



Original research article

Stakeholder perspectives on the future of clean cooking in sub-Saharan Africa and the role of pay-as-you-go LPG in expanding access

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ABSTRACT

Reliance on polluting cooking fuels is linked to three million premature deaths per year as well as other climatic, environmental and social impacts. Numerous clean cooking fuels are available but remain inaccessible to low-income consumers due to affordability limitations. An emerging solution targeting the urban poor is pay-as-you-go (PAYG) liquefied petroleum gas (LPG), which allows gas to be purchased in micropayments. However, little is known about whether this technology can scale and foster widespread adoption of clean cooking.

This study examines the state of the clean cooking market in sub-Saharan Africa and the role of PAYG LPG through semi-structured interviews conducted with $n = 20$ key informants including academics, donors and practitioners. The findings revealed perceptions of slow progress and tensions around the roles of LPG and electricity in the fuel mix. However, there was broad consensus that LPG will play some role in the transition in the short term.

Respondents also revealed the multitude of challenges faced by PAYG LPG providers attempting to scale this technology at a time of increasing controversy about the role of fossil fuels in Africa's energy transition. Nevertheless, participants described how PAYG LPG is an effective demand-side technology that makes clean cooking accessible to new consumers. Data collected by the meters offers opportunities to monetise impacts and target interventions at specific consumer groups. However, the unit economics are challenging and are compounded by a paucity of investment. Further research, dialogue and open debate between stakeholders is required to create a coherent enabling environment for PAYG LPG.

1. Introduction

There are 950 million people in sub-Saharan Africa (SSA) who still rely on polluting fuels to cook, comprising a third of the global total [1,2]. This has severe consequences for both public health and the environment; it is believed cause 697,000 annual deaths [3] and similar levels of anthropogenic climate impacts as the aviation industry [4]. Sustainable Development Goal (SDG) 7 calls for universal access to affordable, reliable and sustainable modern energy by 2030 [5], but this target looks unlikely to be met in several regions of the world, particularly SSA [6].

Cooking fuels and technologies are classified as “clean” if their emissions comply with the World Health Organisation's Air Quality

Guidelines and include electricity, LPG, biogas and ethanol [7]. Expanding access to clean cooking has historically been a neglected piece of the energy access puzzle [8], with the number of people lacking access growing year on year as the rate of population growth outpaces that of intervention [1,2]. However, clean cooking is starting to command increasing levels of attention, reflected by record-breaking amounts of funding going into the sector in 2022 [9] and increasing numbers of countries in SSA setting concrete policy targets [10]. Market-based solutions provided by the private sector are expected to drive progress in the region over the coming decades, likely aided by performance-based mechanisms such as results-based financing [11]. Yet there are few examples of market-based clean cooking solutions in SSA that have successfully scaled [12], and the extent to which they can

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reach bottom-of-the-pyramid consumers is unknown.

There is increasing debate about the role of fossil fuels in Africa's energy transition occurring in parallel to this growing focus on clean cooking. On one hand, the continent is endowed with unexploited fossil reserves that developers claim could trigger economic growth [13–15]. However, opponents argue that advancing these sites will further drive climate change, harm local communities and prevent African countries from leapfrogging to renewable energy [16,17]. This clash came to the fore at COP27, when amidst negotiations about net zero pathways, African leaders announced eight new fossil fuel projects in the name of tackling poverty [18,19].

This discussion is relevant to the clean cooking sector because fossil fuel derived liquefied petroleum gas (LPG) is arguably the most widely available and scalable clean cooking solution [20,21]. Transitions from polluting fuels to LPG for cooking would limit emissions and climate impacts, reduce the burden of disease from household air pollution and result in positive social net-benefits [22–26]. The role of LPG in the clean cooking transition is widely recognised and, in 2023, projections by the International Energy Agency (IEA) indicated that one in three households will gain access to clean cooking through LPG as compared to one in eight for electricity [27]. Importantly, the IEA also predicted that LPG will be decarbonised through replacement with sustainably produced BioLPG after 2030, consisting of propane and butane from renewable biological sources [28], causing a sharp decline in fossil-based LPG use towards 2050. Nevertheless, assumptions about the role of LPG in meeting targets in the near-term are being challenged by academics and practitioners who believe that electric cooking solutions could be in closer reach than previously assumed, especially in urban locations [29–31].

Table 1
Summary of characteristics of study participants.

Participant code	Participant type	Participant regional base	Country or region of focus	Cooking fuel or technology of focus
A1	Academics	Europe	Sub-Saharan Africa	LPG
A2		North America	Global	LPG
A3		Europe	Sub-Saharan Africa	LPG, electric
A4		Europe	Global	Electric
C1	Consultants and advocates in the clean cooking sector	SSA	Kenya	LPG
C2		Europe	Global	LPG
C3		Europe	Global	LPG
C4		Europe	Global	LPG, electric
C5		North America	Global	LPG, electric, others
F1	PAYG LPG donors or funders	Europe	Global	LPG
F2		Europe	Global	LPG, electric, others
F3		Europe	Sub-Saharan Africa	LPG, electric
G1	Government stakeholders	SSA	Kenya	LPG, electric, others
G2		SSA	Rwanda	LPG, electric, others
G3		SSA	Kenya	LPG
G4		SSA	Sub-Saharan Africa	LPG, electric, others
P1	PAYG LPG practitioners	North America	Sub-Saharan Africa	PAYG LPG
P2		Europe	Kenya	PAYG LPG
P3		SSA	Rwanda	PAYG LPG
P4		North America	Kenya	PAYG LPG

It is against this backdrop of optimism about market-based solutions and tensions regarding the promotion of fossil fuels in Africa that a new business model has been proliferating: pay-as-you-go (PAYG) LPG. The key innovation underpinning PAYG LPG is an internet-connected LPG smart meter, which attaches to the nozzle of a standard LPG cylinder. Customers purchase fuel in micropayments from the provider via mobile money instead of needing to buy full cylinder refills at a time, which has traditionally limited poor households' ability to consistently cook with LPG [32–35]. When the customer uses up their credit, the smart meter is remotely instructed to disable the flow of gas, thus prompting the customer to buy more fuel. This system also allows the provider to monitor the remaining fuel in households' homes and to proactively replenish cylinders. All or some of the equipment costs are incorporated into an elevated fuel price compared to full-cylinder, known as the "PAYG premium". This allows the system to be provided to households at a reduced upfront cost. Thus, PAYG LPG addresses many of the key affordability and supply barriers that prevent households from being able to switch to clean fuels [36].

The first PAYG LPG systems emerged in 2015 [6] and there are now multiple providers, mostly in East Africa. The largest of these is Circle Gas (now called MGas), who had over 250,000 customers in Kenya and Tanzania as of 2022 [37] – around 0.2 % of the combined population of these two countries. Studies of PAYG LPG have found that it makes clean cooking affordable to low-income populations [38], that the ability to pay in small increments helps sustain clean cooking in times of economic hardship [39], and that its use is associated with monetary savings, increased dietary diversity and lower stress levels [40]. These findings suggest that although PAYG LPG is operating at a relatively small scale, it is linked to positive impacts that could merit scaling it up.

However, the literature to date focusses on customer-level impacts of PAYG LPG and there are no studies that query its wider potential. Multiple scholars have emphasised the importance of understanding the perspectives of wider stakeholder groups in the clean cooking sector as they can heavily influence the adoption and scale-up of technologies [20,41,42]. Stakeholder interviews are therefore a useful tool for examining the role that PAYG LPG could play in the clean cooking transition. This article presents the findings of twenty such interviews conducted with relevant key informants. It holistically examines both the clean cooking sector in general and PAYG LPG specifically, allowing the role of PAYG LPG to be situated against the wider context of clean cooking in SSA.

2. Methods

Our research uses semi-structured interviews to understand the future potential for PAYG LPG in SSA. Semi-structured interviews have been described as a "conversation with a purpose" [43], entailing a flexible style of interviewing that provides rich, detailed answers with an emphasis on the interviewee's point of view [44]. The interviews were conducted with "key informants", a select group of people able to provide up-to-date information, ideas and insights on the topics of PAYG LPG and clean cooking [45].

Participants were recruited through a mixture of purposive sampling, where relevant stakeholders were identified and approached directly by the principal researcher, and snowball sampling, where participants were asked to identify other potential subjects for the study. The sampling initially only targeted informants with expert knowledge on PAYG LPG. However, after the tension between LPG and electric cooking futures emerged as a prominent theme in the first few interviews, informants with particular knowledge about electric cooking were purposefully recruited.

Table 1 summarises the study participants and their key characteristics. The final sample contained four academic researchers, five

consultants or advocates in the clean cooking sector, three PAYG LPG funders, four government stakeholders and four PAYG LPG practitioners.¹ Sampling terminated once data saturation was achieved in accordance with guiding principles of qualitative research [46]. The interviews took place between February – December 2021 on Microsoft Teams and Zoom and had an average length of 1 h. Both of these platforms benefit from being convenient and easy to use, having high levels of security, and being able to record and automatically transcribe conversations [47].

The conversation began with an unrecorded informal conversation to build rapport. The main body of the interviews consisted of questions about recent progress in clean cooking, the future fuel mix, responsibilities for addressing the clean cooking problem, the role of PAYG LPG in the transition to clean cooking, threats to success for PAYG LPG and how they could be resolved, market or policy interventions that could support PAYG LPG and relevant research gaps. The practitioner stakeholder group (who all actively provide PAYG LPG to paying customers) were asked additional questions about their direct experiences with PAYG LPG. During the interviews, notes and observations were recorded by the interviewer which were also used in the analysis, and in some cases follow-up clarifications were made via email. The interviews focussed on Rwanda and Kenya as they were the two leading countries for PAYG LPG at the time of data collection and the focus countries for the lead author's PhD.

Analysis was conducted thematically using Excel. This began by inductively tagging snippets of the data set with codes that described their content. The codes were then grouped into common themes that emerged from the data, following the process described by Braun and Clarke [48], aiming to maintain the diversity of the dataset whilst also identifying patterns within it. Deriving the codes and themes involved much iteration that is considered to be the basis of goodness for qualitative inquiry [49]. The thematic groupings have been used to present the findings of the study in Section 3.

This work was conducted as part of the lead author's PhD research and the results were also included in her thesis [50]. Ethical approval was granted by University College London (17653/001). A full copy of the participant information sheet was emailed to participants prior to the discussion and was summarised at the beginning of the interview, including assurances of anonymity. Informed consent was recorded both via email and verbally at the outset of the interview.

2.1. Limitations

As this research was part of a wider PhD project, only one person coded and analysed the data. This could limit the rigour of the study. Another source of potential bias was the recruitment strategy, which started by focussing on PAYG LPG and later pivoted to engaging a wider pool of informants. There are some important absent voices, such as researchers based at SSA institutions and electric cooking practitioners. Many of the interview questions were about SSA region but recruitment focussed on people with expertise in Rwanda and Kenya. This could limit the generalisability of the results.

3. Results and discussion

3.1. The global clean cooking challenge

The first part of the interviews established participants' perspectives on the wider clean cooking sector. This section presents and discusses the findings according to the three main themes that emerged: the current state of the clean cooking ecosystem; tensions between the prioritisation of LPG versus electric cooking; and predicting the future fuel

mix to 2030 and 2050.

3.1.1. Clean cooking: the state of play today

3.1.1.1. Perspectives on progress in the clean cooking sector. There was consensus that clean cooking is advancing, but not quickly enough. Progress in East Africa is focussed on isolated pockets (such as urban Kenya) and yet a heavy reliance on polluting cooking persists even in these locations. One academic participant expressed particular pessimism about the SDG7 targets:

“At my most cynical, I have often half joked that we will see the clean cooking problem solved when we either have no more forests; everybody lives in cities; or all women are gainfully employed.”

-A2

Slow progress was mostly attributed to the chronic underfunding of clean cooking initiatives, mirroring arguments made in the literature [6,51,52]. The amount of money flowing into the sector was regarded as insufficient. Academic and consultant informants partially attributed this to the multi-decadal worth of effort wasted on promoting ineffective improved cookstoves. One Kenyan interviewee expressed bitterness at the way that these solutions had been imposed upon their country:

“In the last 30 years in Kenya, and I suppose in the rest of Africa, the Western world has been telling us, ‘use improved cookstoves’. So, these improved cookstoves, people used them for a while. They are too slow to cook, and they are still using the same dirty fuel that we tell people not to use... Therefore, people don't see the reason for adopting them. But I would blame this on the development partners who have been pushing down the throats of Africans to use improved cookstoves.”

-C1

This reflects critiques of the ineffectiveness of ICS programmes [53–55], but also alludes to how international donors and implementation partners have forced unsuitable technologies on the SSA context rather than co-designing appropriate solutions.

Participants reported that transitioning to clean cooking continues to be difficult in all location types. They argued that the urban poor often have no choice but to cook with polluting fuels as they are unable to afford the costs of clean alternatives. In rural areas, the availability of free biomass and lower income levels magnify the challenge. There is often an absence of clean fuel infrastructure, which can take years to finance and install.

Although there are now some instances of successful programmes – participants cited LPG cooking in India [56] and electric cooking in Ethiopia [57] as examples – initiatives in this space continue to have a high failure rate, and the distribution of underutilised (and therefore ineffective) stoves and fuels continues. Multiple participants highlighted the need for more success stories in the private sector. They expressed concerns about how high-profile failures, such as Inyenyeri's pellet stoves [58], may feed the cookstove sector's reputation as high-risk and unprofitable, constraining its growth even more.

3.1.1.2. The important role of policy. Some participants felt there was a growing level of awareness about clean cooking amongst SSA policy makers. Country-level policy engagement was believed to be primarily motivated by combatting local deforestation. This contradicts the agendas of the implementing partners and funders driving much of this progress, who are often based overseas. For example, the UK-based Modern Energy Cooking Services (MECS) programme frames its mission around the transition to renewable energies and the attainment of SDG7 [59] and the Cooking Alliance (CCA) emphasises the climate, environment, gender and health benefits of clean cooking in their 2022 annual report [9]. This could partially explain the perpetuation of ICS solutions in SSA government clean cooking strategies, which are often

¹ For the purposes of this paper, practitioners are defined as senior management in PAYG LPG companies.

seen as a quick fix for reducing wood consumption, but have been criticised for their poor uptake and performance [60,61].

Other participants felt that clean cooking lacks the necessary focus in policy circles and continues to take a back seat to electrification for lighting in the energy access discourse. A number of interviewees ascribed this to the lack of clear accountability for clean cooking, which tends to be divided between several ministries. One policy maker described their personal experience of this:

“There’s the Ministry of Health and all of these partners and parties... it’s very difficult because... first you have to get everyone aligned on which projects you go for first. And also you have to coordinate all the time to ensure we don’t have multiple fragmented efforts that do not really get us close to the target. And sometimes what happens is most people think someone else is doing it when actually no one is doing it.”

-G2

This first-hand account confirms that the clean cooking agenda can be obscured by the number of different areas that it touches [8]. It reveals the need for comprehensive, cross-sectoral approaches for a coordinated policy response. This could help address ministerial fragmentation, the disconnect between electrification for lighting and clean cooking, the silos between different technologies and solutions [62].

Multiple participants also noted that clean cooking can be limited by falling under the jurisdiction of less powerful ministries who are allocated fewer funds (e.g. the Ministry of Environment). There were concerns that the lack of prioritisation is also due to the underrepresentation of women at policy level and the political expediency of it being a poor people’s problem.

In addition to this, different fuels pertain to different stakeholder groups and even individuals, which adds to the fractured nature of policy making:

“For oil and gas, you have an entire stakeholder group, but for biomass, usually there is a flimsy presence within energy, policy-making, and decision making in the ministries. So that constitutes the problem... services and Environmental Protection agencies usually deal with woodfuel in forests.... But the minute it transitions from cut wood to charcoal, to carbonization, and all the way to market supply, it is not their responsibility, so they leave it alone”

-G4

Another strand of policy that commanded attention was criminalisation of biomass use in SSA, as demonstrated by the 2018 Kenyan charcoal production ban [63] and planned Rwandan charcoal use ban [64]. Some praised these policies for raising biomass fuel prices and pushing local populations towards cleaner alternatives. Others criticised them for being ineffective and poorly enforced, describing how the Kenyan logging ban simply exported the logging problem to Uganda rather than curbing charcoal use. This corroborates the findings of a 2023 study, which suggests that the Kenyan charcoal ban is unlikely to achieve its intended impact [63].

3.1.2. The LPG versus electricity debate

Participants were also asked about the future fuel mix, which led to a discussion about the merits of different fuels. The primary comparison that organically arose was that of LPG versus electricity. The results presented in this section reveal a tendency amongst stakeholders to be biased towards the solutions that they themselves work on. This was particularly true for the academics, who were all based outside of SSA, and whose work mostly focussed on the single fuel or technology that they actively advocate for at a policy level. Such partisanship could impact the research they choose to engage in and therefore bias the evidence base. This shows a potentially problematic disconnect between academics and the on-the-ground realities of the sector and a

corresponding risk of repeating the now widely-condemned ICS failures of the 1980s. Research programmes need to reflect that there is no one perfect fuel and a suite of clean options will be required to meet consumer needs.

Overall, there were ten participants who favoured LPG over electric cooking (A1,C1,C2,C3,F1,G3,P1,P2,P3,P4); two participants who favoured electric cooking over LPG (A4,C4) and eight participants were neutrally positioned about the two fuels (A3,A2,C5,F2,F3,G1,G2,G4). This section presents the main arguments put forth about the advantages and disadvantages of these two fuels.

3.1.2.1. Cooking with LPG. There has been historic resistance to LPG because it is a fossil fuel. However, some respondents felt there is growing acceptance of LPG as a transitional fuel. These claims were supported by examples such as the intention for increased capital flows to the LPG sector and the number of African governments engaging technical assistance to help expand LPG for cooking. As one participant argued:

“I can tell you that over time, the winds are starting to blow behind LPG, propelling it towards port in the Land of Action.”

-C3

Participants pointed to the success of LPG in the Kenyan market as evidence of its potential, specifically its strong growth, the rapid increase in number of LPG marketers and resultant falling prices.² The result has been a rapid conversion to cooking with LPG that is perhaps not yet reflected in official statistics. One interviewee, who works in the Kenyan LPG industry, pointed out there are no other modern energy solutions poised to scale as easily as LPG, therefore only LPG has the potential to address the clean cooking crisis here and now:

“I know an LPG marketer who has injected one million cylinders in one year. I have not seen anybody come up with an improved cookstove or any other gadget that can produce even half of that in a year.”

-C1

This sentiment is reflected by a 2022 examination of the political economy of electric cooking, which acknowledged that LPG may be considered a more attractive short-term option because suppliers and distributional networks are already in place, but power shifts at global, international and landscape levels could be sufficient to disrupt the system and challenge the dominance of incumbent fuels [62]. Some of these power shifts have already started to happen. Several participants felt that the international development system is reluctant to support LPG and that donors prefer renewable energy projects. Some also expressed frustration about the fossil fuel narrative against LPG. They pointed out that the small quantity of LPG required by low- and middle-income country (LMIC) households for cooking would have a marginal global warming effect [22,23]. They highlighted to the hypocrisy of Western players, who themselves use gas for cooking, and often support the use of LPG for shipping.

All respondents acknowledged that LPG can play an important role in the short term and in markets where cost-effective infrastructure already exists. However, they put forth some specific concerns about the future of LPG that could justify prioritising other fuels and technologies.

Firstly, several, mostly academic, stakeholders (A2,A3,A4,C4) spoke about how the price of LPG fluctuates according to the global market and is an imported commodity for East African countries. This means that it consumes precious foreign exchange currency on a volatile product that the government has no control over, which is further

² Please note that these interviews took place before 2022, when global LPG prices soared and caused backsliding to polluting cooking fuels in many contexts [94]. Many of them also took place before the Kenyan VAT re-imposition [94].

exacerbated by the instability of currency exchanges. Heavy reliance on LPG may impose large and unpredictable financial burdens on governments, particularly if it was subsidised by them.

Secondly, the shift towards net zero may cause the wider oil market to collapse and decimate supplies of LPG (A1,A4,C1,C4,C5,F2). If fossil fuel subsidies are rescinded in the near term then prices may become even higher and more volatile. This creates a security of supply risk that is likely to amplify as we approach the 2050 net zero deadline. These arguments combine to imply that investing in LPG runs the risk of sinking capital into stranded assets (A4,C4), so supporting other clean cooking fuels and technologies could yield better returns.

3.1.2.2. Cooking with electricity. Electricity is increasingly regarded as the dominant clean cooking alternative to LPG, despite being far less widespread in SSA and still in a niche innovation phase [62]. Like LPG, electricity delivers significant health, gender and climate impacts when compared to polluting alternatives and it is best suited to urban areas with high quality grid infrastructure [65]. One respondent, an academic who works for MECS and focusses on electric cooking, observed that attitudes towards it have transformed in recent years, and believed that this drive is due to the MECS research programme. They explained how MECS has demonstrated that electricity can be cost competitive against alternative cooking fuels in several markets [66] and has advanced technological innovations in efficient electric appliances. These developments widen the accessibility of electric cooking by reducing the associated financial burden.

Academic respondents emphasised the multiple benefits of electric cooking. If the electricity is renewably generated then it offers the possibility of healthy, low-emission cooking. Local power generation can decrease dependence on imports and help build a resilient energy sector. One respondent (A4) pointed out that it is cost-effective to invest in electric cooking infrastructure because of its synergies with the wider energy sector and long lifecycle.

However, a range of interviewees (A1,C1,C4,F1,P4) felt that the electricity narrative is driven more by the remit of the MECS programme than by the realities of implementation and risks diverting funds from more viable solutions:

“Perhaps there’s a little bit too much hype compared to the reality of delivering on the ground within the electrical cooking space.”

-C4

They felt that it is unrealistic for electricity to reach people at scale in SSA in the next ten years because of the infrastructural gaps and high costs of extending sufficient electricity access. However, it is important to acknowledge there are large differences in electrification capacity and that some countries, such as Ethiopia and South Africa, may be able to achieve electric cooking transitions in this period [67].

Interviewees recognised the progress in electric cooking made in the past few years, particularly by the MECS programme, but pointed out that appliances remain expensive, inconvenient to use and not always available:

“We face the challenge that a lot of the donors wants to move out [of the LPG] space because it’s a carbon-based fuel, and there is, I think in some places, a naive suggestion that through off-grid, mini solar and... the expansion of grid we can relatively soon tackle the fact that half the world’s population lacks access to cleaner cooking solutions. And that’s not the case.”

-F1

These respondents argued the case for prioritising the rapid scale-up of LPG in the region and believed it is the only strategy that will extend clean cooking to all by 2030 in accordance with the SDG7 goals.

3.1.3. The future of clean cooking

Although renewably-generated electricity was regarded as the “holy

grail” of clean cooking, most respondents believed that LPG would play an important role in the transition in the near term. They were asked to predict the future fuel mix in SSA in 2030 and 2050. Their responses are summarised below and are broadly aligned with the IEA net zero transition pathway [68], suggesting that either there is growing consensus about the trajectory of clean cooking transitions, or that responses were influenced by the IEA’s research.

3.1.3.1. The 2030 cooking fuel mix. 2030 marks the SDG7 deadline, by which time there should be universal access to affordable and clean energy. Most participants agreed that fossil fuel-based LPG will be needed to achieve this because of its scalability and suitability to urban and peri-urban areas, with some penetration in rural areas too.

There was disagreement about the role of biomass stoves. Some interviewees (A1,C1) believed they have no place in the transition because they fail to deliver on health impacts, but the majority thought it unrealistic to stop rural people from cooking with biomass any time soon:

“It is at emergency level, given the level of deforestation leading to escalating wood and charcoal prices for urban and rural households, exacerbating existing energy security problems on biomass supply. So, when you have that kind of emergency environment, I don’t think you have the luxury to say, let’s leave the existing system alone, let’s focus on new technologies.”

-G4

The majority believed there will likely be further diffusion of ICS to reduce the use of three stone fires (A2,A3,P4,G2,G4). Charcoal may remain part of the energy mix for peri-urban and low-income urban groups with a shift towards more sustainable production (A2, G4). There were mixed opinions about pellet stoves, with two academic informants doubting their impact credentials and ability to scale (A1,A2) and one Rwandan governmental stakeholder (G2) believing they could address the rural market. This could have been based on the pellet company Inyenyeri’s operations in rural Rwanda. Inyenyeri closed down shortly after the interview, which was partially attributed to the challenges of serving rural areas [58].

Most respondents expected to see expansion of electric cooking in the next decade enabled by growth in electrification rates and falling appliance prices. The extent of electricity’s potential contribution was, however, uncertain, and participants thought it was likely to depend on localised factors such as the strength of supply, relative pricing compared to other fuels and the availability of LPG. Other interviewees were pessimistic about widespread electric cooking by 2030, believing it would be limited to urban grid-electrified households in this timeframe because of infrastructural restrictions.

3.1.3.2. The 2050 cooking fuel mix. The interview also asked for predictions about the cooking fuel mix in 2050, the year that marks the net zero deadline [68]. One participant (A2) pointed out that LPG use will continue past 2030 given that half of the SDG7 electrification targets will be met with off-grid technologies. However, LPG use is likely to significantly diminish by 2050, signalling an acceleration away from fossil fuels towards renewable sources. All respondents agreed that there would be an expansion of electric cooking in the decades running up to 2050, and that electricity could become the dominant clean cooking fuel in LMICs.

Fossil LPG may be partially displaced by biologically-derived BioLPG [28], which was regarded as an exciting development, but one that is several decades away from commercialisation. Some participants (A1, C1) were also optimistic about the potential role of bioenergy (such as bioethanol and biogas) because of its scope for local production. Some predicted a decline in ICS (A1,A2), and some believed that there would be continued use of biomass in rural areas (A2,C1,G4), meaning there will be a residual population who do not have access to clean cooking by 2050. It implies that the clean cooking challenge will pervade for several

decades to come and become increasingly concentrated in poor and marginalised communities.

3.2. PAYG LPG as a clean cooking solution

The second part of the interviews focussed on PAYG LPG as a clean cooking solution. This section presents and discusses the findings according to the five main emergent themes: the PAYG LPG target market; the advantages of PAYG LPG; challenges with PAYG LPG; what constitutes success for PAYG LPG; and, the general outlook for PAYG LPG.

3.2.1. The PAYG LPG target market

PAYG LPG was reported to mainly serve urban, peri-urban and informal settlement consumers but there was disagreement about the technology's rural reach. Some interviewees, especially the practitioners (C2,G2,P1,P2,P4), saw rural areas as offering opportunities to convert new customers to LPG. Others (A1,C3,P3) believed it was unrealistic for PAYG to serve these populations due to the logistical challenges of reaching them and the difficulties of displacing gathered biomass – an argument that can be applied to all purchased clean fuels.

With this in mind, three different customer segments emerged from the interviews:

- Poorer households who have either never used LPG or are intermittent LPG users who cannot afford cylinder refills. Practitioners reported this to be the main customer group. A study of Bboxx's PAYG LPG pilots in Rwanda and Kenya found that less than a third of customers in both locations cooked primarily with clean fuels before adopting PAYG LPG, showing that the technology was effective in targeting this demographic [50].
- Wealthier households who can afford to cook with full-cylinder LPG but enjoy the convenience factors of the PAYG model.
- Commercial operators who use PAYG LPG because it helps manage their cash flow and because they value the convenience of cylinder deliveries.

Participants – especially the practitioners and funders - also highlighted that viable PAYG LPG markets must allow providers the freedom to price fuel as they like. Price caps or subsidy regimes can greatly limit profitability and growth for PAYG LPG providers. Governments can help create enabling environments by enforcing safety regulations, ending polluting fuel subsidies and giving fiscal incentives to PAYG LPG practitioners and investors.

3.2.2. Advantages of PAYG LPG

3.2.2.1. Affordability. Affordability was perceived as the primary advantage of PAYG LPG, a finding echoed in the literature [69–71]. Participants identified three nuances of affordability for PAYG LPG. Firstly, they almost all highlighted that PAYG allows people to buy gas in any quantity, thus matching LPG expenditures to the spending profiles of charcoal or firewood users. Secondly, the technology includes financing to overcome the upfront hurdle of purchasing equipment, allowing access to a quality two-burner stoves that are superior to the single-burner LPG stoves that screw directly onto the gas bottle and are widespread in East Africa. Thirdly, the practitioner stakeholder group pointed out that they purposefully price PAYG LPG to be cheaper to cook with than polluting alternatives purchased in small bundles. They reported that their customers save money from switching to PAYG LPG.

Together, these aspects of PAYG make LPG accessible to low income households previously excluded from clean cooking fuels and stoves. This insight has been verified by studies of Bboxx's PAYG LPG pilots in Rwanda and Kenya, which found that in both cases four-fifths of customers used a clean fuel (PAYG LPG) as their main cooking fuel, versus less than a third prior to acquiring the technology [50]. However, poor

households' capacity to afford clean fuels is highly variable due to factors such as gender dynamics, variable incomes, prices of competing fuels and other budgetary demands [72]. PAYG LPG is subject to temporal fluctuations in LPG fuel price, which is mostly outside of providers' control and can be significant [73]. Therefore, adoption of PAYG LPG is still subject to affordability constraints.

3.2.2.2. Convenience. Participants also recognised the benefits of customers being able to buy fuel on demand via mobile money and to have refills delivered to their homes. Practitioners highlighted how customers cite time savings as one of the biggest advantages of PAYG LPG.

3.2.2.3. Safety. LPG safety risks include leaks, explosions and burns [74]. Accidents occur most frequently in the least developed countries where standards are less enforced and safety fears can hinder uptake [75,76]. However, safety was recognised as an important advantage of PAYG LPG (C1,F2,G2,G3,P1,P3). One governmental interviewee observed that the assurances of provider installation can persuade people who are wary of gas to try PAYG LPG:

“It gives an opportunity for people who are not certain about the safety of gas, or the efficiency of gas, or the convenience of gas, to taste, and once they taste... they get hooked.”

-G3

Conversely, a participant with extensive experience in the Kenyan LPG market warned that the meters can introduce additional risks through meter tampering, which can cause gas leaks. Just one of the practitioners (P1) acknowledged encountering tampering issues. Their company was addressing this through design improvements to tamper-proof the meter and actively repossessing units that are interfered with. The topic of repossessions did not arise further in the interviews and the extent to which PAYG LPG providers reclaim tampered, underutilised or indebted units is unclear. Abuse of this practice has been heavily criticised in the context of PAYG solar home systems [77,78] presenting an opportunity for PAYG LPG providers to capitalise upon these learnings.

3.2.2.4. Digitalisation of supply chains. The PAYG fuel consumption data sets drive supply chain efficiencies by allowing providers to predict requirements for cylinder inventory and distribution. PAYG thus offers the opportunity to reform the conventional value chains that characterise the LPG industry, which relies on historic macro-level sales trends to manage its supply chains.

These data sets could also allow providers to operate with reduced cylinder inventory. Two participants estimated that the PAYG model is able to operate at scale with half of the cylinders of a traditional LPG model (C3,P2). This could result in large cost savings for the providers. This is supported by the findings of an early PAYG LPG pilot in Tanzania, which estimated that the PAYG model could double cylinder inventory turnover compared to the industry average [69]. Further independent analysis of larger-scale PAYG LPG operations is needed to validate these claims.

3.2.2.5. Applications of usage data. The PAYG meter data gives providers rich insights into how customers are using their products. This could allow real-time verification of impacts that can be monetised through carbon credits, health and gender funds. As one participant, who supports companies scaling clean cooking solutions, explained:

“In the previous worlds, you sell a stove to a consumer. To get any sense of the impact of that stove - how much it's being used, what is it displacing in the home - you have to literally go out and do a survey, have to have air quality monitors in the household. Gathering any kind of data for verification, for example, of carbon revenues becomes really expensive... I can envision a marketplace for a range of certificates that make providing support much more accessible to

investors, to donors, and to corporate or private companies that might be interested in investing in those impacts.”

-C5

The metered usage data could therefore be an important asset for PAYG LPG providers, especially given the trend of increased impact-based revenues from clean fuel use [12] and the requirement for this data in the latest Gold Standard metered stove methodology for carbon credits [79]. Indeed, three out of four PAYG LPG practitioners hoped that these sources could provide them with additional revenue streams and drive down prices for customers. It could help household budgeting and allow more accurate cost comparisons between cooking with PAYG LPG and other fuels, helping dispel myths about the costs of cooking with LPG. However, for companies who charge a large premium compared to full-cylinder LPG, there is a risk that such a comparison could illuminate the additional expense caused by the premium and nudge customers back towards alternative providers.

Since data collection was conducted in 2021, carbon credits have emerged as a leading financing mechanism for clean cooking technologies, notably fuelling the proliferation of KOKO Networks' ethanol solution in Kenya [80]. Innovations that track fuel usage such as the PAYG LPG smart meter theoretically allow for more accurate crediting. However, the latest carbon methodologies do not allow fossil fuel solutions like LPG to claim the same level of emissions reductions [79], which contradicts academic research revealing the climate credentials of LPG cooking [22]. PAYG LPG is therefore arguably disadvantaged compared to other technologies in the market.

3.2.2.6. Targeted subsidies. Four interviewees were excited about the potential for PAYG LPG meters to act as a tool for directly delivering clean cooking subsidies to consumers (A2,C5,P1,P3). As one practitioner explained:

“If a government or a donor says, ‘we want all pregnant women, we want everybody who qualifies for this program to get gas at a cheaper rate, and we’re going to subsidize that cost’, we can vary gas prices by household.”

-P1

Others disagreed with incorporating subsidies into fuel delivery and believed that governments could better support the technology through fiscal measures like waiving taxes on equipment or fuel (C2, F2,F3,P2, G2). In theory, this would better support market development whilst indirectly reducing prices for customers, although one participant (G1) was sceptical about whether the benefits of these policies would truly filter down to end-users.

3.2.3. Challenges with PAYG LPG

3.2.3.1. The PAYG LPG meter. One of the most frequently cited challenges (A1,A2,C1,C2,C3,C5,P2) was the high cost of the PAYG meter. As one participant explained:

“As of today, the meters are very expensive. They are more than two times the cost of the cylinder, and therefore it doesn’t seem to make economic sense to have a meter.”

-C1

No PAYG LPG practitioners disclosed their meter costs, but one LPG sector consultant (C3) reported that they ranged from 50 to 100 USD at the time of the interview. This greatly increases the capital expenditure involved in PAYG LPG and imposes large additional costs onto the customer. Practitioners were confident that prices would reduce in the near future, but the 2022 component costs of a PAYG LPG meter were estimated to be 43 USD [81], suggesting that radical technological innovation may be required to significantly reduce costs.

An interviewee who works in the Kenyan LPG sector had encountered reliability issues with the meters, reporting that some devices fail

to deliver consistent quantities of gas, and that connectivity issues can cause delays in assigning payments to meters. These problems point towards the need to improve the meter functionality. Providers are therefore faced with the double-barrelled engineering challenge of improving product quality whilst simultaneously reducing cost.

3.2.3.2. Business model aspects. Funder and consultant respondents noted that PAYG LPG is a high-risk business model as it serves a low-income demographic with an expensive product via extended credit. The model also relies on consumers using over a threshold amount of fuel in order to recoup costs. Fuel stacking can undermine this as it represents lost revenues towards other fuels.

Practitioners reported that their customers easily adapt to cooking with gas and tend to use LPG for quick cooking meals, whilst certain foods (e.g. beans) are seen as too expensive to cook on LPG. This agrees with many other studies examining clean fuel adoption in the region [82–85]. Three of the four practitioners observed there is often a knowledge gap about how to cook with LPG – for example how to adjust the flame and to use gas efficiently – and one in particular regarded customer education as an important part of their operations.

3.2.3.3. Access to finance. These business model pressures are accentuated by PAYG LPG being a low-margin business that requires scale to work (C1,C5,F2,P2,P3,F1,F2,F3,P1,P2, P3,P4). Providers need access to plenty of soft finance and working capital to achieve this and there simply is not enough flowing into the clean cooking sector at present:

“What’s missing is an influx of cash just to get things moving along. And it’s going to be the private sector, I think, that moves a lot of this, with the government making conditions appear attractive for commercial operators.”

-A1

Multiple stakeholder groups recognised that it can be challenging for PAYG LPG companies to find appropriate funders. They hypothesised that traditional LPG financiers may be put off by the high costs of provision, whereas development funders may overlook it on climate grounds.

3.2.3.4. The PAYG premium. All participants spoke about the challenges posed by the PAYG premium, which reportedly varies widely between providers. Several expressed ethical concerns about how the premium places inequitable burdens on poorer households:

“We are essentially making poor people pay more for the same product that rich people pay less for.”

-C2

The premium generates a risk of customers switching back to polluting alternatives or full-cylinder LPG to save money. This price sensitivity of PAYG LPG has been clearly shown through modelling performed by the Global LPG Partnership (GLPGP), which highlighted how the PAYG premium limits customer acquisition and retention. They found that with pricing set to the same level as full-cylinder LPG, PAYG LPG firms would only capture 1 % of Kenyan market share by 2030, but would struggle to attract investment due to poor financial performance. The inclusion of a PAYG premium of 7 % over the average end-user price of full-cylinder LPG improves financial performance but limits the addressable market even further [86]. However, the GLPGP used a full-cylinder LPG business model that did not account for supply chain efficiencies enabled by PAYG and did not consider how there could be increased willingness to pay for PAYG LPG compared to full-cylinder LPG. More research is needed to understand how much customers are willing to pay for this technology and what constitutes a fair PAYG premium.

Perspectives on customers' willingness to tolerate the PAYG premium varied. One practitioner was adamant that PAYG LPG providers

should aim to eliminate it altogether in order to be equitable:

“The price point needs to go down. It should ideally match the savings on the operational side, on the logistics side, so savings in terms of investments in cylinders.”

-P3

Other practitioners justified the premium by pointing out that PAYG LPG is still purposefully priced to be cheaper than the polluting fuels it displaces. They emphasised the importance of educating customers about the price point so that they understand the reasons for the premium and the value of the added services that come with PAYG.

There are parallels that can be drawn with the “poverty premium” in the UK energy market – a widely-studied phenomenon where those living beneath the poverty line pay more for their gas and electricity than higher-income households [87]. One of the main drivers of the poverty premium is poorer households’ tendency to use pre-paid gas and electricity meters as they are perceived to give greater budgetary control than paying through direct debit [88]. As with PAYG LPG, the premium arises due to the meter costs and is estimated to be 21 % higher than paying via direct debit [89]. This is lower than most PAYG LPG premiums and yet is still widely considered to be unacceptable by left-leaning commentators in the British press [90,91]. A similar mark-up could represent an unideal-but-acceptable mark-up for PAYG LPG.

3.2.4. What constitutes success for PAYG LPG?

There was agreement that the PAYG LPG sector would be catalysed by the success of players within it. Such a success would also help the wider cookstove sector overcome its stigma of failure:

“Our hope is that we can we can shift that conversation with data that replaces the anecdotal evidence that’s been out there for the last couple years. And that’s been a tough shift to motivate, because anecdotes are very powerful and we haven’t always had the data to make an alternative case.”

-C5

PAYG LPG could similarly be harmed by more instances of failure. There are already some examples of PAYG LPG operations that have not progressed past pilot stage (such as Bboxx’s original Rwandan operation and Envirofit SmartGas in Kenya) and of others that have chosen not to pursue the model because they believed it was unviable [81,92]. One participant believed that just one more high-profile market exit might turn investors and other potential providers away for good (P3).

Practitioners considered success in terms of progress towards SDG7, whereas others defined it by proving out the unit economics throughout the supply chain. This would also coincide with the point where PAYG LPG becomes financially self-sufficient, no longer requiring donor money to prop it up, and is instead attractive to external investors. A third category defined success for PAYG LPG by its ability to reach large numbers of households, with estimates of the success threshold ranging from 500 to 50,000 households, with practitioners tending to cite higher figures in the tens of thousands. These are likely to be more accurate as they are influenced by first-hand experiences with the technology. As of 2023, only one company (MGas) has reached this scale.

3.2.5. The general outlook for PAYG LPG

Respondents consistently pointed to innovation in clean cooking technologies and business models as cause for optimism because of how they are making clean cooking more accessible. There was hope that these data-driven innovations might mark a new era for clean cooking: one that is able to deliver the promised impact by building ongoing customer relationships and verifying customer usage.

It is therefore unsurprising that most participants were very positive about PAYG LPG. They believed the technology solves issues of affordability and safety and extends LPG to a population that is currently excluded from it. This was also the view of all four PAYG LPG

practitioners, who cited key achievements to substantiate their positions, such as profitable depots, successful entry into new markets and growing customer portfolios.

Some participants (F2,F3,G2,G4) believed that PAYG LPG has some way to go before it can be considered a proven solution. They emphasised that most companies are still operating at a pilot level, that the business model will require several more years of refinement and that scaling up will be extremely challenging. Others (C4,G1) were more negative. They pointed out that some PAYG LPG companies have already been operating for more than five years and that the relatively small customer numbers show that the product does not fit the market. Whilst this may true for other providers, research conducted by the authors shows that this was not the case for Bboxx’s two pilots in Rwanda and Kenya [38,50]. In both cases, demand and product adoption were high but scale was limited by supply-side factors such as meter sourcing.

As of 2023, the only PAYG LPG company that appears to be actively expanding is MGas in Kenya. MGas scored a 25 USD million private-sector investment in 2020, thought to be the largest in the clean cooking sector to date [93]. This demonstrates the immense resources required to scale PAYG LPG.

4. Conclusions

This paper has presented the results from twenty semi-structured interviews conducted with academics, consultants and advocates in the clean cooking sector, PAYG LPG donors and funders, government stakeholders and PAYG LPG practitioners. The findings were grouped into those concerning the wider clean cooking sector and those concerning PAYG LPG specifically.

The first part of the interview highlighted the slow progress in the clean cooking sector which was attributed to underfunding and historic support for inappropriate ICS solutions. Participants felt that clean cooking was still failing to attract sufficient policy attention and there were mixed perspectives about whether this is starting to change.

The research revealed tension between the roles of electricity and LPG in the future fuel mix. Stakeholders were biased towards the solutions that they focussed on, which could be generating a skewed evidence base. This reveals a potential disconnect between the research being conducted clean cooking sector and the grounded realities of the problem. The arguments for and against LPG and electric cooking were elucidated. There was agreement that LPG would likely play an important role in some locations in the near-term with a shift towards electric cooking by 2050.

Practitioners reported that PAYG LPG is an effective demand-side technology that can unlock new market segments by making clean cooking affordable, safe and convenient. The remotely collected fuel consumption data sets allow them to streamline their supply chains, optimise their product offerings and better understand their customers. These data could also help monetise positive impacts (although carbon credit potential is limited under current methodologies) and act as a tool for policy makers to deliver targeted interventions.

However, the PAYG LPG business model is low-margin, meaning that it needs high levels of scale to reach profitability. It is also high risk, which could deter investors. These two factors make fundraising exceptionally challenging, especially given the shortage of funding in the sector at large. On top of this, the metering technology is not yet mature and further technological advancement is required. There were widespread concerns about how the meters push up the PAYG premium and cause equity and affordability concerns.

It is clear from this analysis that the future of PAYG LPG is intertwined in the use of LPG as a clean cooking fuel. This in turn depends on a number of macro-level factors that are outside of the control of both PAYG LPG providers and national policymakers. The clean cooking sector in SSA is increasingly polarised into those who believe a concerted effort should be made to scale up full-cylinder LPG and those

who believe resources would be better spent on increasing capacity for electric cooking. However, local policy makers were more pragmatic. We call for further research, dialogue and open debate between promoters of different solutions to reach consensus on cooking technology strategy, recognising that combinations of fuels are likely required. This would be invaluable in guiding coherent policies and investments to accelerate the sustained uptake of clean cooking.

CRediT authorship contribution statement

T. Perros: Writing – original draft, Validation, Methodology, Formal analysis, Data curation. **J. Tomei:** Writing – review & editing, Validation, Supervision. **P. Parikh:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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

The data that has been used is confidential.

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