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Factors associated with the use of liquefied petroleum gas in Ghana vary at different stages of transition

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Clean-cooking transitions have the potential to generate large public health, environmental and societal gains for 2.6 billion people in the Global South. Here we use data from Ghana's largest household energy survey (n = 7,389) to provide two main insights. First, regression analysis of 13 commonly cited socio-economic and demographic determinants of household fuel use indicates remarkably different relationships with clean-fuel use at different stages of the transition process. We propose a stage-based transition framework that can help inform the rollout of clean-cooking interventions. Second, we identify factors that are associated with the exclusive use of liquefied petroleum gas (LPG) using a statistically powered sample of exclusive LPG users (n = 693). We show that, all else equal, increases in wealth and urbanicity are not—contrary to conventional wisdom—associated with a transition from primary to exclusive LPG use. Whereas further research is needed to determine causality, our findings highlight the potential for more careful measurement, isolating each stage of the clean-cooking transition, to inform new insights and policy opportunities.

Around 2.6 billion people, primarily in low- and middle-income countries in Asia, Africa and South America, depend on polluting cooking fuels[1]. These households burn unprocessed solid biomass fuels (for example, firewood, crop residue, cattle dung), charcoal, kerosene or coal in open fires or inefficient stoves to meet their cooking energy needs. Incomplete fuel combustion leads to the emission of an array of pollutants such as fine particulate matter ($PM_{2.5}$), black carbon and carbon monoxide, collectively referred to as household air pollution (HAP)[2]. In contrast to solid fuels, modern fuels such as natural gas, liquefied petroleum gas (LPG) and electricity produce little or no pollution during cooking[3]. Transitioning households away from solid and towards clean fuels directly contributes to several United Nations Sustainable Development Goals[4]. A recent study estimated that the lack of universal clean-cooking costs about US$2.4 trillion each year globally, driven by adverse impacts on public health (US$1.4 trillion), environment (US$0.2 trillion) and women (US$0.8 trillion from lost productivity)[5].

From a supply perspective, LPG is widely considered to be the most scalable clean-cooking fuel in most developing economies[5,6]. LPG—a mix of propane and butane— is easy to transport and is generally safe

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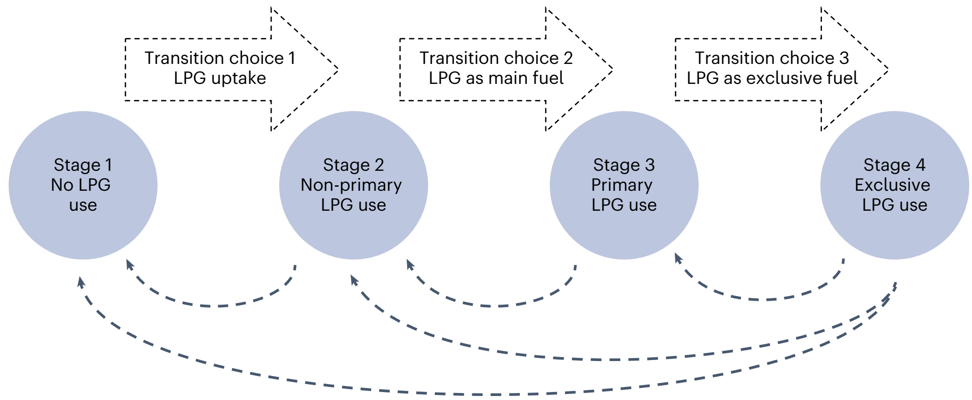

Fig. 1 | Conceptual framework of stage-based clean-cooking transition. The four stages (circles) of the clean-cooking transition are shown with the three transition choices (arrows). The three transition choices (LPG uptake (1), LPG as main fuel (2) and LPG as exclusive fuel (3)) determine the outcome: the stage of a household's energy choice. Whereas the transition is here drawn as sequential and unidirectional for simplicity, we expect both stage-skipping and backsliding (dashed lines) in some cases.

if handled properly[6]. Both firewood and charcoal are associated with forest loss and black carbon emissions, meaning that the transition from biomass to LPG (fossil fuel) has a net positive climate impact[7–10]. Many national governments with clean-cooking goals have specifically committed to LPG access or penetration targets, and some have rolled out major LPG programmes on the ground[5,11–13]. For example, India has provided 95 million low-income women with access to LPG through a capital subsidy[14]. Several member countries under the Economic Community of West African States declared ambitious targets for LPG penetration in 2015[15].

In Ghana, the focus of this study, about 37% of the population (urban: 51%, rural: 15%) use LPG as the primary cooking fuel according to the 2021 Population and Housing Census[16]. This validates the government's stated aim to increase LPG penetration to 30% by 2020 as per its strategic national energy plan (2006–2020). However, this target fails to meet the 'Sustainable Energy for All' Action Agenda 2015, which aimed to have 50% of households use LPG as their primary cooking fuel by 2020[17]. Limited progress in the clean-cooking energy transition is not unique to Ghana. Despite several multi-institution, multi-country efforts over the last two decades, progress in the clean-cooking energy transition in developing economies has been modest[5,12,18]. Whereas the local availability of LPG and initial uptake have improved, low-income households that adopt LPG tend to use it sporadically as a non-primary cooking technology, at best, or abandon it after a brief period of use[12,14,19,20]. Notably, qualitative studies have also reported that the primary cook (mostly women) is often familiar with LPG and have reported time gains and comfort from LPG use over traditional cooking[21,22].

In this Article, we first discuss two key gaps in our understanding of the clean-cooking energy transition. We then propose a conceptual framework to analyse the stages of transition from exclusive biomass fuel use to exclusive LPG use. Using survey data from a national sample of households in Ghana, we find that commonly cited predictors of clean-fuel use have remarkably different relationships with cooking choices at different stages of the transition process. We also find that transitioning from primary to exclusive use of LPG is largely associated with factors that fall outside of the scope of most clean-cooking interventions, with the exception of behavioural perceptions. Though the relationships we measure should not be interpreted causally, we use our findings to discuss the ways that policy might better respond to the nuances of each stage in the transition process.

Contradictory insights on clean-cooking energy transitions

To identify gaps in current understanding of the clean-cooking energy transition, we compiled systematic reviews related to clean-cooking energy transitions and other studies specific to cooking in Ghana. We pay particular attention to findings on factors (observable characteristics of households, communities or the environment) that predict the transition process. Notably, we use the term 'predict' to describe the relationship between household, community and contextual factors and households' energy choices. These terms refer to the modelled relationship, typically in a regression framework, and should not be interpreted as causal—for example, we do not mean to imply that household size causally impacts clean-cooking adoption. Furthermore, 'driver' denotes a positive relationship and 'barrier' a negative one, without implying causality.

First, the literature includes contradictory findings on whether a given factor is a driver or barrier to the transition away from solid fuels. Recent systematic reviews have identified a diverse set of factors or determinants that include technological characteristics, demographic and socio-economic conditions, the market economy, institutional capacity, supply chain infrastructure and others[6,18,23,24]. However, the comparative importance of factors and even the direction of their relationship with cleaner cooking (driver or barrier) is sometimes inconsistent and often unclear. For example, studies find mixed evidence on how the size of the household (small or large) or the gender of the household head (male or female) relate to clean-cooking choices[18,23]. Even seemingly straightforward factors such as income vary in the sign of their relationship with clean-fuel adoption across studies[23] (Fig. 1).

We argue that some of the discrepancies in results may be attributed to differences in how 'adoption' of clean fuels is defined. Fuel use has been defined and measured differently across studies. For example, there exists no scholarly consensus on what the frequently used word adoption implies in the context of clean-cooking transitions: in some cases, it refers to 'uptake'[25] and in others to 'some use'[23] or 'use'[26]. Some studies use terms such as 'primary adoption'[27] or 'sustained adoption'[28] to refer to the energy dimension or time dimension of fuel choice. As a result, tallying of individual study results, such as Fig. 2 in Lewis and Pattanayak[23], or Fig. 5 in Guta et al.[18], while useful as a snapshot, can be misleading without careful attention to definitional differences. Improved understanding of how the magnitude and direction of the relationship between particular factors and cleaner cooking varies

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Table 1 | Key transition factors

Factor type	Factor description	Discussion (based on published literature)
Socio-economic	Wealth index score	One of the most important drivers of clean-cooking transitions across several studies is household wealth. Various indicators of wealth such as total household income, total cash income, a household wealth index and dwelling characteristics are used as proxies for wealth[18,23,40].
Socio-economic	Family/household size	An increase in household (family) size acts as a transition barrier. When more food has to be cooked, it increases fuel demand.
		Firewood is free and allows cooking in large pots, providing a distinct advantage over standard-size LPG burners for larger households. Larger households would also require more frequent cash purchases of LPG[20,41]. We use the 'standard adult' criteria detailed in Supplementary Note 1.
Socio-economic	Age of primary cook	Strong habit formation is associated with age[59]. Older cooks find it difficult to switch to new technologies.
Socio-economic	Gender of primary cook	Male primary cooks are found to hold more decision autonomy compared with female cooks regarding clean-fuel use[18].
Socio-economic	Education of primary cook	More-educated primary cooks are more likely to be aware of the risk of household air pollution. Education is positively correlated with cash income activities, which can lead to greater autonomy in decision-making[18,30].
Socio-economic	Age of household head	The age of the household head is associated with increased willingness to take risks (higher age may be indicative of greater financial capacity for risk-taking) to take up new technologies[29].
Socio-economic	Gender of household head	Female household heads are more concerned with cooking in a smoky kitchen and hence more likely to use LPG[19].
Socio-economic	Education of household head	More educated household heads are more likely to be aware of the risk of household air pollution[20,31].
Behavioural	Positive perceptions about regular LPG use	Attitude and perceptions play a key role in cooking solution choices[24,49]. A higher sentiment score signals enhanced acceptance of the advantages of using LPG, that is, more favourable feelings towards LPG use (Supplementary Note 2).
Behavioural	Negative perceptions of regular LPG use	Negative perceptions may matter differently than positive perceptions. For consistency with other measures, a higher score indicates that respondents downplay the negative perceptions about LPG, thereby leading to a more favourable perception of LPG (Supplementary Note 2).
Behavioural	Number of burners in LPG stove	The number of burners is a predictor of primary LPG use[41]. This may be because it aids cooking or because the purchase of multiple burners implies an intention to use LPG more frequently. The intent to perform a behaviour is considered a key driver of behavioural action[60,61].
Urbanicity	Urban or rural	Compared with rural, urban areas are characterized by better physical access to LPG stores (travel convenience, travel distance) and lower access to competing polluting fuels (higher cost, lower availability of solid fuels). Urban households also typically have a higher opportunity cost of solid fuel gathering effort and time[18,62].
Supply chain	Convenience to access LPG fuel	The cost and time involved in procuring LPG cylinders are considered barriers to LPG use[41,42,63].

Thirteen factors identified as drivers and barriers based on a review of published literature on the clean-cooking energy transition factors.

with the stage of transition (for example, uptake vs sustained use) can help shape policy design and implementation.

Second, research on factors that contribute to the disadoption of polluting solid fuels is relatively limited, with a few notable exceptions[19,29–32]. This margin of behaviour is particularly important because gains from transitioning to clean fuels depend on corresponding reductions in the use of polluting fuels. Transitioning low-income households, particularly in rural areas, to exclusive use of clean fuels such as LPG (that is, complete disadoption of solid fuels) remains a challenge across the Global South. Even in Ecuador, where LPG is subsidized at around ~90% of its market price, solid fuels are used in 40% of households as a secondary fuel[11,13]. The health risk reductions associated with clean-fuel transitions are greatest when there is little or no use of solid fuels by a household[33]. In densely populated communities, health gains also depend on the cooking practices of the community at large[6,34]. Studies have indicated that factors that predict—and in some cases drive—the use of clean cooking and the disadoption of polluting fuels have some overlap but are not identical[29,31]. Qualitative analysis in a recent systematic review indicates that factors associated with uptake of clean fuels such as LPG are not necessarily relevant in the decision to disadopt solid fuels[18]. For example, past studies show that subsidizing capital costs helps with the uptake of clean fuels but has little bearing on long-term use of polluting fuels[18,35]. Another study has found that factors that predict 'any use' of LPG are different from those that predict complete disadoption of other fuels[31].

In conclusion, the current knowledge base provides apparently contradictory insights on whether a factor in the clean-fuel transition process acts as a driver or barrier to cleaner fuel use. If the drivers of clean-fuel use differ from the drivers of disadoption of polluting fuels, apparent contradictions across studies may in fact be reconcilable. Hence, identifying factors relevant to each step in the transition from primary to exclusive use of clean-cooking fuels will address an important gap in the energy poverty literature. In the next section, we offer a conceptual framework to analyse the role of these factors.

A stage-based transition model as a conceptual framework

Given the knowledge gaps described in the previous section, we propose and empirically assess a conceptual framework of clean-cooking energy transitions. This is in line with earlier studies that viewed change as progression instead of a binary flip from exclusive solid fuel use to exclusive clean-fuel use; for example, Herington et al. describe it as a 'haphazard, incremental' process[36]. We describe four distinct stages in the transition process from exclusive polluting fuels to exclusive clean fuels (Fig. 1). We develop the figure in the context of our research, where the polluting fuel is firewood or charcoal (solid fuels) and the clean fuel is LPG. Households typically begin their journey at stage 1, no LPG use, that is, exclusive use of solid fuels. Some households transition to stage 2, where they use LPG as a non-primary (secondary or tertiary) fuel while continuing to use solid fuels as their primary cooking fuel. Households may then progress to stage 3, where they use LPG as the primary cooking fuel. Finally, households that completely disadopt solid fuels reach stage 4, where they exclusively use LPG. Importantly, given the low cost of switching back to solid fuels, a transition is not stable and can be reversed at any stage (see also Herington and Malakar's caution about the fluid and dynamic nature of energy transitions)[37].

These transitions are often associated with targets for clean-cooking interventions[5,38]. We posit that the relationship—both its sign and its magnitude—between household fuel choice and different household and contextual factors may be stage-specific.

We argue that this entire transition process from exclusive use of solid fuels to exclusive use of LPG may be viewed as the outcome of three consecutive transition choices. In the first stage, we consider all households that have LPG as 'success' and those without access to LPG as 'failure' for the 'LPG uptake' transition choice. Notably, the terms success and failure for transition choices are strictly used in the context of progression in the clean-cooking transition and should not be interpreted as the authors' judgement of a household's fuel choice. Similarly, for all households with LPG, 'failure' implies non-primary use of LPG whereas 'success' implies use of LPG as primary or exclusive cooking fuel for the 'LPG as main fuel' transition choice. Along the same lines, for all households that use LPG as the main (primary/ exclusive) fuel, 'failure' implies primary use of LPG whereas 'success' implies use of LPG as exclusive cooking fuel for the 'LPG as exclusive fuel' transition choice. In other words, we refer to progression rightward along the transition pathway as a transition 'success', that is, a household that moves from stage 1 to any higher stage is success in transition choice 1; similarly, a household that moves from stage 2 to any higher stage is a success in transition choice 2. For convenience, hereafter the terms *uptake*, *main* and *exclusive* are used as shorthand for the three transition choices. Note that different transition choices reflect substantially different underlying choices by the household. For example, uptake requires acquisition of durable goods (stove, cylinder), whereas subsequent transitions reflect changes to the intensity of usage of that technology. In sum, framing the transition out of energy poverty as a stepwise process allows for a more nuanced analysis of the energy transition process and may help resolve apparent contradictions in findings across studies that define clean energy transitions in different ways.

Key factors that impact transition

Previous systematic reviews of drivers and barriers to clean-cooking transitions (including those involving clean fuels other than LPG) were reviewed to identify predictors of transition choice[18,23,24,30,39,40]. In addition, we also reviewed recent Ghana-specific clean-cooking studies[17,20,41–44]. We identified 13 common factors, which include eight household-level socio-economic factors, three household-level behavioural factors and two community-level factors (Table 1). Please refer to Supplementary Notes 1 and 2 for the details on why these predictors (independent variables) were selected and how the survey data were processed for final analyses.

Variation in LPG use and transition predictors

We conducted a nationwide in-person survey of the primary cook in 7,389 households across all 16 administrative regions of Ghana relying on the Ghana Statistical Service's enumeration areas (EAs), which are used for collecting Ghana's national census data. The Methods section provides details on the sampling design.

We find that 7,276 (98.5%; urban: 3,468; rural: 3,808) reported their primary cookstove (Table 2). About 90% of the respondents (primary cooks) were female. The median age of the primary cook and the household head is 37 and 45 years, respectively. About 73%, 7%, 10% and 10% of respondents were in stages 1 (no LPG use), 2 (non-primary), 3 (primary) and 4 (exclusive), respectively. Average household characteristics vary considerably across the stage of LPG use. About 80% of exclusive LPG users lived in urban areas; in contrast, only 37% of exclusive solid fuel users (stage 1) lived in urban areas. Among households exclusively cooking with LPG (stage 4), 67% of primary cooks had completed some level of higher education (secondary, vocational or university) compared with only 10% of households with no LPG use. We also observe notable stacking phenomenon across respondent categories across geographies with different fuel mix (Supplementary Note 3).

Table 2 | Key economic and demographic characteristics of respondents by LPG use stage

				LPG as main fuel	
Variable	**Overall**	**Stage (S) 1: no LPG**	**S2: non-primary**	**S3: primary**	**S4: exclusive**
Sample size	7,276	5,313	513	757	693
Urbanicity					
Rural	52%	63%	29%	20%	20%
Urban	48%	37%	71%	80%	80%
Household size	2.80	3.10	3.10	2.80	1.60
Primary cook gender					
Female	90%	91%	95%	92%	70%
Male	10%	9%	5%	8%	30%
Primary cook age	37	38	36	34	31
Primary cook education					
No higher education	80%	90%	72%	53%	33%
Higher education	20%	10%	28%	47%	67%
Primary cook = household head	40%	38%	35%	37%	64%
Household head gender					
Female	38%	38%	41%	38%	42%
Male	62%	62%	59%	62%	58%
Household head age	45	46	45	40	35
Household head education					
No higher education	76%	86%	67%	50%	31%
Higher education	24%	14%	33%	50%	69%
Household average monthly income (Cedi)					
≤250	23%	27%	15%	13%	11%
251–500	24%	27%	20%	16%	17%
501–1,000	20%	19%	28%	25%	24%
1,001–2,000	13%	10%	16%	20%	20%
>2,000	19%	17%	21%	27%	28%

'Household size' represents median 'standard adult' size; 'age' value represents median age; household head data include primary cook data when primary cook is also the household head.

Notably, some observable factors (listed in Table 1) can serve as proxies and often co-vary. For example, urbanicity is associated with numerous different factors that may affect both demand and supply of LPG: compared with their rural counterparts, urban households may be more likely to earn income in cash, have access to LPG suppliers and interact with a network of peers that includes more LPG users. We note this as a caution for interpretation upfront and return to it in our discussion of the results (see for example Heltberg on the role of supply side factors in shaping clean-cooking decisions)[45]. We present additional descriptive plots, including broken out by geographic region, in Supplementary Figs. 1 and 2.

We analyse different observable factors associated with LPG use in the literature. The results (here and elsewhere in the manuscript) should not be interpreted as causal; omitted variables and reverse

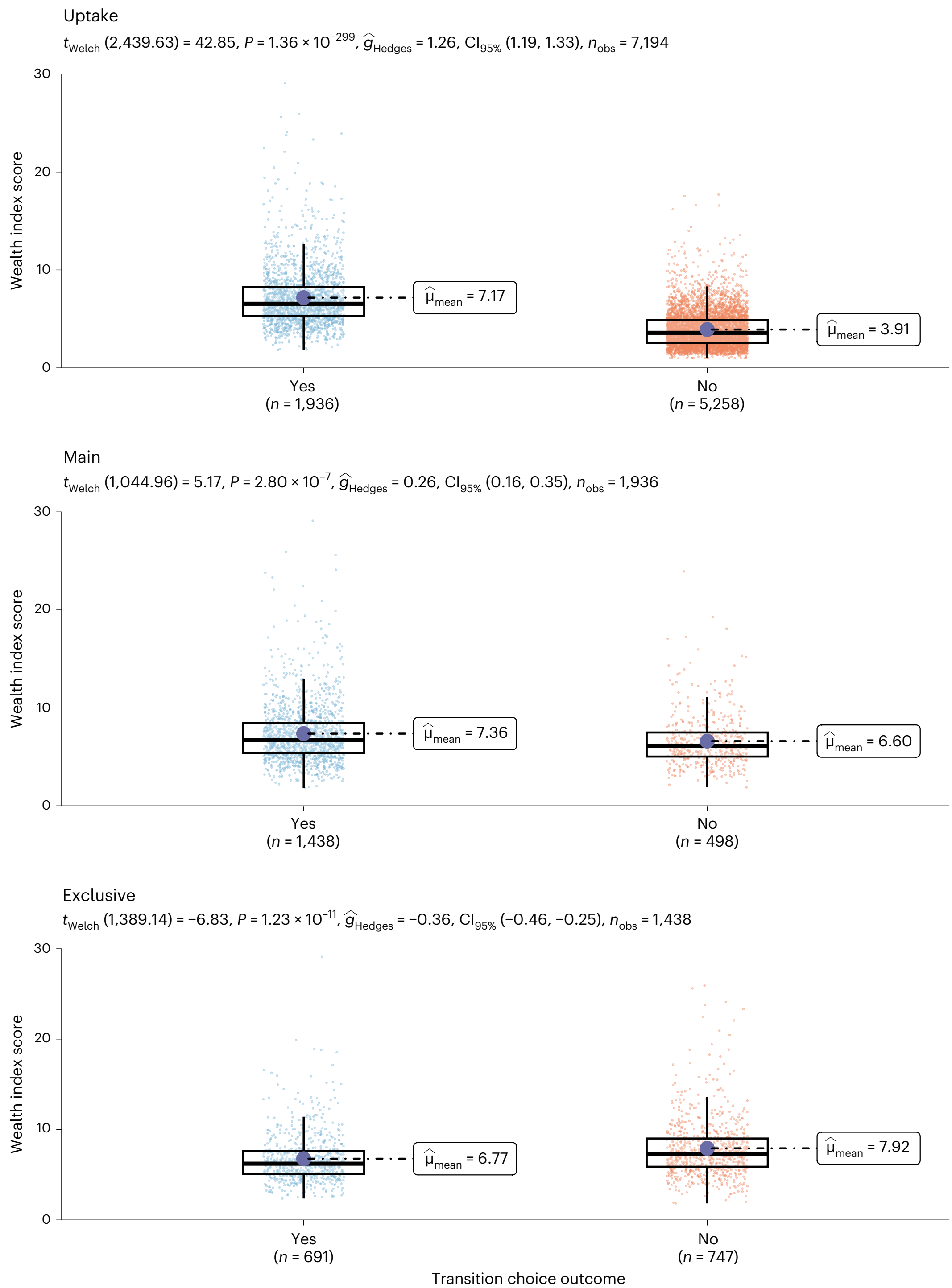

Fig. 2 | Wealth score distribution for the three transition choices. Boxplots show Uptake, Main and Exclusive transition choices. The *x* axis represents the outcome (success—yes/failure—no) for all three transition choices (uptake, main and exclusive), whereas the *y* axis represents the wealth index score of the sample households. Respondents with 'success' outcomes are indicated with blue dots, whereas those with 'failure' outcomes are yellow for each transition choice node. The shade of dots for uptake looks brighter due to the intensity—more respondents (points) per unit area. We show the Welch's two-sample two-way *t*-test to test the null hypothesis that the wealth index (predictor) between the two outcome (success/failure) distributions have equal mean for a given transition choice. For clarity on the difference across the transition choices in the plot, we have only displayed the wealth index scores up to 30 (maximum score is 48.705) without affecting the overall statistics for the figure. The boxplot centre line indicates the median value, and the box bounds indicate the 25th (Q1) and 75th (Q3) percentiles; IQR is the inter-quartile range or distance between the first and third quartiles (Q3 − Q1). The upper whisker extends from the hinge to the largest value no further than 1.5 × IQR from the hinge (Q3 + 1.5 × (Q3 − Q1)). The lower whisker extends from the hinge to the smallest value no further than 1.5 × IQR from the hinge (Q1 − 1.5 × (Q3 − Q1)). The boxplot centre lines, box bounds and whisker lower bound are not impacted by the display restrictions. The outcome group-wise average ($\hat{\mu}_{mean}$) and effect size (Hedge's *g*) $\hat{g}_{Hedges}$ are also shown. $CI_{95\%}$, 95% confidence interval.

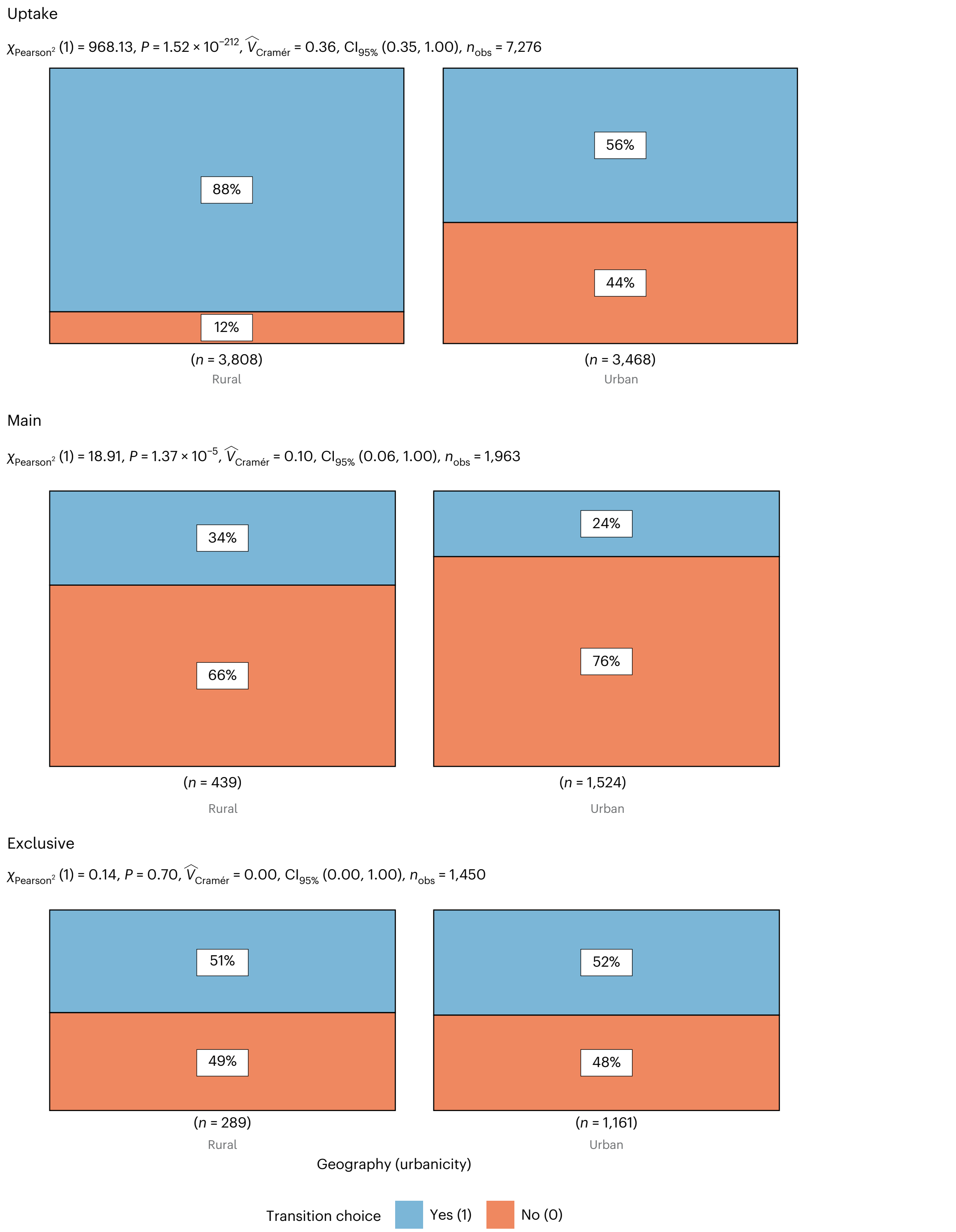

Fig. 3 | Urbanicity and LPG transition by transition choice. The x axis represents the urbanicity (rural/urban geography), whereas the stacked bars represent the proportion of respondents in a geography for all three transition choices (uptake, main and exclusive). The percentage of respondents with success (blue/1) and failure (yellow/0) and the Pearson chi-square test statistics ($\chi_{Pearson}2$) along with $CI_{95\%}$ are displayed. Cramér's V ($\hat{V}_{Cramér}$) denotes the strength of association.

causality mean that they are associations. In the conclusion, we discuss potential approaches to isolating causal relationships.

We have excluded two factors for transition choice 1 (LPG uptake) that are directly associated with LPG use: (1) the number of LPG burners (including zero, no stove ownership), which is only relevant for households using at least some LPG and (2) convenience accessing an LPG fuel point, which is relevant for households at stage 2 or beyond. For a detailed, additional discussion on the choice of independent factors and rationale for the exclusion of other cited factors, please refer to Supplementary Note 1.

A plot of wealth index of households across the three transition choices is shown in Fig. 2. We find that the mean wealth index score of respondents who reported success in uptake (moved to stage 2 or beyond) is 1.8 times ($P < 0.01$) higher than that of respondents who

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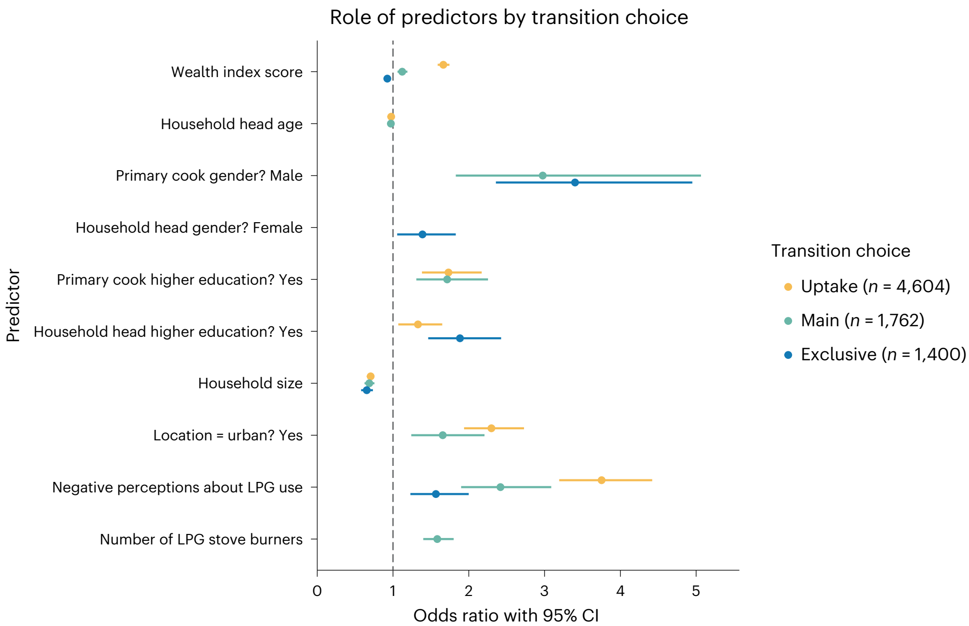

Fig. 4 | Role of predictors by transition choice. Coefficient plot for all three transition choices (Fig. 1) of LPG transition showing predictors that were found to be statistically significant for the three choices. The exp(Estimate) provides the odds ratio of the factor using the exponential of the estimate (coefficient value) of the binary logistic regression. The solid circles, or measure of centre, represent the odds ratio, whereas the horizontal lines show the $CI_{95\%}$CI around the odds ratio. The vertical dashed line is the line of 'no effect', corresponding to the value 1 for the null hypothesis that a given predictor has no impact on the transition choice outcome. Full model estimates are provided in Supplementary Figs. 4–6.

are at stage 1 (uptake failure). For the main transition choice, successful households (stage 3 or higher) still score higher ($P < 0.01$) than unsuccessful households (stage 2), but the gap in wealth index scores is considerably narrower. In contrast, this pattern is reversed for the exclusive choice node: the average household wealth index score is lower ($P < 0.01$) among households in stage 4 (exclusive = 1) than in stage 3 (exclusive = 0).

We also find that 12% and 44% of rural and urban respondents respectively report success in the uptake choice node (Fig. 3). The urban–rural gap ($P < 0.01$) persists in the main choice node with 66% and 76% of rural and urban respondents reporting success, but the gap narrows. However, there is no statistically significant urban–rural gap for the outcome of the exclusive transition choice node. It should be noted that while the sample size of total urban and rural respondents in the survey is roughly equal for uptake, the number of urban households is 3.5 and 4 times more than rural at the main and exclusive transition choices respectively. Variance in transition choice by both wealth index and urbanicity is provided in Supplementary Fig. 1.

The coefficient plot for binary logistic regression for the three transition choices is plotted in Fig. 4, showing only factors that significantly predict transition odds ($P < 0.05$). The figure shows the odds ratio, with exp(Estimate) equal to the exponential coefficient estimate (log odds) from the regression. In line with our hypotheses, we find that the relationship between factors and transition outcomes differ across the three transition choices, both in magnitude and sign. Overall, seven, eight and six factors out of 13 are predictive (statistically significant, $P < 0.05$) of the uptake, main and exclusive transition choices, respectively, as shown in Fig. 4. Notably, only three factors (out of 12) are predictive of all three transition choices. (1) Household size is predictive of all three transition choices in a consistent way: smaller households are more successful in all transitions and with a similar magnitude across the three transition choices. (2) LPG disadvantage perception score is consistently predictive, though the magnitude of the relationship diminishes along the transition path. (Note, a higher 'disadvantage perception score' is scaled such that a higher score is associated with less weight on the disadvantages of LPG.) (3) The wealth index is predictive of all three choices, but the direction of the relationship is inconsistent across transitions. It is a positive predictor (driver) only for the uptake and main nodes. As a result, we are left with only two factors (family size and disadvantage perception score) of the initial 13 that have consistent predictions (statistically significant and in the same direction) for the three transition choices. Only family size is also consistent in magnitude. Notably, factors that predict transition odds for at least two transition choices do so progressively (uptake and main or main and exclusive) except the household head's higher education, which predicts transition odds in the uptake and exclusive choices, but not in the main choice node. Also, three factors do not significantly predict any of the three transition choices: age of the primary cook, the strength of positive perceptions about the advantages of LPG use and the level of convenient access to LPG.

Discussion

Whereas the transtheoretical model of change (and its variants) has been widely used in other development and social psychology domains, its direct application has been limited in the clean-cooking space. At the same time, past research has highlighted the value of viewing progress as stage-based in nature (for example, Herington et al.[46]). Stage theories in behavioural sciences, such as the transtheoretical model, advocate that behaviour change is a multi-stage process wherein perceptions across stages are distinctly different; stage theory proponents recommend stage-specific interventions to target relevant perceptions to move people from one stage to another in a process of behaviour change[47,48]. Applications ranging from smoking cessation to mammography screening have shown the utility of stage-specific interventions that target stage-relevant factors over generic interventions[48].

Our data and analysis show that in Ghana, household and environmental factors are associated with LPG transitions in ways that depend on the transition stage. Hence, we argue that decomposing the cooking energy transition into stages when assessing drivers and barriers to LPG uptake and use is important for policy design. Keeping in

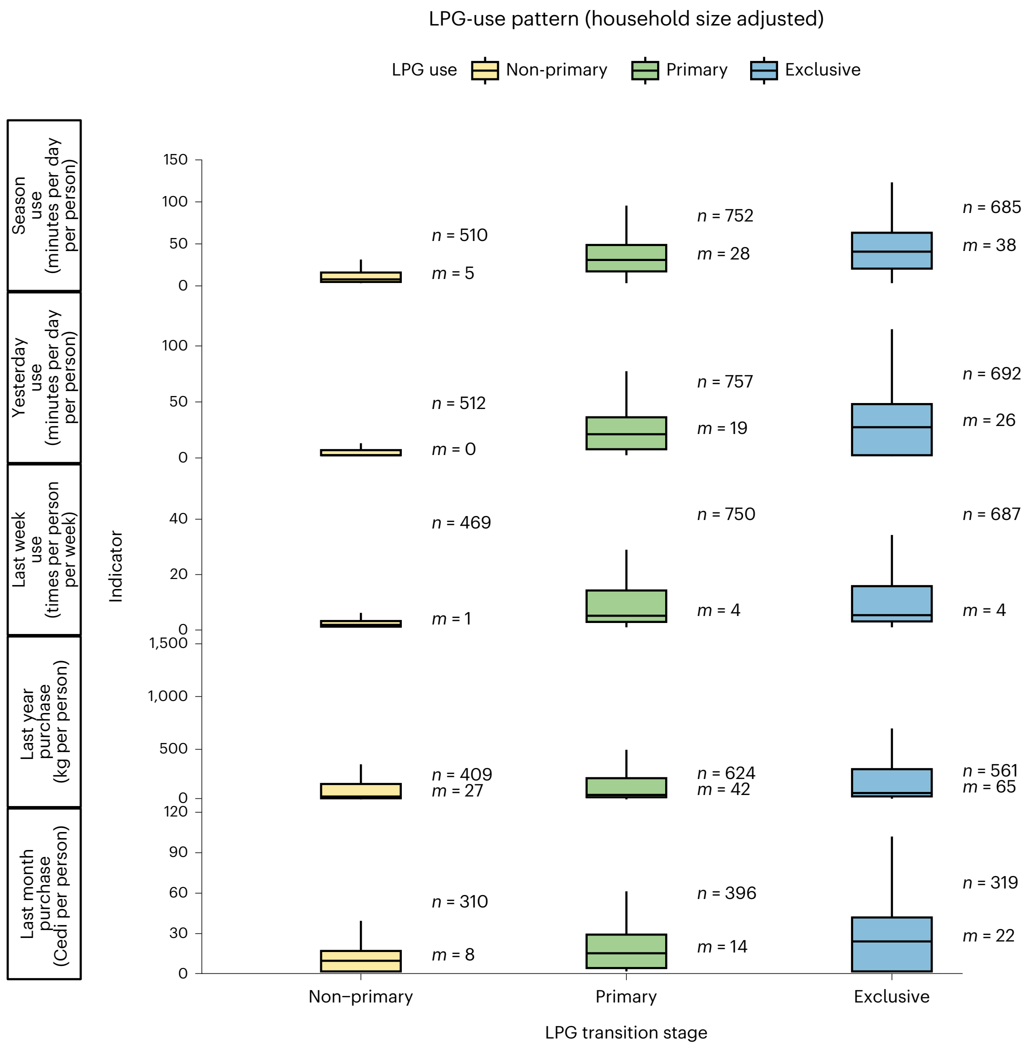

Fig. 5 | Qualitative response versus quantitative responses. The median value (*m*) and sample size (*n*) are shown for each indicator for each of the three transition stages for LPG users. Whereas *m* and *n* values are calculated for all respondents, for plotting boxplots we use a modified dataset. Modified boxplots with outliers removed (>99 percentile) are presented for visual clarity without impacting statistics of the overall data. The boxplot centre line indicates the median value, and the box bounds indicate the 25th (Q1) and 75th (Q3) percentiles; IQR is the interquartile range or distance between the first and third quartiles (Q3 − Q1). The upper whisker extends from the hinge to the largest value no further than 1.5× IQR from the hinge (Q3 + 1.5 × (Q3 − Q1)). The lower whisker extends from the hinge to the smallest value no further than 1.5× IQR from the hinge (Q1 − 1.5 × (Q3 − Q1)).

mind the caveat that the relationships we have measured are not necessarily causal in nature, we discuss two main implications of this transition framework for the design of clean-cooking interventions.

First, households at a given stage should be targeted with interventions that are stage-specific in nature. Currently, most policy approaches are either focused on the uptake transition (for example, subsidies for stoves) or are generic in nature (for example, information campaigns)[49]. We propose that future programmes should aim to capture stage-specific drivers of and barriers to clean-cooking energy transitions and design interventions accordingly. For example, we find that at transition choice 1 (uptake), negative sentiments about LPG significantly predict transition success (higher success with lower negative sentiment), but positive sentiment does not. This is consistent with general principles of prospect theory in which losses outweigh gains[50]. Hence, targeting negative perceptions related to safety concerns via a behavioural intervention package may be more useful than promoting positive messaging about LPG's benefits for households at transition stage 1[14]. We view this as a promising area for future research, given the prevalence of behaviour change campaigns based around various forms of messaging.

Second, utilizing knowledge about stage-specific predictors can help target those most likely to succeed. For example, factors such as age or household size are fixed on the timescale of cooking interventions so cannot themselves be manipulated to increase the likelihood of successful transition; however, they may be utilized to identify the groups more or less likely to transition. Specifically, targeting groups associated with successful stage transitions can improve the likelihood that other interventions (for example, information or subsidies) are successful. For example, Guta et al. suggest that the higher education of the primary cook predicts LPG adoption[18]. We observe that while education predicts success in the uptake and main transitions, its role in the exclusive transition is not statistically significant. Considering this finding, targeting households for a successful outcome at uptake and main might do better by focusing on households where the primary cook has higher education. However, for a programme wishing to increase exclusive use, the primary cook's education may not be a suitable targeting criterion from a resource-prioritization perspective.

Our findings suggest that out of 13 factors analysed, only four are statistically significant predictors of the exclusive transition, that is, are significantly and positively associated with the success of transitioning from primary to exclusive LPG use. These are: gender and education of the household head, gender of the primary cook and the negative perception score. None of the three can be feasibly manipulated within the scope of short- to medium-term clean-cooking interventions. Moreover, clean-cooking interventions explicitly aiming for exclusive LPG use are—according to our descriptive analysis—most likely to succeed if they target households with primary LPG use and the following characteristics: a family size of less than two (standard) adults, a female head of household, a household head with higher education and/or a male primary cook (Fig. 4). Unfortunately, these characteristics do not represent a substantial percentage of Ghanaian households. Among the respondents with a primary cookstove, the median family size is 2.8 (standard adult), 38% of all surveyed households were female-headed, 24% of household heads have higher education and 10% of households have a male primary cook (Table 2). Hence, there is a poor alignment between predictors of exclusive use and the average household socio-demographics. This leaves the perception score as a potential area of focus; behavioural campaigns to change perceptions of LPG may be critical to a successful transition from primary to exclusive use.

The analysis of differentiated predictors in the transition process hinges on the self-reported level of LPG use, which allows households to be classified according to transition stage (Fig. 1). This is a self-reported qualitative variable that has at least two accuracy-related risks. One, it is subject to social desirability and other sources of bias: a respondent may over-report LPG use to an 'outsider' surveyor to 'look good'[51]. Similarly, other biases and heuristics can influence responses, either intentionally or unintentionally[52]. Two, the interpretation of 'main' or 'primary' cooking technology may be ambiguous when a household stacks multiple fuels. Different respondents may perceive these labels differently. For example, primary use may represent the stove that burns for the most time (cooking time), has the greatest number of unique cooking instances (start/stop instances), cooks the most food or incurs the highest (time or monetary) cost for fuel. These measurement challenges are not limited to this study. Several international organizations track 'primary' or 'main' stove/fuel choices. For example, the United Nations Sustainable Development Goal 7.1.2 refers to the 'population with primary reliance on clean fuels and technologies'; the use of the word 'primary reliance' can be interpreted in multiple different ways[1].

Cross validating the accuracy of response at the household level is difficult. The survey we analyse undertook the following approach: respondents were first asked to qualitatively assess their LPG use level. On the basis of this, the surveyor followed up with five quantitative questions about LPG use. We map the qualitative question (level of LPG use) to the five different quantitative questions, asked across multiple recall structures: (1) use (seasonal and yesterday), (2) use (minutes per day), (3) frequency of use (times per week), (4) LPG purchase (kg per year) and (5) LPG purchase (Ghana Cedi per month). For an individual household, these responses may be subject to recall bias and depend on the respondent's memory. At the same time, particular sources of bias are likely to cancel out across them and the detailed information also allow us to validate the qualitative self-assessed stage. We find reasonable consistency between quantitative measures of LPG use and the qualitative assessment (Fig. 5); across all quantitative measurement frames, the self-assessed stage increases monotonically. This provides reasonable assurance on the overall consistency of respondents' self-assessments of the stage of transition. (Correlation plots across the five indicators are presented in Supplementary Fig. 3).

Conclusion

Our analysis relies on the largest (n = 7,389) national-scale survey of clean-cooking fuels and preferences in Ghana. The data present two major advantages over most existing data sources. First, the survey questions captured LPG use patterns at a finer resolution (exclusive to tertiary) than do most large-scale surveys, which measure only an indicator for whether LPG is the primary fuel. Responses to the questions facilitated the development and use of a stage-based transition approach to identify factors that predict different stages of the clean-cooking energy transition process. Second, the sample included 685 exclusive LPG users, which allowed analysis of disadoption of solid fuels, that is, the transition to exclusive LPG use.

This study depends on self-reported LPG use and other survey-based measures. Past research has shown that self-reported data during surveys administered by 'outsider' surveyors can suffer from biases[51]. We minimize these biases by avoiding quantitative metrics on LPG use in the main analyses, as these have a higher scope for measurement error[41]. Furthermore, because household decision-making is a complex and dynamic process, cross-sectional survey-based analyses and modelling may miss out on important nuances that are better captured with qualitative methods or longitudinal study designs. An important limitation of our data is its cross-sectional nature, which means we observe differences in factors across transition choices but do not observe the transitions (that is, changes over time) themselves. Drawing conclusions about the causal effect of household and contextual factors on clean-cooking energy transitions, for example, requires exogenous variation in a factor of interest, which may be best obtained with an experimental design or with panel data that allow for the measurement of changes in cooking technology and practices.

Like other case studies, the generalizability of our findings is limited to our study setting. In our case, however, this limitation is somewhat mitigated by the national scale of our data and the importance of Ghana as a representative country in the clean-cooking energy transition. We also, by restricting our analysis to data from a household survey, do not consider factors such as climate and geography that may shape fuel choice decisions. For example, in colder climates, households may prefer traditional stoves for the heat they generate[53]. In any household cooking energy decision, numerous societal, environmental, regulatory, community-scale, household-level and individual-level factors are intertwined. Consequently, our literature review-based set of independent variables almost certainly omits important determinants of the transition stages, and variables may interact in ways that are beyond the scope of our straightforward analyses. We also note that while we have not explicitly focused on gender in our analysis (in part because 90% of our respondents were women), the standing of the primary cooks within the household decision-making structure also plays an important role. For example, the time and energy from cleaner fuels may only translate into cooking energy choices when women are empowered to make decisions and pursue economic and educational opportunities[54].

This study presents evidence that observable household and community factors display different associations with cleaner cooking at different stages of the clean-cooking energy transition process. In contrast with prior work, we find that all else equal, wealth and urbanicity are not associated with exclusive clean-fuel use. We propose a stage-based intervention strategy and targeting approach that could improve the cost effectiveness of clean-cooking interventions.

Methods

The research proposal was approved by the Institutional Review Boards (IRB) of Columbia University, Kintampo Health Research Centre and the Ghana Health Services. The survey was designed by an interdisciplinary team of the authors listed in the paper and representatives from the Ghana Statistical Service, Government of Ghana.

Measurement and analysis framework

We aim to evaluate the association of observable factors (listed in Table 2) with outcomes (success or failure) at each transition choice node (Fig. 1). To elaborate, for each transition choice node associated with a given stage, we have two possible outcomes: success is defined as 1 (desired progress to any higher stage) and failure as 0 (remain at the given stage). Importantly, each transition choice includes only the immediately adjacent lower stage (associated with failure) and all higher stages (associated with success). For example, for the second transition choice (main) we omit households where there is no LPG uptake (stage 1). At this choice node, those at stage 2 are categorized as failure (= 0) whereas all households in stages 3 and 4 are counted as a success.

We test following hypotheses:

1. The set of statistically significant ($P < 0.05$) predictors are not the same for all three transition choices.
2. When a factor is a statistically significant ($P < 0.05$) predictor of success in more than one transition choice, its effect size (Hedges's g) is not the same across transition choices.

First, we conducted descriptive analyses to demonstrate how observable factors vary when respondents are grouped by transition stage. We also visually examined the role of the two most cited predictors of cooking energy transitions: household wealth index and urbanicity. (Plots for the other 11 predictors are available in Supplementary Note 4). Household wealth or its proxy variables are often cited as the most important factor for clean-fuel transitions because an LPG purchase requires a market transaction[18,23,30]. Wealth index development is detailed in Supplementary Note 5. Past studies also highlight the importance of urbanicity for access to LPG and lack of access to firewood[18,30]. Second, we conducted binary logistic regression for each of the three transition choices. When the probability of success is p for a given choice node, the odds of success are $p/(1-p)$ for a respondent. We refer to factors whose coefficients (b_k) are statistically significant ($P < 0.05$) as having strong association or being a significant predictor for a given choice node. The transition odds are defined as the odds of success for a given factor, calculated as $\ln(b_k)$. If there are k predictor variables for a given choice node, X_1 to X_k, then we can calculate the log odds of the probability of success by the following equation with error term e:

$$\ln\left(\frac{p}{1-p}\right) = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \cdots + b_kX_k + e$$

Data collection

A consortium of researchers from the 'Combating Household Air Pollution (CHAP)' study conducted a nationwide survey focused on household energy use in Ghana.

The survey was administered in person by trained enumerators to 7,389 households across all 16 administrative regions of Ghana. Sampling relied on the Ghana Statistical Service's enumeration areas (EAs), which are used for collecting Ghana's national census data and often borrowed as a national sampling frame for other surveys. We sampled 20 households per EA across 370 (urban: 177; rural: 193) EAs to arrive at the target sample size of ~7,400 households. The minimum sample size of 370 EAs was estimated with the following sampling parameters: confidence level (95%), design effect ($D = 1.5$), estimated proportion ($p = 0.50$, in absence of past data), error ($e = 5\%$) and strata (urban/rural). We have not weighted our analyses, following the guidance of Deaton[55]. The survey was carried out between 19 February and 27 March 2021. Surveys were administered to the adult primary cook in a household. Surveys were done in the respondents' households using Android tablets and Open Data Kit software. Additional details on the survey design and implementation, detailed in the field manual, are available on request[56].

The data analysis was carried out in R version 4.1.2 using RStudio[57]; 68 other packages were also used (please refer to ref. 58 for individual package version and codes along with output tables and plots). Incomplete data and recording errors (for example, physically impossible to have more than 24 cooking hours in a day) were removed for specific indicators. However, no other removal of outliers was carried out. However, for visual clarity in some figures, we have removed the outliers but retained their summary statistics, as indicated in figure legends. For regressions related to a given transition choice node, incomplete responses, that is, where valid responses for all the questions related to the predictors were not available, were dropped to allow for advanced statistical tests.

Ethics statement

Ethical approval for this study was obtained from the Institutional Ethics Committees at the Kintampo Health Research Centre (KHRCIEC/2020-5), Ghana Health Service Ethics Review Board (GHS-ERC:003/03/20) and the Institutional Review Board of Columbia University (IRBAAAS8293). All respondents provided their written, fully informed consent, and participation remained voluntary. By holding interviews in settings free from outside distractions and in which respondents felt at ease, privacy and secrecy were further guaranteed. A digital copy (photo) of the participant's written informed permission was taken and uploaded alongside the interviews. No compensation was provided to survey respondents.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The anonymized household survey data and shape files used for data analyses are available at https://doi.org/10.6084/m9.figshare.20124173 (ref. 58).

Code availability

The html of the codes and outputs (figures and tables based on survey data) used for data analyses are available at https://doi.org/10.6084/m9.figshare.20124173 (ref. 58).

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Author contributions

A.K. conceptualized theoretical framework, led survey design, performed data analysis and wrote the paper. T.T. contributed to survey design, data collection and paper preparation. L.G. contributed to data analysis and paper preparation and revisions. G.O.-A. contributed to survey design, data analysis and paper preparation. M.D. contributed to survey design, data analysis and paper preparation. F.M. contributed to survey design, data analysis and paper preparation. S.C. contributed to survey design and paper preparation. E.E.H. contributed to paper revisions. S.I. contributed to survey design, data collection and verification. E.A.A. contributed to survey design, data collection and verification. R.T. contributed to survey design, data collection and verification and led data cleaning. S.A. contributed to survey design, data collection and verification and contributed to data cleaning. K.J. conceptualized the project, contributed to theoretical framework, survey design, data analysis, paper preparation and led paper revisions. S.W.A. contributed to survey design, led data collection and verification and contributed to data analysis and paper preparation. D.J. conceptualized the project and contributed to theoretical framework, survey design, data analysis and paper preparation and revisions. K.P.A. conceptualized the project, contributed to theoretical framework, survey design, data analyses, paper preparation and oversaw the administration of the project.

Competing interests

The authors declare no competing interests.

Additional information

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☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

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Software and code

Policy information about availability of computer code

Data collection	Open Data Kit (ODK)- an open source data collection software was used in Android tablet to record and upload survey response data on a real-time basis
Data analysis	The data analysis was carried out in R version 4.1.2 using RStudio; 68 other packages were also used (please refer to the linked .html file for individual package versions, codes, output tables, and plots available in the Figshare weblink: https://doi.org/10.6084/m9.figshare.20124173).

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Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	Gender of the primary cook was recorded as per self- assessment of the respondent. Overall, 90% of primary cooks identified as Female and rest as male.
Population characteristics	Available details provided in the section: 'Behavioural and social sciences study design'
Recruitment	From Ghana Statisitical Service designated enumeration areas (EAs) , list of urban and rural EAs randomly chosen by a team from Kintampo Health Research Centre, Ghana Health Service, Government of Ghana . The team approached local community leaders and after briefing them about the scope of the study, the survey team approached households randomly, sought permission, received consent and then proceeded with the survey immediately. By holding interviews in settings free from outside distractions and in which respondents felt at ease, privacy and secrecy were further guaranteed. All respondents provided written, fully informed consent, and participation remained voluntary.
Ethics oversight	Ethical approval for this study was obtained from the Institutional Ethic Committees at the Kintampo Health Research Centre (KHRCIEC/2020-5), Ghana Health Service Ethics Review Board (GHS-ERC:003/03/20) and the Institutional Review Board of Columbia University (IRBAAAS8293).

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☒ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Quantitative cross-sectional survey to identify significant predictors of transition from solid to clean fuels across stages
Research sample	7,276 (urban: 3,468; rural: 3,808) primary cooks of households in Ghana with median age of 37 years. Primary cooks are best placed within a household to respond to questions around cooking fuel choices and have been surveyed in similar past studies. The sample design was constructed by Kintampo Health Research Centre (KHRC) under Ghana Health Service,Government of Ghana) in collaboration with the Ghana Statistical Service (GSS), Government of Ghana to be nationally representative, but as stated in the data collection section of the paper the analysis presented here does not use survey weights.
Sampling strategy	Stratified sampling in 370 Enumeration Areas (EAs) covering all 16 regions in Ghana as per suggestions from Ghana Statistical Service. We assumed 80% response rate with the sample size of 461 households per EA. The total target HH size was 7, 376 (461 x 16). Once the threshold was crossed, it was decided to stop the survey. Overall, data for 7,389 households were collected by survey team at KHRC and transmitted to the larger set of collaborators under the CHAP study (listed as authors) for further analyses. No qualitative data was analysed for this paper.
Data collection	Android tablet with ODK platform was used. We only captured response from adult primary cook in a household at household doorstep. While studies in the Global South have observed presence of other family members or neighbours, particularly in rural areas, no such data has been collected during the study. The surveyors were neither aware of the conceptual framework nor about the statistical tests planned for the data analyses
Timing	The survey was carried out between 19 February and 27 March 2021
Data exclusions	We received data of 7,389 households from Kintampo Health Research Centre (Govt. of Ghana Health Service). However, only 7,276 (urban: 3,468; rural: 3,808) households (98.5%) in the survey reported their primary cook stove (which was critical information for any form of data analyses). So, we used data from 7,276 households with no other data exclusions for data analyses. For regressions related to a given transition choice node, incomplete responses, i.e., where valid responses for all the questions related to the predictors were not available, were dropped to allow for advanced statistical tests. No other data exclusion were carried out such as outlier management.
Non-participation	Designed for participation rate of 80%
Randomization	Enumerators were trained to do random cross-walks in the communities within EA as is the norm for random surveys in developing countries.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging