pans. The frying pan halved the cooking costs for both LPG (33 KES/*0.31 USD* with a normal pan and 17 KES/*0.16 USD* with the frying pan, Fig. 12c) and charcoal (133 KES/*1.23 USD* with the normal pan and 67 KES/*0.62 USD* with the frying pan, Fig. 12d). These results were unanticipated and show that the intervention frying pan would have substantially increased the efficiency of participants' cooking, resulting in potential decreases in PAYG LPG consumption as the pan was often used to cook dishes prepared on PAYG LPG in both phases – acting in opposition to the intended effect and further undermining the theory of change outlined in Fig. 7.

There are well-established methods for measuring the efficiency of different cookstoves [74,75] and extensive research has been conducted in this realm [76–79]. However, understanding about how the choice of pan affects the overall efficiency of the cooking system is limited and consists of comparing different metal pans in high-income country

Table 8
Learnings from the theory of change for the Kenya Interventions study.

	Theory of change	What actually happened
Pressure cooker	Recruited participants said they prefer not to cook long boiling foods on LPG because of affordability. The pressure cooker makes it affordable to cook these foods on LPG, so should allow people to switch to using PAYG LPG to cook these foods, thus increasing LPG consumption	Some households recorded cooking long boiling foods on LPG in phase 1, despite saying they preferred to use charcoal in the interventions survey in Chapter 7. Therefore, pressure cookers would reduce LPG consumption for these households. Other households chose to use the pressure cookers on charcoal instead of on LPG, yielding no changes in PAYG LPG use.
Frying pan	The frying pan is quick to heat up and does not burn chapatis so easily, makes it possible to cook chapatis on LPG instead of charcoal, thus increasing PAYG LPG consumption.	Some households were already cooking chapatis on LPG. Due to sourcing issues, participants were provided with a non-stick frying pan instead of a chapati pan, which could also be used to cook a wide range of other foods too. Cooking foods on the frying pan turned out to consume significantly less fuel than standard pans. Therefore, the frying pan increased the efficiency of cooking a wide range of foods that were already being prepared on PAYG LPG, thus decreasing their consumption of PAYG LPG.
Both pans	Assumed that there would be similar dietary patterns in phase 1 and phase 2 as the phases were short and within the same season	Diets were not static between the phases and, crucially, there were sharp changes in the frequency of cooking some of the foods being targeted by the pans (specifically beans and chapatis). It is likely that providing the pans facilitated this change.

Table 9
The financial viability of providing pressure cookers and frying pans through different business models. Note that ongoing monthly gain to Bboxx is due to increased amount of PAYG LPG used as a result of introducing pans and that in all three scenarios customers pay the same amount for the equipment. The ongoing monthly gain to Bboxx is estimated based on a 25 g median daily increase in gas consumption in phase 2.

	Risk level to Bboxx (KES)	Initial cost to customer (KES)	Initial cost to Bboxx (KES)	Ongoing monthly cost to customer (KES)	Ongoing monthly gain for Bboxx (KES)	Net gain for Bboxx after 3 years (KES)
Upfront sale	Low	3696	3460	0	150	5636
Pay back via three-year equipment loan	Medium	0	3460	100	150	5540
50% upfront and 50% subsidy	Medium	1848	3460	0	150	3788
0% upfront and 100% subsidy	High	0	3460	0	150	1940

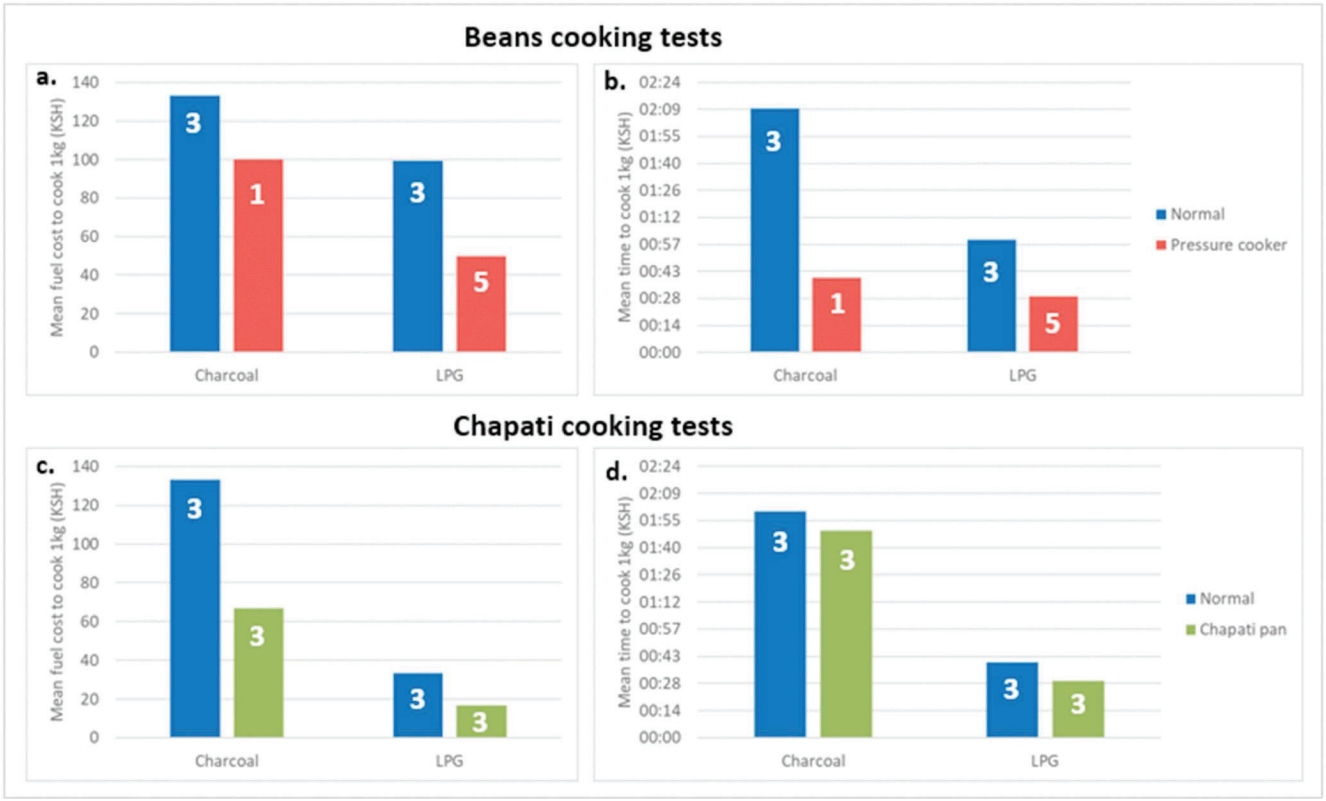

Fig. 12. Cooking test results for different fuels and pans comprising (a) cost of cooking 1 kg of beans; (b) time taken to cook 1 kg of beans; (c) cost of cooking 1 kg of chapatis; (d) time taken to cook 1 kg of chapatis. The white numbers in the bars show the number of repeat tests conducted and the bars show the mean value taken across the repeats.

contexts [80] and different pot shapes native to India [81]. This study therefore presents novel results that compare traditional and modern pan designs commonly found in SSA. Further research is required to better quantify the potential efficiency gains from pan upgrades.

4.4. Limitations

This research consisted of a case study drawing upon a small sample size, which could weaken the validity of the findings. However,

polluting fuel stacking is a ubiquitous problem (Shankar et al. 2020), and numerous other studies conducted in East Africa have attributed this practice to the same drivers as this case. This strongly suggests that the intervention developed through this research is relevant to other contexts and that the findings of this study may apply to other clean cooking providers.

The intervention phase of the research therefore limited by its study design (pre-post), small sample size and relatively short implementation phases. The study was knowingly underpowered, partially because of budgetary constraints which dictated the small sample size, but also because of the lack of available data to estimate the effect size in advance. The results should enable future researchers to adopt more rigorous designs, such as randomised controlled trials, and operate over longer timescales. This would eliminate sources of bias and provide stronger evidence about the efficacy and sustainability of the intervention.

The study aimed to reduce polluting fuel use through the provision of a fuel stacking intervention. However, a significant limitation of the research is its reliance on self-reported data about charcoal use, which other researchers have found to be of varying reliability [17,25,82]. The original study design included placement of stove use monitors (SUMs) on charcoal stoves to obtain objective data about charcoal use, but unfortunately data management and integrity issues meant that the data could not be used in the analysis. This strengthens the need for other, more rigorous research studies on this topic, which use polluting fuel use, measured by SUMs, as the primary measurement variable.

5. Conclusions

The results of this study demonstrate that it is possible to influence rates of fuel stacking through interventions that are tailored to the cooking practices of a target population. It also presents a quantitative, evidence-based methodology for identifying the most prominent stacking drivers in a given population and using these insights to design appropriate and effective fuel stacking interventions.

The intervention – which consisted of distributing pressure cookers, non-stick frying pans and training - succeeded in increasing rates of cooking chapatis, githeri, beans and peas on LPG, resulting in a significant increase in PAYG LPG use and an insignificant decrease in charcoal use. A third of participants stopped cooking with charcoal altogether, but some residual charcoal usage perpetuated amongst the remainder. These findings suggest that clean cooking practitioners could aid more exclusive uptake of clean cooking fuels by actively incorporating fuel stacking interventions into their product designs. The analysis shows that such interventions have the potential to save money and time for users whilst boosting revenues for providers. The research also reveals the need for policy makers and donors to broaden the scope of funding and policies to support the wider cooking system, not just stoves. Through facilitating the abandonment of polluting fuels, such an approach could have far-reaching co-benefits with multiple other Sustainable Development Goals, such as SDG3 (Good Health and Well-being), SDG5 (Gender Equality) and SDG13 (Climate Action) [83].

A key learning was that the efficiency gains of new cooking equipment can distort the results and alter participant cooking practices, so it is recommended that future research should take the usage of the stove being displaced as the primary measurement variable (in this case charcoal) rather than the one being promoted (in this case PAYG LPG). It also revealed the importance of training participants on how to use new cooking equipment, and that new LPG users may struggle to learn to regulate the stove. Addressing this could lead to more energy-efficient cooking practices and higher adoption of LPG.

SDG7 calls for universal access to affordable, reliable and modern energy services by 2030 [83]. The sub-Saharan African region is not on track to meet these targets, having been plagued by decades of clean cooking interventions that have failed to displace traditional biomass cooking practices [14,84,85]. This study highlights the potential for market-based solutions to deliver sustained use of clean cooking devices that can be enhanced through targeted stacking interventions, thus accelerating progress towards SDG7.

Credit author statement

TP: Conceptualisation, Methodology, Formal analysis, Writing – original draft and editing, Visualisation, Funding acquisition. ALA: Methodology, writing – reviewing. JT: Conceptualisation, Supervision, writing – reviewing. VA –; Project administration. PP: Conceptualisation, Supervision, writing – reviewing, Funding acquisition.

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.

Data availability

Data will be made available on request.

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