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Abstract

Globally, rates of electrification and clean cooking are low, particularly in Sub-Saharan Africa. Off-grid energy solutions have a vital role to play in accelerating clean energy access to address Sustainable Development Goal 7. For organisations aiming to provide both electricity and cooking services, there is a need for holistic studies on adoption determinants to aid market expansion. This paper presents a comprehensive literature review of the adoption determinants and barriers for liquefied petroleum gas (LPG), solar home systems (SHS) and electric cooking (e-cooking) in Sub-Saharan Africa. A total of 40 adoption determinants were identified across the 71 publications examined. Of these, 30 determinants were shared by at least two of the technologies, whilst six were specifically linked to LPG and four to SHS. Key determinants that cut across technologies included reliability of alternative technologies (such as grid supply), reliable energy supply through the technology in question, affordability, household size and location (urban/rural). The findings show that there is an overlap in the demographics that use these technologies, as urban households often use SHS as a backup to the electricity grid and their cooking needs can feasibly be met by LPG or e-cooking devices. There is a clear opportunity for e-cooking devices to be sold as appliances for SHS. E-cooking devices such as electric pressure cookers can be complementary to LPG due to their suitability for cooking different foods. Pay-as-you-go models, which have a proven track record with improving access to SHS and are beginning to also be applied to LPG, have the potential to provide a strong foundation for scaling up of LPG and e-cooking services.

1. Introduction

The world is falling behind on the energy access targets set in the Sustainable Development Goals (SDGs), and specifically SDG 7, which calls for universal energy access by 2030. There are around 759 million people globally without access to electricity and more than 2.6 billion people who primarily cook with polluting biomass fuels, such as charcoal, firewood and animal waste [1]. Access to clean, modern, affordable and reliable energy is transformative; it enables women to partake in additional employment [2] improves educational performance for children [3] and saves households time and money [4,5]. Other wide-ranging benefits cut across sectors such as healthcare, climate change mitigation and adaptation, and livelihood creation [6].

Sub-Saharan Africa (SSA) is among the regions with the lowest rates of electrification and access to clean cooking solutions compared to other parts of the world [7,8]. There has been relatively slow progress on the extension of grid infrastructure in the region, partly due to the high cost of transmission, maintenance and operation costs in rural areas [9–11]. Off-grid decentralised solutions provided by the private sector, such as Solar Home Systems (SHS), offer viable means to increase electricity access and build energy resilience [12]. As defined by Bisaga [13], SHSs are "[…] stand-alone [DC] solar PV [photovoltaic] systems with power storage in a form of a battery (usually lithium-ion or lead-acid) which can supply sufficient power for appliances such as lighting, mobile phone charging, televisions, radios, and other small household use appliances [and which come] in a wide range of capacity: from 11Wp up to 300Wp or more" (p. 1). Clean and modern energy cooking technologies, such as liquefied petroleum gas (LPG) and electric cooking (e-cooking) appliances, such as Electric Pressure Cookers (EPCs) or rice cookers, can significantly reduce exposure to harmful smoke and provide a safer, faster and more efficient way to prepare meals, often at a lower cost than polluting biomass alternatives [8]. Although it is a fossil fuel, LPG offers considerable public health and climate benefits and is arguably the most scalable cooking fuel in SSA in the short-term because of its minimal additional infrastructure requirements [14–17].

The pay as you go (PAYG) model of SHS provision has been behind the rapid uptake of this technology in the last decade and has the potential to act as an anchor on which PAYG cooking services could be built to cover the two main domestic energy needs: lighting and cooking [18,19]. This would leverage the last-mile financing and distribution infrastructure already created by off-grid solar (OGS) companies [20]. The PAYG model offers customers the same level of payment flexibility as the well-known PAYG model in the telecommunications industry. There is typically a down payment to get a SHS installed, followed by daily, weekly or monthly payments, which either cover the amount of energy consumed or, more commonly, are incremental repayments of the value of the system. After a period of anything between 1-3 years, full ownership of the system is transferred to the customer - effectively making it a rent-to-own model. As a result, high barriers to entry, if there was to be a lump sum payment for a SHS, are removed [13].

In SSA, cooking with modern fuels and stoves is often complemented by traditional biomass sources such as charcoal, which are preferred for cooking energy-intensive 'hard' foods like beans [21–23]. Thus, e-cooking appliances that are suited to cooking these foods, such as Electric Pressure Cookers (EPCs), could be added as complementary devices to achieve a clean cooking energy stack and help fully eliminate reliance on biomass fuels [8]. However, currently there are very few examples of private sector providers offering combinations of energy services. Fenix International, an OGS company, operating in six markets in SSA, ran one of the first pilots with a PAYG LPG initiative in Uganda in 2019; it appears to have been discontinued [24]. Similarly, another OGS provider, Bboxx, have also expanded into LPG cooking services in Rwanda, Kenya and Democratic Republic of Congo [23,25]. Two companies, Sunspot and EarthSpark, have adopted an alternative approach by providing solar electric cooking systems along with SHSs for a complete off-grid rural energy solution in Haiti [26]. Little research has been conducted to inform strategies promoting such holistic approaches to energy access provision, which would help reach net zero targets.

Understanding the different conditions under which various technology combinations are feasible, and the factors that drive their adoption, could enable more companies to expand their services to offer integrated energy access packages for households. To date, scholars have examined adoption determinants for electricity by examining users' perceptions and fuel stacking behaviours for SHS, and access to energy for cooking by looking at adoption barriers for clean cooking solutions [27,28]. However, there is a paucity of studies that compare adoption drivers and barriers for both types of energy access technologies. The novelty of this study is in using adoption determinants for both off-grid electricity and cook solutions to evaluate under what conditions co-provision would be feasible. This can inform market expansion strategies for the private sector and influence decision making on integrated energy planning and subsidies for policy makers. This is of particular importance in light of the recently launched *Universal Integrated Energy Plans* by the Sustainable Energy for All (SEforALL) initiative [29] and the *Clean Cooking Planning Tool* created by the World Bank's Energy Access Sector Management Program (ESMAP) and the Modern Energy Cooking Services (MECS) programme [30], which also aims to consider electrification and clean cooking access in a joint manner. Achieving net-zero ambitions requires a shift to clean electricity and cooking solutions for which testing feasibility, acceptance and affordability will be vital.

Our study aims to fill this gap by understanding opportunities for off-grid co-provision of electricity and LPG in SSA. It contributes to the critical evidence base needed to speed up transitions to clean energy by leveraging progress made in the off-grid electricity sector. In our study, adoption includes purchase, usage and retention, which have been identified as key elements for the early and mid-stages of customer life cycles of SHS [31]. We focus on household-level off-grid solutions, namely SHS, LPG (as joint stove and fuel combination) and e-cooking appliances. These solutions are compatible with the PAYG model and have the potential to grow rapidly over the coming years. The objectives of this study are: to conduct a structured literature review to identify factors driving adoption of SHS, LPG and e-cooking in SSA; to compare demographic intersections between the three technologies; and to derive insights about how providers can expand into holistic energy provision. Section 2 of this paper describes the methodology for the literature review. Section 3 examines factors driving or hindering adoption of the three selected energy access solutions. Section 4 discusses commonalities and differences among the adoption factors, and the final section provides recommendations.

2. Methodology

This paper consists of a comprehensive literature review on LPG, SHS and e-cooking in Sub-Saharan Africa. The search was conducted in the following databases: ScienceDirect, Web of Science and Scopus.

The inclusion criteria consisted of peer-reviewed research articles, conference or proceeding papers that were published between January 2000 and December 2020. In both Science Direct and Scopus databases the following subject areas were selected: 'Energy', 'Environmental Sciences', 'Social Sciences'. The focus of the paper needed be predominantly on either SHS, LPG or e-cooking technologies, or a mixture of these. The article also needed to evidence at least one adoption determinant or barrier that influenced the likelihood of a household purchasing the technology. The exclusion criteria consisted of papers not written in English and review papers. Articles that did not focus on at least one Sub-Saharan African country were also excluded.

The initial search results derived from the utilised search criteria for each database and technology are highlighted in Table 1.

Table 1 Database search criteria

Technology	Database	Search criteria	Search output	First screen	Second screen
SHS	Science Direct	Article (("solar home system" or shs) and ("fuel switch" or "fuel substitution" or adoption or purchase or “adoption determinants” or diffusion))	869	168	24
	Scopus	All ("fuel switch" or "fuel substitution" or adoption or purchase or "adoption determinants" or diffusion) and all ("solar home system" or shs)) and (limit-to (doctype, "ar") or limit-to (doctype, "cp")) and (limit-to (subjarea, "ener") or limit-to (subjarea, "soci") or limit-to (subjarea, "envi"))	789	82	11
	Web of Science	(TS=("solar home system" or shs) and TS=("fuel switch" or "fuel substitution" or adoption or purchase or "adoption determinants" or diffusion)) and language: (English) refined by: document types: (article or proceedings paper)	292	1	0
LPG	Science Direct	Article(("liquid petroleum gas" or lpg) and ("fuel switch" or "fuel substitution" or adoption or purchase or “adoption determinants” or diffusion))	3,343	151	20
	Scopus	All ("fuel switch" or "fuel substitution" or adoption or purchase or "adoption determinants" or diffusion) and all ("liquid petroleum gas" or lpg)) and (limit-to (doctype, "ar") or limit-to (doctype, "cp")) and (limit-to (subjarea, "ener") or limit-to (subjarea, "soci") or limit-to (subjarea, "envi"))	1,276	58	10
	Web of Science	(TS=("liquid petroleum gas" or lpg) and TS=("fuel switch" or "fuel substitution" or adoption or purchase or "adoption determinants" or diffusion)) and language: (English) refined by: document types: (article or proceedings paper)	295	13	1
E-cooking	Science Direct	Article (("electric cooking" or ecook or “e-cook”) and ("Fuel switch" or "Fuel	91	8	3

		substitution" or adoption or purchase or “Adoption determinants” or diffusion))			
	Scopus	All ("fuel switch" or "fuel substitution" or adoption or purchase or "adoption determinants" or diffusion) and all ("electric cooking" or ecook or “e-cook”)) and (limit-to (doctype, "ar") or limit-to (doctype, "cp")) and (limit-to (subjarea, "ener") or limit-to (subjarea, "soci") or limit-to (subjarea, "envi"))	37	7	2
	Web of Science	(TS=("electric cooking" or ecook or “e-cook”) and TS=("fuel switch" or "fuel substitution" or adoption or purchase or “adoption determinants” or diffusion)) and language: (English) refined by: document types: (article or proceedings paper)	4	0	0
			6,996	**488**	**71**

The search was first conducted in ScienceDirect, followed by Scopus and Web of Science, where each iteration excluded duplicate papers from previous databases. This explains the considerably smaller number of papers identified through Web of Science. The screening process consisted of examining the title and paper contents to ensure that the paper satisfied the inclusion and exclusion criteria. For cross-validation, the authors swapped groups of papers and sorted these by their title before checking every fifth paper to ascertain whether they agreed with the paper’s inclusion and a consensus was reached in cases of disagreement. Following this process, 35 SHS, 31 LPG and 5 e-cooking papers remained, totalling to 71 articles. Out of these, three papers covered both SHS and LPG technologies but were included as part of the SHS group for the purposes of not double counting information about the papers. The lead author extracted the key information from each paper into an Excel spreadsheet, which included the adoption determinants for which evidence was provided and whether it had a positive, negative or no effect on the technology adoption (Appendix 1). To cross-validate this process, the remaining authors checked every fifth paper of their assigned sections to see whether they agreed with the data extracted from the papers. This resulted in the identification of 40 adoption factors in total.

3. Results

3.1. General Information

The 71 papers were spread relatively evenly between SHS and LPG technologies with only five studies examining e-cooking (Figure 1).

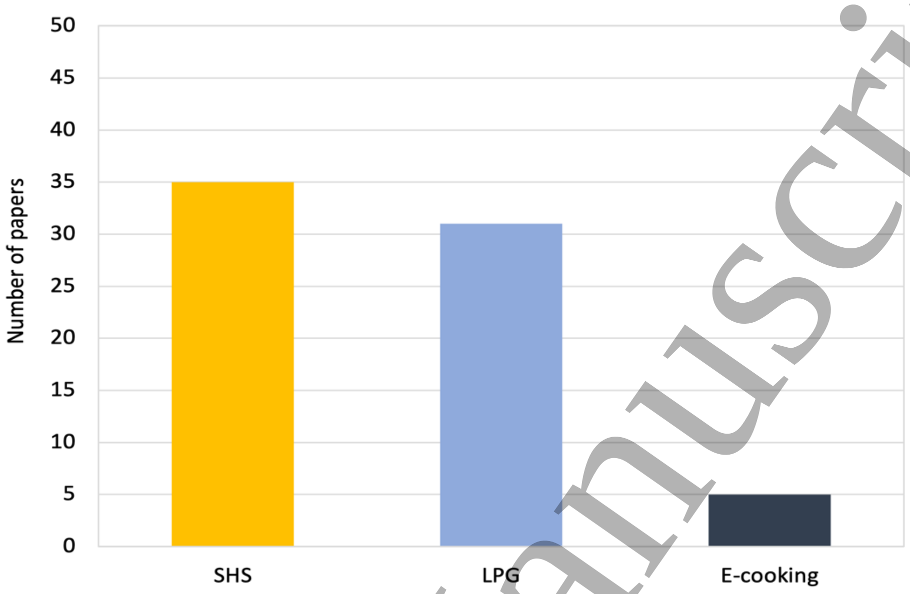

Figure 1 Technology focus of literature

There has been an increase in the number of papers published for each technology in recent years (Figure 2). The largest rise occurred between 2018 and 2020, with 69% of LPG, 60% of e-cooking and 52% of SHS papers published in that period. Figure 2 highlights the relative novelty of e-cooking in comparison to SHS and LPG.

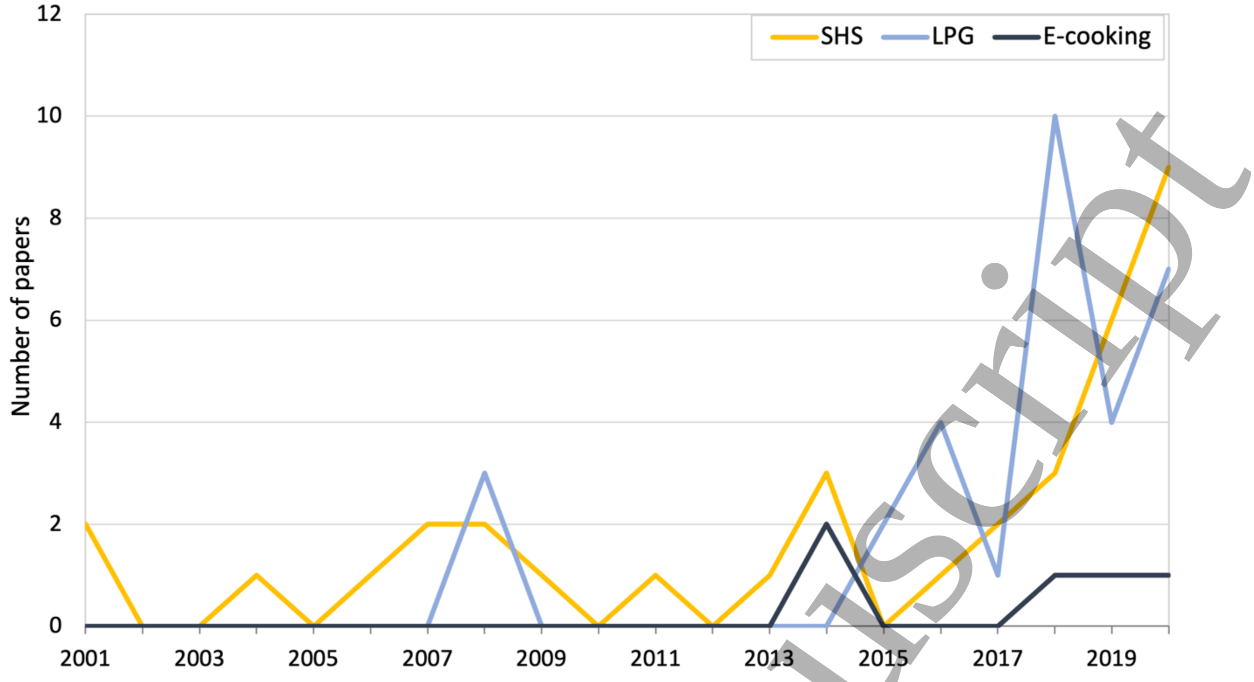

Figure 2 Publication dates of literature

The papers were categorised according to their research methodology. This analysis revealed that 63% of papers were classed as qualitative methods, with mixed and quantitative methods accounting for the remainder in a relatively even split (Figure 3). The low number of quantitative studies could be due to a lack of reliable electricity and clean cooking data in the off-grid sector in SSA.

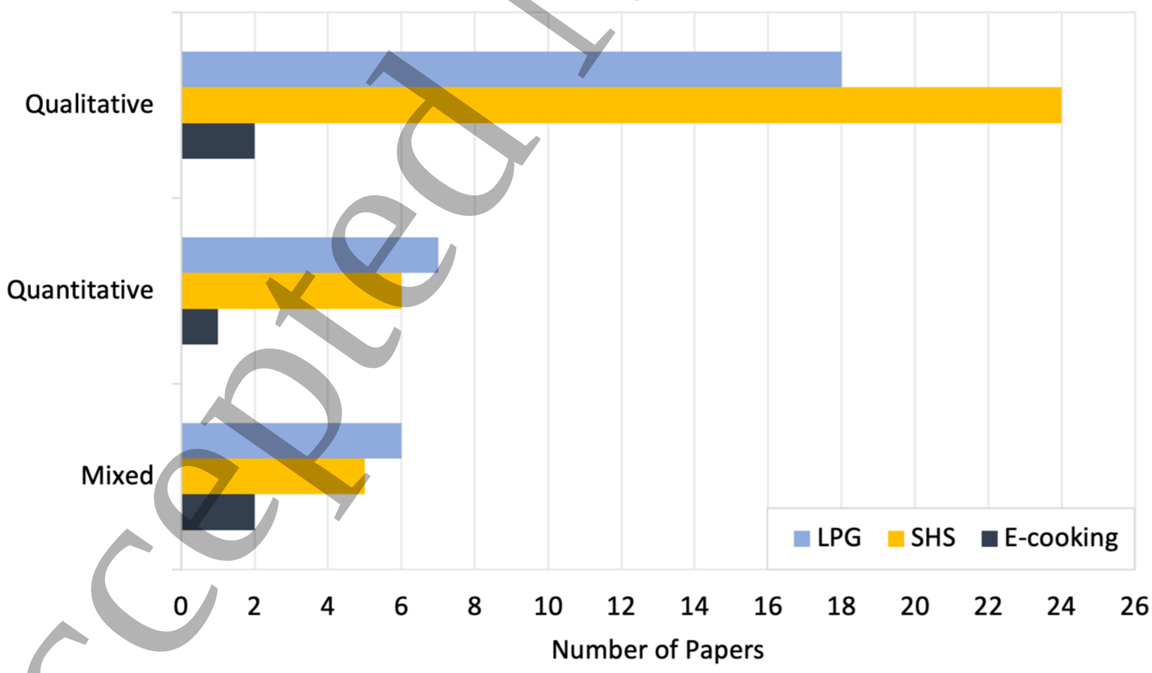

Figure 3: Methodology of literature

Figure 4 shows the geographical focus of the literature for e-cooking and LPG compared to SHS. There is no existing academic knowledge base for most countries in SSA. Remarkably, similar clusters of countries are covered by the two diagrams despite there being very little overlap between the technologies in the literature. This could be because of the ease of conducting research in these countries, the presence of governments that are particularly engaged in off-grid energy policies (e.g. [32]) or extensive localised private sector involvement in the off-grid space. Off-grid policies have provided an enabling environment for private sector involvement both for energy service delivery and operation and maintenance.

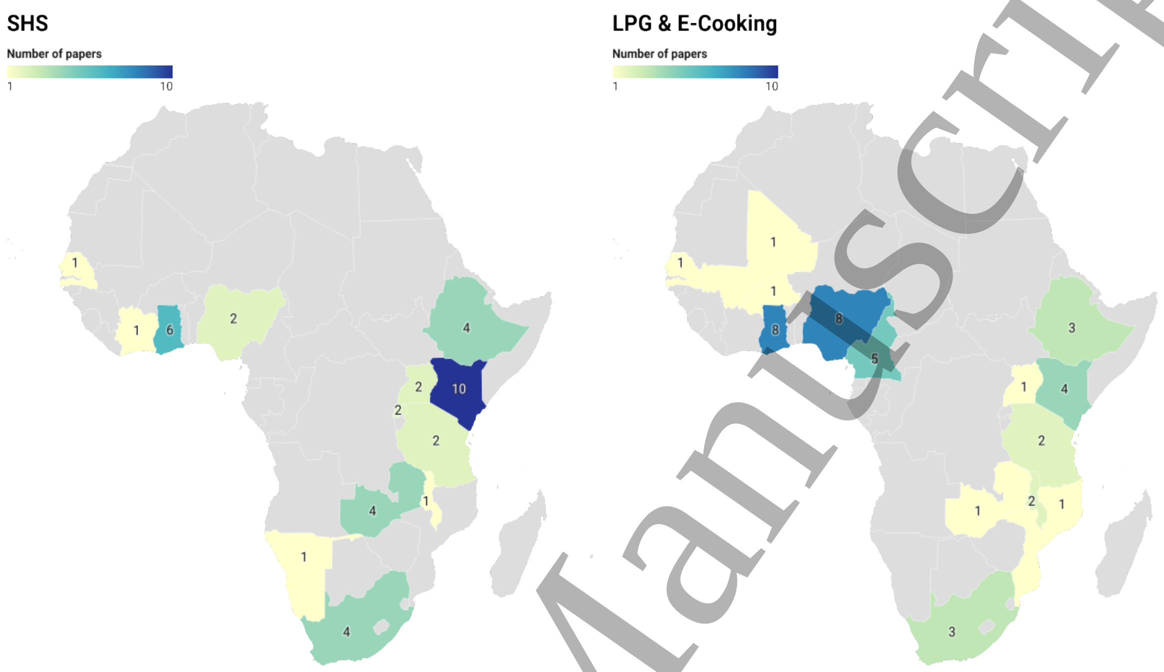

Figure 4 Geographical focus of literature search for cooking and electrification

3.2. Adoption Determinants

The literature review highlighted 40 total adoption determinants, out of which 30 were shared by at least two of the technologies (Appendix 1), whilst six were specifically linked to LPG (Appendix 2) and four to SHS (Appendix 3). Figure 5 highlights the 20 most common shared determinants identified by the papers and whether their effect on a household's adoption decision for each technology was positive or negative, excluding ones which had no effect.

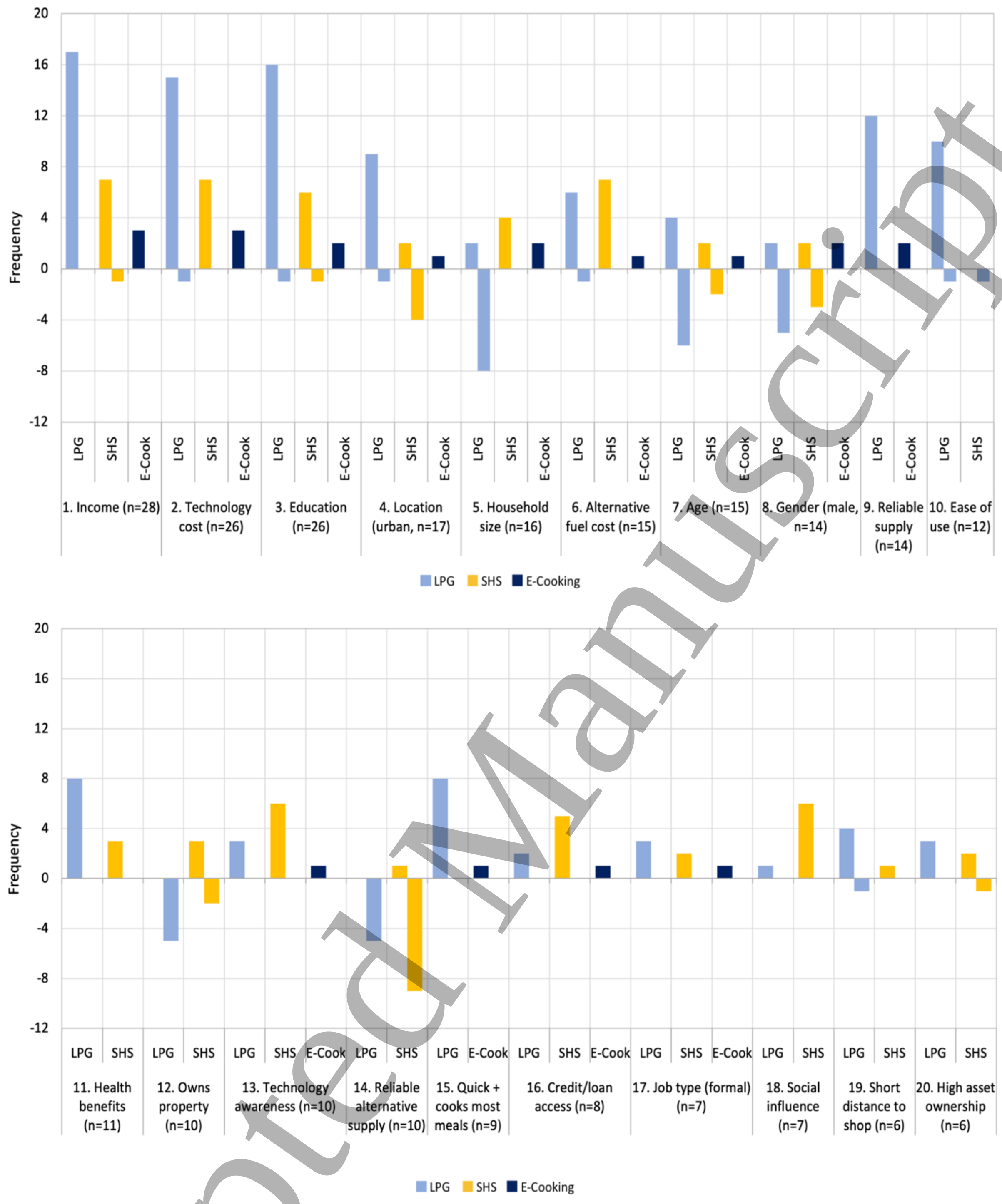

Figure 5: Top 20 adoption determinants

The factors influencing the uptake of LPG, SHS or e-cooking were found to be highly similar. The importance of technology cost and affordability is notable, with three of the top ten determinants linked to these factors. There were a few noteworthy differences between technologies on whether the determinant had a positive or negative effect. Larger households were more likely to adopt SHS and e-cooking, but less likely to use LPG. The negative effect of an urban location on the SHS adoption might be associated with the higher prevalence of grid connections in urban centres compared to rural areas, where households are less expectant of a connection and more willing to accept SHS as an alternative [33–35]. In contrast, LPG is inherently more suited to urban areas because of the complex supply chains supporting its use and the challenge of displacing free biomass in rural areas [36]. This indicates that different technologies may be more viable in different settings.

There were only a few individual adoption determinants that applied solely to LPG or SHS technologies (Figure 6).

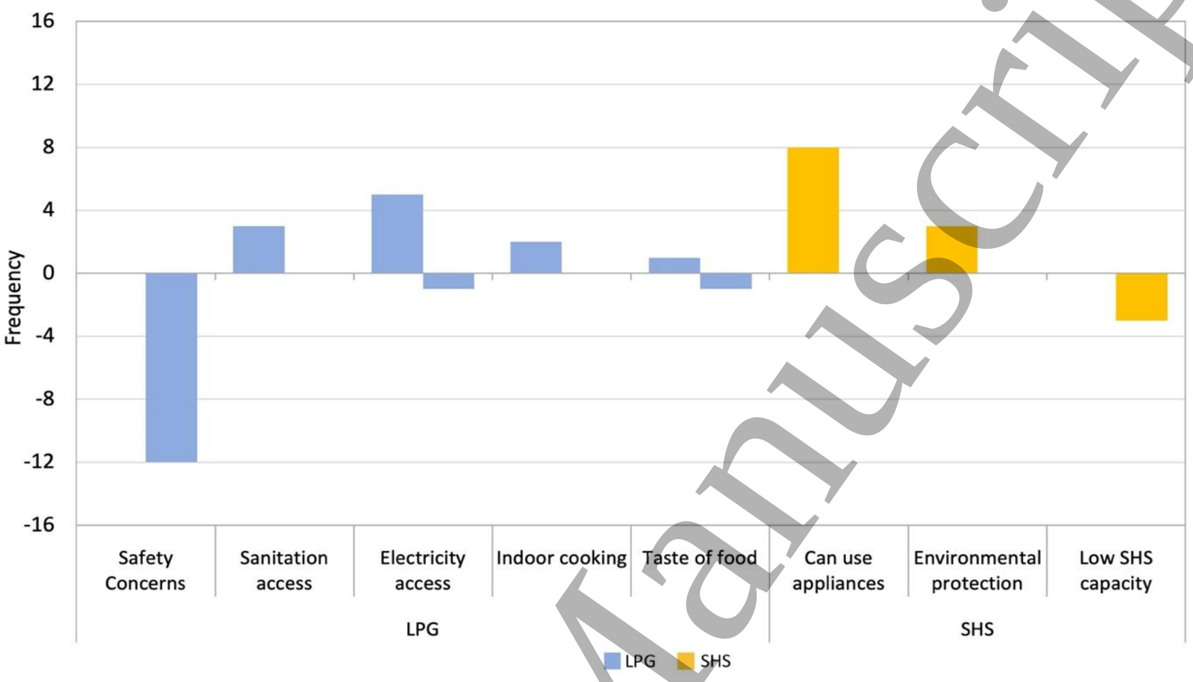

Figure 6: Adoption determinants applying only to LPG or SHS

Concerns around the safety of LPG use have been identified as barriers to LPG adoption by numerous scholars across different countries and contexts [37,38]. The association between LPG adoption and electricity access is likely due to collinearities with income and urban locations, which tend to have more advanced infrastructure; the same applies to sanitation access. Low capacity of SHS as a factor detracting households from adopting such solutions has been discussed by Chowdhury and Mourshed [39], Laufer and Schafer [40], and Azimoh et al. [41] among others. This is associated with the prevalence of small SHS, which typically fall in the 10W-50W bracket. As these are more affordable than larger SHS (e.g. 80W or 100W), to date they have taken the largest market share [42] and tend to support only basic uses, such as lighting, phone charging, radios, televisions and fans.

The following sections consider the top adoption determinants for SHS, LPG and e-cooking.

3.3. SHS

The top three determinants for SHS adoption were the reliable supply of alternative fuels (e.g. grid electricity) (n=10), SHS appliance use (n=8) and income (n=8). While there is consensus in the literature that the ability to use appliances offered by SHS, such as light bulbs or phone chargers, drives the likelihood of households to adopt such solutions, the other two determinants are more complex. In particular, income and the (un)reliable supply of electricity are closely linked, as is further discussed below.

3.3.1. Reliability of SHS and Alternative Fuels

There are two dimensions of reliability in the literature. Firstly, the lack of reliable supply of grid electricity is a factor that motivates households to adopt SHS (n=9) [29–33]. Unreliable grid access refers to households experiencing frequent blackouts, thus compromising their ability to use appliances. Grid-connected households sometimes adopt SHS as back-up power systems to mitigate such disruptions. In their study of Ghana, Boamah and Rothfuß [48] observed that secure electricity access was particularly valued by wealthier urban households who had elderly family members living with them. This also indicates that income determines whether households can safeguard against an unreliable grid. Low-income, grid-connected households might not be able to afford both connections, though some might opt to disconnect from the grid altogether and choose a SHS instead.

The other dimension of reliability is a comparative one between grid and SHS (n=3), where households ultimately decide to adopt a SHS based on their experienced or perceived increased reliability [5,44,49,50]. For example, a study in urban Nigeria has shown that "innovative adopters described PV as rugged, regular, uninterruptible, efficient and the most rational source of power supply" [35, p4]. However, the two dimensions are clearly interlinked, meaning that the unreliability of one power source (here mainly the grid) leads people to what they believe is a more reliable source: a SHS. Reliability is also seen as having control over one's power source and independence from the utility network, which is associated with the sense of agency of one's own energy access [44]. It is worth noting, however, that some studies have found that SHSs are seen as unreliable and/or insufficient in their capacity to support a range of different appliances, especially in times of overcast weather (n=3) (e.g. [51,52]). Low or insufficient capacity is a determinant unique to SHS.

3.3.2. SHS Appliance Usage

The ability to access and use appliances such as lights, phone chargers, radios and televisions is the second most common adoption factor identified in the reviewed literature (n=8) [5,33,53–58]. Lighting is among the most important, transformative and popular services that households adopting SHS benefit from. It enables longer productive hours in the evening and facilitates improved safety and security, especially at night due to its energy storage capacity [59]. This could be to protect from theft or other intrusion, or to provide the ability to move around in the dark without tripping over objects [56,60]. Improved safety also stems from the elimination of lighting fuels such as candles or kerosene lanterns, which can cause fires [61]. Lighting also enables household members to spend more time socialising and it helps to shift daily practices: activities that previously needed to be performed in the early morning hours can now take place in the evening as sunlight hours no longer dictate the rhythm of the day [56]. Another common service the SHS offers is phone charging. Phone charging can have a positive effect on the overall ability to stay connected to friends, family members or job opportunities. Having phone charging at home also means that there is no longer the need to walk long distances or pay for transport to phone charging stations, and to spend money and time doing so [62]. There is also evidence showing that household members benefit from more time to read in the evening due to SHS adoption [54].

Other appliances include radios and televisions, with the latter being more aspirational due to their high price. Both appliances offer the opportunity to access new information. For example, in their study in South Africa, Gustavsson and Ellegård [41, p1071] found that "the possibility to use a TV set with a video machine is a major attraction" to SHS adopters. Another study in Kenya has also found households installing SHSs with a range of appliances instead of waiting for a grid connection. This has been observed in other contexts where households were no longer willing to wait for the grid expansion despite being told it would come soon [58,63]. While the uncertainty about the grid's arrival can encourage SHS adoption, Green et al. [64] found that, to the contrary, it can also be a barrier, as households who have received messages from the government saying the grid would be extended to their areas 'soon' would hesitate to adopt SHS. This is due to the belief that it would prohibit them from accessing the more aspirational, and perceived superior, grid power.

3.3.3. Income

Our review shows that higher income has been more frequently found to be an adoption factor (n=7) than low income (n=1). As discussed above, regarding the (un)reliability of the grid, higher-income households have been observed to adopt SHS more often than lower-income households. In a study of 209 Ghanaian households, Obeng et al. [65] found that households without solar PV had less income than households with such systems. This was measured through the assessment of the overall monthly household expenditure. Among the quantitative studies, three showed a significant positive effect of high income on the adoption of SHS [34,66,67], two showed a non-significant positive effect [33,68], whereas one had a non-significant negative effect of low income on SHS [69]. Our review found no studies that focused on disposable income (as opposed to income more generally). This could be an important consideration for future research to better understand how households allocate their disposable income and whether and how they prioritise energy access.

Other determinants impacting the adoption of SHS identified in this review include cost of alternative fuels (n=7), installation and usage costs of SHS (n=7) and education (n=7), where households with a higher level of education have been seen to be more likely to adopt SHS (e.g. [34,66,68]).

3.4. LPG

The top three determinants for LPG were income (n=17), installation and usage costs (n=17) and education (n=17). These three factors are highly interconnected as educated households are likely to earn more money and therefore be able to afford the upfront and recurring costs of using LPG.

3.4.1. Income

There were several variations of the income variable. The majority of papers used total income or income per capita (n=11) but others included wealth status (n=1), socio-economic status (n=1), affordability (n=1), total expenditure (n=1), economic well-being (n=1) and whether household members were employed in high-income formal jobs (n=1).

There was consensus across the literature that there was a positive relationship between income and likelihood of using LPG. This trend was found to be significant and positive in all cases where hypothesis testing was performed (n=13 papers). Income variation was also acknowledged as a factor that could cause a transition backwards to cooking with traditional fuels [70]. Future studies could consider the role of disposable income in the adoption of LPG.

There was variation in the importance of income by geographical location; for example, a 20% higher income led to a change of the proportion of clean fuel use of 39% in Uganda but only 16% in Ghana [71]. The location type was also relevant, with income being less important for urban households than rural ones [71,72]. This was attributed to clean fuels being more affordable and available in urban centres as well as the higher opportunity cost of labour in these locations.

3.4.2. Installation and Usage Costs

There was agreement across the examined papers on the negative relationship between the cost of cooking with LPG and the likelihood of using the fuel, but very few (n=3) performed hypothesis testing on this variable. This was because most studies collected data from just one location, where the price of LPG was fixed, meaning it was not possible to assess the relationship between LPG adoption and LPG price.

There were three interpretations of the costs of using LPG, although papers did not always distinguish between these three dimensions, instead referring to generic affordability or cost variables that acted as barriers (e.g. [73–75]). The first was the upfront cost of equipment (stove, cylinder and in some cases also the regulator), which was relevant in seven papers [76–82]. The second was the transaction size, or the ability to afford to buy fuel in discrete refills, which was found to be a barrier to adoption in three papers [83–85]. The third was how the cost of cooking with LPG compared to the alternatives being displaced. This was a barrier in three papers where biomass alternatives were cheaper [80,82,86], although one paper found this not to be relevant [87]. Even when LPG was cheaper than the competing fuel there was not necessarily an understanding of this amongst study participants [82,88]. As Ozoh explained: "Monthly expenditure on LPG was significantly lower than for kerosene but kerosene was erroneously considered a cost-effective fuel choice" [67, p.11].

Like income, there was country-level variation in the relationship between cost and adoption. A 20% lower LPG price led to an increase in the proportion of clean fuel use of 11.9% in Ghana and 46.3% in Nigeria [71]. This combination of the multi-dimensionality of LPG cost, limited understanding of cost comparisons between fuels and geographical variation may explain the mixed results from the limited hypothesis testing performed on this variable, with some studies finding cost of LPG to be a significant factor [90,91], whilst others did not [92].

3.4.3. Education

Education could refer to the highest education level of anyone in the household (n=16), the education level of the head of household (n=2), education level of women in the household (n=2) or the proportion of educated members of the household (n=1).

Households with educated members are more likely to use LPG than those with less educated members. This could be because of increased awareness about the benefits of clean fuel use amongst educated consumers or because of collinearities between higher levels of education and increased income. This association was found to be significant in 12 out of 15 papers that performed hypothesis testing on education variables. One paper found that there was negative correlation between education and LPG use, but this is an unreliable finding because only 6% of the sample used LPG [91]. Papers that differentiated between education levels found that the more educated household members were, the more likely they were to use LPG [93–95].

3.5. E-cooking

Very small sample sizes mean there is a weak evidence base for adoption determinants of e-cooking. The top determinants were income (n=3) and installation and usage costs (n=3).

There was a positive relationship between income and e-cooking that was found to be significant [96]. This is likely to be because of the high upfront costs of e-cooking devices and the relatively high costs of cooking with electricity compared to biomass alternatives. As with LPG, the literature differentiated between these categories of costs. The upfront costs of cooking devices and the perception that they are expensive to use was found to be a barrier [97]. The price of electricity had a significant negative impact on adoption of e-cooking [98,99], whereas the price of competing fuels (e.g., firewood) had a significant positive impact [99].

4. Discussion

More action is required to meet SDG7's goal for all households to have both sustainable and clean electricity and cooking access by 2030. The literature has largely treated lack of electricity and clean cooking as separate issues thus far. However, households often lack access to both and thus it might be possible for providers to offer products that can provide inclusive energy access services. To achieve this, providers need to understand whether the adoption determinants for different electricity and cooking technologies are similar, or whether such an expansion would require altered service offerings or the targeting of different population segments.

This review addresses this gap by providing valuable insights into the adoption determinants of SHS, LPG and e-cooking technologies. Most of the 71 papers examined focussed on SHS and LPG, whilst only a handful discussed e-cooking, which is still a nascent field in the academic literature. Only three papers discussed multiple technologies, showing that holistic considerations of energy access are in their infancy. A key finding was that 30 out of the 40 determinants identified (75%) were shared by at least two of the technologies, suggesting they have similar target markets and thus confirming that opportunities for co-distribution exist.

The most important overarching factor for all three technologies was relative affordability, which was illustrated by the way that income, technology cost and the price of alternative fuels featured heavily in the literature. Alternative fuel options vary extensively in the cooking sector, whilst there are few other electrification options to SHS in areas where they have been deployed, apart from the main grid or mini-grids [100]. The adoption likelihood of the three technologies also seems to be highly dependent on the cost comparison against alternative fuels and/or technologies.

A few key differences were identified between the technologies. A larger household size was linked to a lower likelihood of adopting LPG and a higher likelihood of purchasing a SHS. As household size increases, demand for energy may rise, which pushes households towards cheaper energy sources to satisfy demand [101]. Most clean cooking research to date has focussed on rural locations [28], where the alternative to modern cooking fuels is gathering firewood. Larger households have a lower opportunity cost of collecting biomass [102,103], which means they are less motivated to switch to LPG. On the other hand, the ongoing costs of alternative electricity service options, such as battery-powered torches and kerosene, are more expensive than SHS [104], so the larger the household the greater the potential financial saving from using a SHS. The other key difference was location. LPG users were more likely to live in urban areas, which enable easier access to a reliable fuel supply, with distance to sale points being a crucial adoption metric [105]. SHS tend to be adopted by those residing in rural areas, partly due to the absence of an alternative fuel supply, such as an electricity grid connection. Figure 7 highlights key similarities and differences in adoption determinants between the technologies.

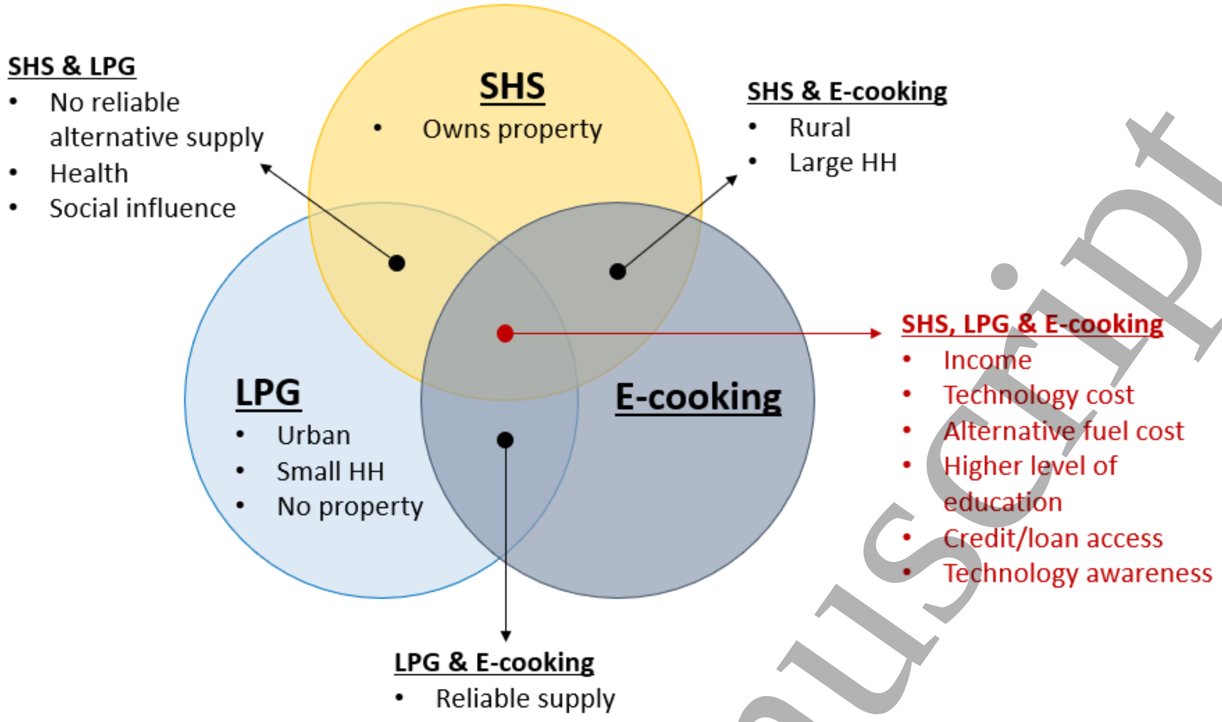

Figure 7: Similarities and differences in adoption determinants between technologies

4.1. Opportunities for Combining Energy Access Technologies

4.1.1. SHS and LPG

There is a tension between the urban focus of LPG and rural focus of SHS. However, there is an intersection in the market, as urban households often use SHS as a backup to the electricity grid and may be interested in LPG for cooking. For rural SHS users to be able to purchase LPG stoves, the provider may need to strengthen LPG fuel supply chains. This might be more feasible in peri-urban areas, which have more infrastructure than rural ones.

LPG tends to be adopted by smaller households for reasons of affordability, whereas SHS are favoured by larger ones; therefore, we recommend targeting higher income SHS customers and providing stoves sufficient for family cooking (2-4 burner) or 'upselling' e-cooking appliances to those customers. However, those would need to be compatible with the adopted SHS, i.e. be able to run on DC power, and the SHS would require sufficient capacity to support such appliances.

SHS are considered as a relatively mature technology to provide off-grid electricity access, especially as many providers rely on an established PAYG technology and tariff structure to enable households to better afford the technology. LPG is the most scalable clean cooking solution for SSA but is often rendered unaffordable by the high upfront cost of equipment and the need to buy discrete cylinder refills. There is therefore a clear opportunity for LPG to tap into the PAYG infrastructure already set up for SHS and the credit history that customers have built up with providers. There are currently a number of companies selling PAYG LPG (e.g., Circle Gas, PAYGO Energy) but only one looking at combining PAYG SHS and PAYG LPG (Bboxx).

4.1.2. SHS and E-cooking

E-cooking has great potential if it can be reliably powered. There is a clear opportunity for e-cooking devices to be sold as ‘add-ons’ for SHS. SHS packages could also include financing for e-cooking devices, thus overcoming affordability adoption determinants. The inclusion of e-cooking would also benefit providers by increasing the utilisation rate of their SHS and boosting their revenue.

The challenge here is power provision: cooking requires a lot of energy and certain e-cooking devices, such as kettles, would simply be incompatible with the limited power ratings of most SHS. E-cooking devices that could be successfully combined with SHS are lower-powered ones such as electric pressure cookers (EPCs) and rice cookers. Given that larger families are more likely to adopt SHS, we recommend the provision of larger capacity (8 litre plus) devices to suit cooking needs. It is also important to deliver training and invest in marketing as these appliances are not commonplace in SSA. Therefore, there may be limited awareness of their availability, benefits and use practices.

4.1.3. LPG and E-cooking

LPG is considerably more diffused in SSA than e-cooking, which is currently only beginning to appear in SSA countries and markets [8].Therefore, when considering co-provision of LPG and e-cooking, it is likely this would consist of introducing e-cooking to current LPG users. These tend to be the wealthier urban segment of the market (Figure 7) but asset financing may still be required to make e-cooking affordable. In such scenarios, e-cooking may facilitate a ‘clean’ cooking stack by displacing biomass used for specific long-duration cooking tasks.

LPG has mostly penetrated urban areas in SSA [8] with a greater likelihood of grid electricity access [106], meaning power consumption is less of a problem if introducing e-cooking to current LPG users. Therefore, we recommend the provision of e-cooking devices that are complementary to LPG, such as kettles, EPCs, rice cookers, microwaves, which may already be perceived as aspirational. Induction stoves may have lower utility to users as they are suited to high-intensity cooking events, such as frying [107] and thus serve a similar function to LPG.

5. Conclusion

To address the energy access gap, a combination of grid and off-grid solutions will be needed. An improved understanding of adoption determinants for off-grid electricity and cooking solutions will enable the private and public sectors to address service gaps, funders to better finance energy services and different government factions to develop cohesive policies. Private sector have a critical role to play in scaling up off-grid solutions to address current service gaps. This study on adoption determinants would enable the private sector to focus on the high frequency adoption determinants for SHS, LPG and e-cooking for both market expansion and co-provision of energy services within those markets.

Whilst studies have explored adoption determinants for SHS and LPG and e-cooking individually, there is a gap in research on comparing demographic intersections between the technologies and how they could address needs in various settings. By combining knowledge on these adoption determinants, this study provides an opportunity to break down traditional silos between those who research electricity and those who focus on cooking, improving the evidence base for practitioners and policy makers. This will also accelerate clean energy transition pathways through improved up-take of off-grid technologies especially for last mile users and those currently bypassed by mainstream grid solutions.

In this study, we have reviewed academic literature to identify 40 adoption determinants for SHS, LPG and e-cooking. These were remarkably similar, with 30 of those determinants shared by at least two of the technologies. Reliability of alternate technology options, reliability of the technology in question, affordability, household size and location (urban/rural) were identified as determinants that cut across technologies. The uptake of LPG is currently concentrated in urban areas and SHS in rural locations. However, that does not exclude the potential of scaling up SHS in urban settings that have unreliable or unavailable grid access. There is also an opportunity to build on PAYG SHS infrastructure to improve access to clean cooking in rural settings. This could consist of financing e-cooking appliances as part of the SHS package or leveraging the customer relationship to also provide PAYG LPG.

Our study did not explore causality and there was limited published material available for e-cooking. Further piloting and research are required to understand how to effectively and simultaneously address cooking and electricity access issues, particularly with respect to critical success factors for co-distribution. For instance, there is more research needed on the co-provision of LPG and e-cooking, and how the two fuels compliment or substitute each other, including in grid and mini-grid settings. Given the important role of the private sector in energy provision in SSA, there is also a need to understand how novel business models could help eliminate critical adoption barriers across both energy types, such as the high upfront costs of equipment. Potential climate change and green funds create a strong incentive for the private sector to scale up a range of off-grid solutions for electricity and clean cooking to support net zero ambitions for communities not connected to grids and using polluting cooking fuels.

Further research is also needed to understand synergies that emerge from combining technologies and productive uses of energy. For example, both SHS and LPG are associated with creating or freeing up leisure time and improved health due to the reduction in indoor air pollution. It is conceivable that the aggregate benefit of providing both technologies in combination could be greater than the sum of its parts. Similarly, offering combined electricity and cooking solutions to businesses can maximise the benefits they can yield from clean and reliable energy, and potentially extend their service offering, thus boosting revenue and income opportunities.

The world is currently not on track to achieve the Sustainable Development Goals by 2030, including on energy. With less than a decade to go, novel and ambitious approaches are needed to close the energy access gap. Combining the provision of electricity and clean cooking fuels could accelerate progress towards SDG7 by leveraging existing customer relationships, distribution channels and infrastructure. This also provides an opportunity to address net zero and climate change through scale-up of clean technologies. We hope this process will be catalysed by the novel understanding of adoption barriers and target market characteristics for SHS, LPG and e-cooking identified through this literature review, as well as future research inspired by this study.

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7. Appendices

7.1. Appendix 1: Shared adoption determinants

Adoption determinants	Technology	Description	Total	Authors
1. Income	LPG	More likely to adopt LPG if income is high	17	[71,108–118][34]
	E-cooking	More likely to adopt e-cooking if income is high	3	[99,119,120]
	SHS	More likely to adopt SHS if income is high	7	[33,34,53,66–68,121]
		Less likely to adopt SHS if income is high	1	[69]
			28	
2. Technology installation cost and usage cost	LPG	More likely to adopt if LPG cost is lower	15	[71,82,112,113,122–132]
		Less likely to adopt if LPG cost is lower	1	[116]
		Non-significant difference	1	[115]
	E-cooking	More likely to adopt if e-cooking	3	[133–135]

		device and electricity cost is lower		
	SHS	More likely to adopt if SHS cost is lower	7	[44,51,64,136–139]
			26	
3. Education level	LPG	More likely to adopt LPG with higher educational level	16	[108–113,115–117,122,140–142][119]
		Less likely to adopt LPG with higher educational level	1	[116]
	E-cooking	More likely to adopt e-cooking with higher educational level	2	[119,120]
	SHS	More likely to adopt SHS with higher educational level	6	[34,44,66–69]
		Less likely to adopt SHS with higher educational level	1	[33]
			26	
4. Household size	LPG	More likely to adopt LPG if household size is large	2	[140][119]
		Less likely to adopt LPG if household size is large	8	[108,110,112,115,116,122,125]
		No difference	1	[143]
	E-cooking	More likely to adopt e-cooking if household size is large	2	[119,120]
	SHS	More likely to adopt SHS if	4	[33,66,67,69]

		household size is large		
			17	
5. Urban location	LPG	More likely to adopt LPG if household lives in an urban location	9	[108,113,117,122,124,128,140,141,144]
		Less likely to adopt LPG if household lives in an urban location	1	[110]
	E-cooking	More likely to adopt e-cooking if household lives in an urban location	1	[133]
	SHS	More likely to adopt SHS if household lives in an urban location	2	[33,43]
		Less likely to adopt SHS if household lives in an urban location	4	[5,34,66,69]
			17	
6. Cost of alternative energy sources (e.g. biomass, electricity)	LPG	More likely to adopt LPG if alternative fuel cost is higher	6	[71,82,116,123,125,143]
		Less likely to adopt LPG if alternative fuel cost is higher	1	[113]
	E-cooking	More likely to adopt e-cooking if alternative fuel cost is higher	1	[145]
	SHS	More likely to adopt SHS if alternative lighting/power sources are higher	7	[34,44,47,49,66,146,147]
			15	

7. Reliable supply of alternative fuels (e.g. charcoal, electricity)	LPG	Less likely to adopt LPG if household has access to reliable supply of alternatives	5	[108,113,117,123,124]
	SHS	More likely to adopt SHS if household has no grid electricity access or unreliable grid supply	9	[33,34,43–45,47,55,69,138]
		Less likely to adopt SHS if household has access to grid electricity	1	[57]
			15	
8. Age	LPG	More likely to adopt if older	4	[108,109,122,140]
		Less likely to adopt if older	6	[110,111,113,117,125,143]
	E-cooking	More likely to adopt if older	1	[99]
	SHS	More likely to adopt if older	2	[33,67]
		Less likely to adopt if older	2	[66,68]
			15	
9. Gender	LPG	More likely to adopt if male	2	[119] [110]
		Less likely to adopt if male	5	[108,113,115,117,140]
	E-cooking	More likely to adopt if male	2	[99,119]
	SHS	More likely to adopt if male	2	[33,45]
		Less likely to adopt if male	3	[66–68]
			14	
10. Reliable supply of	LPG	Less likely to adopt LPG if	12	[82,108,113,115,117,122–124,126,127,131,143]

technology fuel		household lacks reliable access to LPG supply		
	E-cooking	Less likely to adopt e-cooking if household lacks reliable access to fuel (electricity)	2	[133,135]
			14	
11. Technology is easy to use/ convenient/ fast	LPG	More likely to adopt as LPG is easy to use/ convenient/ fast	10	[82,124,125,127,129,130,132,143,148,149]
		Less likely to adopt as LPG is not as easy to use/ convenient/ fast	1	[123]
	SHS	Less likely to adopt due to SHS being less easy to use/ convenient/ fast than alternatives	1	[5]
			12	
12. Owns property	LPG	Less likely to adopt if household owns a property	5	[113,115,116,142] [114]
	SHS	More likely to adopt if household owns a property	3	[34,69,138]
		Less likely to adopt if household owns a property	2	[33,150]
		No difference between owners and renters	1	[49]
			11	
13. Health benefits	LPG	More likely to adopt due to health benefits of LPG compared to alternatives	8	[82,123–125,127,132,143,148]

	SHS	More likely to adopt due to health benefits of SHS compared to alternatives	3	[5,33,57]
			11	
14. Technology awareness	LPG	Less likely to adopt if household does not know about LPG or how to use it	3	[122,126,143]
	E-cooking	Less likely to adopt if household does not know about e-cooking and how to use related devices	1	[133]
	SHS	Less likely to adopt if household does not know about SHS, its benefits or how to use it	6	[44,49,51,55,64,139]
			10	
15. Quick and cooks most meals	LPG	More likely to adopt if LPG can cook most meals, handle a large meal amount and cooks fast	8	[82,109,112,123,128,130,144,151]
	E-cooking	More likely to adopt if meal type cooking duration is short	1	[120]
			9	
16. Access to credit/ loan	LPG	More likely to adopt if household has access to credit/loan	2	[82,124]
	E-cooking	More likely to adopt if household has access to credit/loan	1	[99]

	SHS	More likely to adopt if household has access to credit/loan	5	[44,51,67,138,152]
			8	
17. Job type	LPG	More likely to adopt if non-farmer or formal sector employee	3	[116,122,132]
	E-cooking	More likely to adopt if formal sector employee	1	[99]
	SHS	More likely to adopt if non-farmer or formal sector employee	2	[67,68]
		No difference based on employment	1	[153]
			7	
18. Neighbour/ friend influence	LPG	More likely to adopt if neighbours/friends etc. use LPG	1	[122]
	SHS	More likely to adopt if neighbours/friends etc. use SHS	6	[5,34,44,50,51,55]
			7	
19. Distance to market/ shop	LPG	More likely to adopt LPG if short distance to market/shop	4	[82,125,132,140]
		Less likely to adopt LPG if short distance to market/shop	1	[122]
		No difference in distance travelled based on fuel	1	[143]
	SHS	More likely to adopt SHS if short	1	[154]

		distance to market/shop		
			7	
20. Asset ownership (e.g. car, telephone, television, livestock)	LPG	More likely to adopt LPG if household owns assets	3	[109,111,140]
	SHS	More likely to adopt if household owns assets	2	[33,67]
		Less likely to adopt SHS if owns appliances that cannot be powered by SHS	1	[52]
			6	
21. Number of children	LPG	Less likely to adopt if large number of children	2	[110,140]
	E-cooking	More likely to adopt if large number of children	1	[99]
	SHS	More likely to adopt if large number of children	1	[68]
			4	
22. After-sales service + maintenance	LPG	Less likely to adopt if after-sales or maintenance not present	1	[82]
	SHS	Less likely to adopt if after-sales or maintenance not present	3	[51,136,139]
			4	
23. Roof type	LPG	More likely to adopt if high quality roof (e.g. concrete, tiles, metal)	2	[140,142]

	SHS	More likely to adopt if low quality roof (e.g. grass)	1	[68]
			3	
24. Seasonality/ Weather	LPG	More likely to adopt/use LPG in rainy season	1	[123]
		Less likely to adopt/use LPG in rainy season	1	[125]
	SHS	Less likely to adopt/use SHS in rainy season	1	[53]
			3	
25. Number of rooms	LPG	More likely to adopt if property has a higher number of rooms	1	[113]
	SHS	More likely to adopt if property has a higher number of rooms	1	[66]
			2	
26. Marital status	LPG	No significant difference if married	1	[143]
	SHS	Less likely to adopt if married	1	[66]
			2	
27. Dwelling type	E-cooking	Less likely to adopt e-cooking if live in traditional dwelling	1	[120]
	SHS	More likely to adopt LPG if live in modern dwelling	1	[66]
			2	
28. Aspirational technology	E-cooking	More likely to adopt e-cooking as it is aspirational	1	[133]

	SHS	More likely to adopt SHS as it is aspirational/ increases social status	1	[44]
			2	
29. Poverty	LPG	More likely to adopt LPG if household is facing poverty	1	[149]
	SHS	Less likely to adopt SHS if household is facing poverty	1	[65]
			2	
30. Number of retail shops	LPG	Less likely to adopt LPG if there are few shops offering LPG equipment	1	[82]
	SHS	Less likely to adopt SHS if there are few shops selling SHS	1	[139]
			2	

7.2. Appendix 2: LPG specific adoption determinants

Adoption determinants	**Description**	**Total**	**Authors**
Safety concerns	Less likely to adopt LPG due to safety concerns	12	[82,122–126,128,129,131,132,143,155]
Access to Sanitation (e.g. piped water, toilet)	More likely to adopt LPG if access to sanitation	3	[109,111,140]
Electricity access	More likely to adopt LPG if access to electricity	5	[108,113,117,122] [53]
	Less likely to adopt LPG if access to electricity	1	[110]
Indoor cooking	More likely to adopt LPG if cooking inside	2	[109,112]
Cook is also financial decision maker	Less likely to adopt LPG if cook is also financial decision maker	1	[122]

	No significant different	1	[143]
Taste of food	More likely to adopt LPG as food tastes better than when cooked with alternative fuels	1	[125]
	Less likely to adopt LPG as food tastes worse than when cooked with alternative fuels	1	[112]

7.3. Appendix 3: SHS specific adoption determinants

Adoption determinants	**Description**	**Total**	**Authors**
Appliance usage (e.g. lighting, phone charging)	More likely to adopt as SHS enables appliance usage	8	[5,33,35,53–57]
SHS capacity	Less likely to adopt if SHS capacity is low	3	[51,53,64]
Environmental protection	More likely to adopt SHS due to environmental benefits compared to alternatives	3	[33,43,139]
SHS reliability	Less likely to adopt SHS if household does not believe they will receive reliable electricity from their SHS	3	[44,49,51]