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Why rising charcoal prices fail to drive clean cooking transitions: evidence from urban Malawi

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The transition to clean cooking energy remains a major challenge in low-income countries, where reliance on biomass fuels persists despite increasing policy attention and rising fuel costs. In urban Malawi, this study analyzes the determinants of cooking fuel transition using 2024 household survey data from 1,613 households across four major cities (Lilongwe, Blantyre, Mzuzu, and Zomba). A multinomial logistic regression model was applied to estimate three outcomes: exclusive biomass use, energy stacking, and clean fuel adoption. Results show that despite substantial increases in charcoal prices, biomass remains dominant, used by 82.8% of households. Charcoal price is positively associated with movement away from exclusive biomass use, but the effect is stronger for energy stacking ($\beta = 0.842$) than for clean fuel adoption ($\beta = 0.215$), indicating partial rather than full transition. Economic factors, particularly affordability ($\beta = 0.963$) and household income ($\beta = 0.785$), are the strongest predictors of clean fuel adoption. Market access plays a crucial role in the adoption of clean fuels, as evidenced by the positive impact of LPG availability ($\beta = 0.854$) on usage. Conversely, greater distance to suppliers negatively affects adoption ($\beta = -0.902$). Additionally, behavioral factors such as cultural preferences ($\beta = -1.124$) and established energy stacking practices ($\beta = -1.356$) pose significant constraints to the transition. Furthermore, the interaction between charcoal price and income ($\beta = 0.742$) indicates varying responses among different income groups. These findings indicate that increasing charcoal prices primarily lead to energy stacking instead of a complete transition. This emphasizes the necessity for comprehensive policies that tackle issues of affordability, accessibility, and behavioral obstacles.

KEYWORDS
clean cooking, energy transition, household energy demand, LPG adoption, urban Malawi, willingness to pay

1 Introduction

1.1 Research background

Access to clean cooking energy continues to be one of the most enduring and complex obstacles in the global energy transition regardless of progress in improving access to electricity. In spite of decades of policy focus aimed at achieving universal energy access and technological progress, around 2.3 billion people worldwide still depend on traditional biomass fuels in the form of firewood, charcoal, and agricultural residues for their cooking needs (Bajpayee and Mohanty, 2025; Awan et al., 2026; Chen and Wang, 2026). Dependence on these polluting fuels poses significant consequences for environmental sustainability, human health, and socio-economic progress (Adjei-Mantey, 2024). Forests are being cleared for biomass fuel, emerging as a major contributor to deforestation and land degradation, especially in low-income countries where demand for charcoal and fuelwood is increasing alongside population expansion and urban growth (Atteridge et al., 2013; Dianda et al., 2025). As forests disappear, firewood is becoming scarce; as a result, women, who are tasked with cooking and collecting firewood, walk long distances and spend many hours collecting firewood, which exposes them to sexual exploitation and harassment (Anshori et al., 2026; Awan et al., 2026). Additionally, these women are denied time to engage in important income generation activities (Chen and Wang, 2026; Gill-Wiehl and Ray, 2026). Household air pollution caused by the inefficient burning of biomass fuels is linked to millions of premature deaths each year, with women and children bearing the greatest burden (Chen et al., 2024; Adjei-Mantey, 2024; Anshori et al., 2026; Atteridge et al., 2013; Awan et al., 2026).

Regardless, many developing countries are localizing global frameworks, such as Sustainable Development Goal 7 (SDG 7) and Sustainable Energy for All (SE4ALL), which seek to guarantee universal access to affordable, reliable, sustainable, and modern energy by the year 2030 (Anshori et al., 2026; Awan et al., 2026; Chen and Wang, 2026); advancement in clean cooking has fallen far behind the progress achieved in electricity access (Gupta et al., 2025; Adjei-Mantey, 2024; Gill-Wiehl and Ray, 2026). At a time when charcoal is becoming scarce due to deforestation and efforts by the governments to regulate charcoal production are failing to persuade households to shift to cleaner cooking fuels, it can be assumed that higher prices for traditional fuels will motivate households to shift to cleaner alternatives. This concept is based on neoclassical economic theory, which posits that households react rationally to market price changes by opting for alternatives that are perceived as more efficient or cost-effective (Doremus et al., 2022; Jiang et al., 2024). Yet growing empirical research indicates that such a price-induced transition is neither automatic nor adequate, especially in low-income settings, which are shaped by many factors, including structural barriers and market failures (Gill-Wiehl et al., 2026; Gould et al., 2026).

In Sub-Saharan Africa (SSA), cooking energy poverty is severe, and the region contains the largest share of the world's population without access to modern cooking energy, with more than 80% of households still dependent on solid fuels (Atteridge et al., 2013; Debebe et al., 2025a; Dianda et al., 2025; Gould et al., 2026). This dependence continues despite increasing recognition of the environmental degradation and health consequences associated with the use of biomass for cooking (Atteridge et al., 2013). In Eastern Africa, countries such as Kenya, Tanzania, and Uganda have made meaningful strides in expanding access to liquefied petroleum gas (LPG) and improved cookstoves through policy reforms, private-sector engagement, and donor-backed programs (Anshori et al., 2026; Mutlu et al., 2026). Even so, these relatively more developed markets have not achieved complete transition, as many households continue to practice energy stacking rather than fully switching to clean cooking fuels (Yadav et al., 2026). In Central Africa, countries such as the Democratic Republic of Congo (DRC) and Cameroon exhibit an even greater reliance on charcoal. This dependence is driven by weak infrastructure, limited institutional capacity, and abundant forest resources, which discourage households from transitioning to clean cooking fuels that are often available at a higher cost (IEG, 2015; Nlom and Karimov, 2015; Tshimungu et al., 2026). Likewise, in Southern Africa, countries including Zambia, Mozambique, and Malawi continue to depend heavily on biomass fuels, and in urban areas charcoal remains the dominant cooking fuel (Atteridge et al., 2013; Price et al., 2021; Sapnken et al., 2025).

Most of the developing countries are experiencing rapid urbanization, yet the development of key infrastructure, including energy, has not caught up with the increasing population in the urban areas (Gould et al., 2026). This unsustainable development has further increased charcoal demand, producing complicated supply chains that connect rural production areas to urban markets, often within informal or weakly regulated systems (Zheng, 2023). These processes contribute to rising charcoal prices, which are shaped by deforestation, transport expenses, and the enforcement of regulations.

Urban households in Sub-Saharan Africa are particularly important for understanding transitions in cooking energy. Compared to rural households, urban residents face shortages in biomass supply and higher prices due to deforestation in urban and peri-urban areas. However, they typically have greater access to modern energy alternatives, such as LPG, electricity, and ethanol-based fuels. Nevertheless, charcoal remains the fuel of choice because it is seen as affordable when compared with alternative cooking fuels and is considered to be more accessible and suitable for local cooking habits (Gurkan et al., 2026; Mandal, 2026; Tshimungu et al., 2026; Venegas-Vásconez et al., 2026). Even when charcoal prices rise, households often do not completely shift to clean fuels. Instead, they tend to adopt coping responses, such as lowering fuel use, moving to lower-quality fuels, or combining several fuels through energy stacking (Chen and Wang, 2026; Khosravi et al., 2026; Oluoch et al., 2026).

The persistence of energy stacking challenges the traditional energy ladder model, which depicts the household energy transition as a simple progression from biomass to modern fuels as household income increases (Mutlu et al., 2026; Tshimungu et al., 2026; Chen and Wang, 2026). Malawi offers a valuable setting in which to investigate these dynamics. Malawi is among the most biomass-reliant countries globally, with over 90% of households relying on firewood and charcoal for cooking (NSO, 2016, 2020). Urban centers such as Blantyre, Lilongwe, and Mzuzu exhibit high charcoal consumption due to limited access to alternative fuels and constraints in infrastructure. In recent years, Malawi has experienced substantial increases in charcoal prices, driven by pressures from deforestation, restrictions on supply, and implementation of forestry regulations under the National Charcoal Strategy (NCS) (2017). These price increases have often been viewed as a possible trigger for a transition toward cleaner fuels such as LPG (Mutlu et al., 2026; Tshimungu et al., 2026; Chen and Wang, 2026). Evidence from literature shows that household energy behavior is more accurately understood as a portfolio of fuel choices shaped by multiple influences, including income fluctuations, fuel availability, cultural preferences, and strategies for managing various emerging risks (Gill-Wiehl et al., 2026; Pillarisetti et al., 2026). From this perspective, it can be urged that increasing charcoal prices may not automatically translate to a full switch to clean fuels but instead to partial adjustments within a diversified energy mix.

Despite higher charcoal prices, uptake of clean cooking fuels in urban Malawi remains low. Existing literature reveals that affordability is a major challenge constraining adoption of clean and alternative cooking fuels, especially LPG, because it requires both an initial investment in equipment and continued spending on fuel refills (Babayomi et al., 2022; Chen and Wang, 2026; Gill-Wiehl et al., 2021;

Gill-Wiehl and Ray, 2026; Gill-Wiehl and Ray, 2026; Gould et al., 2026). At the same time, supply-side problems, such as limited distribution networks, high transport costs, and inconsistent LPG availability, further restrict access and hinder adoption (Venegas-Vásconez et al., 2026). Behavioral and cultural considerations are also important, as households may regard traditional fuels as better suited to certain cooking practices or may worry about the safety of LPG due to lack of awareness (Gunasegaran and Hasanuzzaman, 2025; Sapnken et al., 2025). In addition, the relationship between price and income is central to how households respond to rising charcoal costs. For low-income households, increases in charcoal prices may not encourage a shift to clean fuels but instead result in lower energy consumption or continued dependence on biomass that is of low quality, such as agricultural waste, which can also be accessed at no cost as long as modern cooking energy options are not affordable (Awan et al., 2026; Gill-Wiehl and Ray, 2026). For higher-income households, rising charcoal prices may make clean fuels more appealing, but this shift depends on the cost, availability, and reliability of supply (Lahnaoui et al., 2024; Shahid et al., 2025). These patterns underscore the need to account for variation in household responses to changing cooking energy prices on the market rather than assuming that all households react similarly.

Although the literature on clean cooking adoption has expanded, an important gap remains in understanding the specific effect of rising charcoal prices within a broader framework that incorporates economic, behavioral, market, and technological dimensions. Many studies use binary indicators of adoption, which do not adequately capture the transitional character of household energy use marked by energy stacking (Yadav et al., 2026). In addition, relatively little empirical research in Malawi has directly examined whether increases in the price of traditional fuels are enough to drive a shift to clean cooking. This study addresses these gaps by investigating why rising charcoal prices are insufficient to drive clean cooking transitions in urban Malawi. The analysis applies a multinomial framework to distinguish among three outcomes: exclusive biomass dependence, energy stacking, and complete adoption of clean fuels. The study offers a more comprehensive explanation of the barriers to clean cooking adoption through the inclusion of a broad set of explanatory factors, such as income, affordability, willingness to pay, market access, cultural preferences, and perceptions of technology.

We acknowledge that similar studies have been conducted in other Sub-Saharan African countries, including Zambia (Mukanema et al., 2026), Tanzania (Ntiyakunze and Stage, 2025), and Senegal (Rose et al., 2024), examining household energy transitions and fuel-stacking behavior. However, this study offers several important contributions. First, it focuses on urban Malawi, a context characterized by distinct charcoal market dynamics, energy access conditions, and policy frameworks. Second, it applies a multinomial modeling approach that differentiates between exclusive biomass use, energy stacking, and clean fuel adoption, thereby capturing a broader range of household energy transition pathways than studies relying on binary adoption measures. Third, it explicitly examines the interaction between charcoal prices and household income, revealing heterogeneous responses to price changes across income groups. Finally, the analysis integrates behavioral and technological perception factors with economic and market determinants, providing a more comprehensive understanding of household fuel-choice decisions. Collectively, these contributions advance the literature by offering deeper insights into the factors that constrain clean cooking transitions and explaining why rising charcoal prices alone are insufficient to drive sustained adoption of cleaner cooking fuels in low-income urban settings.

The study makes three main contributions to the literature. First, it provides empirical evidence that increases in charcoal prices tend to encourage energy stacking rather than a full transition, thereby challenging the idea that price signals alone can generate clean energy adoption. Second, it emphasizes the central importance of structural barriers, especially affordability and accessibility, in shaping household fuel choices. Third, it adds to the literature on energy transitions in low-income settings by showing the importance of integrating both demand-side and supply-side factors into policy design. These findings carry important implications for policymakers and practitioners working to accelerate clean cooking transitions in Malawi and comparable contexts. They indicate that interventions must extend beyond price-based approaches to address deeper systemic constraints, including expanding access to affordable finance, improving supply chains, and encouraging behavioral change. Without tackling these underlying barriers, increases in charcoal prices alone are unlikely to produce substantial reductions in biomass dependence.

1.2 Conceptual framework

This study is grounded in the energy stacking theory, which posits that households use multiple cooking fuels simultaneously rather than transitioning linearly from traditional to modern fuels (Nshimiyimana et al., 2025; Rose et al., 2024; Yenlide and Okey, 2024). In this context, cooking fuel transition is conceptualized as a three-category outcome: exclusive biomass use, energy stacking, and adoption of clean fuels such as LPG. Charcoal price is treated as the main trigger influencing household decisions; however, the framework assumes that rising prices alone are insufficient to drive full transition. Instead, households respond by adjusting their fuel mix depending on constraints. Economic factors (income, affordability, and willingness to pay) determine the ability to adopt clean fuels, while market factors (LPG availability and distance to suppliers) influence physical access. Behavioral factors, including cultural preferences and existing energy stacking practices, further reinforce continued biomass use, even when alternative fuels are available.

The framework further posits that technological perceptions (efficiency, convenience, and safety) and socio-demographic characteristics (education, household size, gender, and location) condition household preferences and adoption decisions. Importantly, the interaction between charcoal price and income captures differences in how households respond to rising fuel costs, with higher-income households more likely to transition compared to low-income households. Consistent with the energy stacking theory, the expected outcome is that rising charcoal prices primarily lead to energy stacking rather than full adoption of clean fuels unless affordability and accessibility constraints are addressed. This conceptualization directly informs the empirical strategy, where cooking fuel transition is modeled as a categorical dependent variable using a multinomial logistic regression framework. Figure 1 shows the conceptual framework.

The four cited sources inform specific components of Figure 1. Dai et al. (2025) provide evidence on how economic factors (digital economy, income) shape household fuel transitions in China. Janikowska et al. (2024) offer insights from European contexts on the interaction between energy poverty and policy interventions. Mandal (2026) demonstrates how technological perceptions influence LPG adoption in Nepal. Mukanema et al. (2026) contribute evidence on behavioral and socio-demographic determinants of clean cooking transitions in urban Zambia. Together, these sources justify the

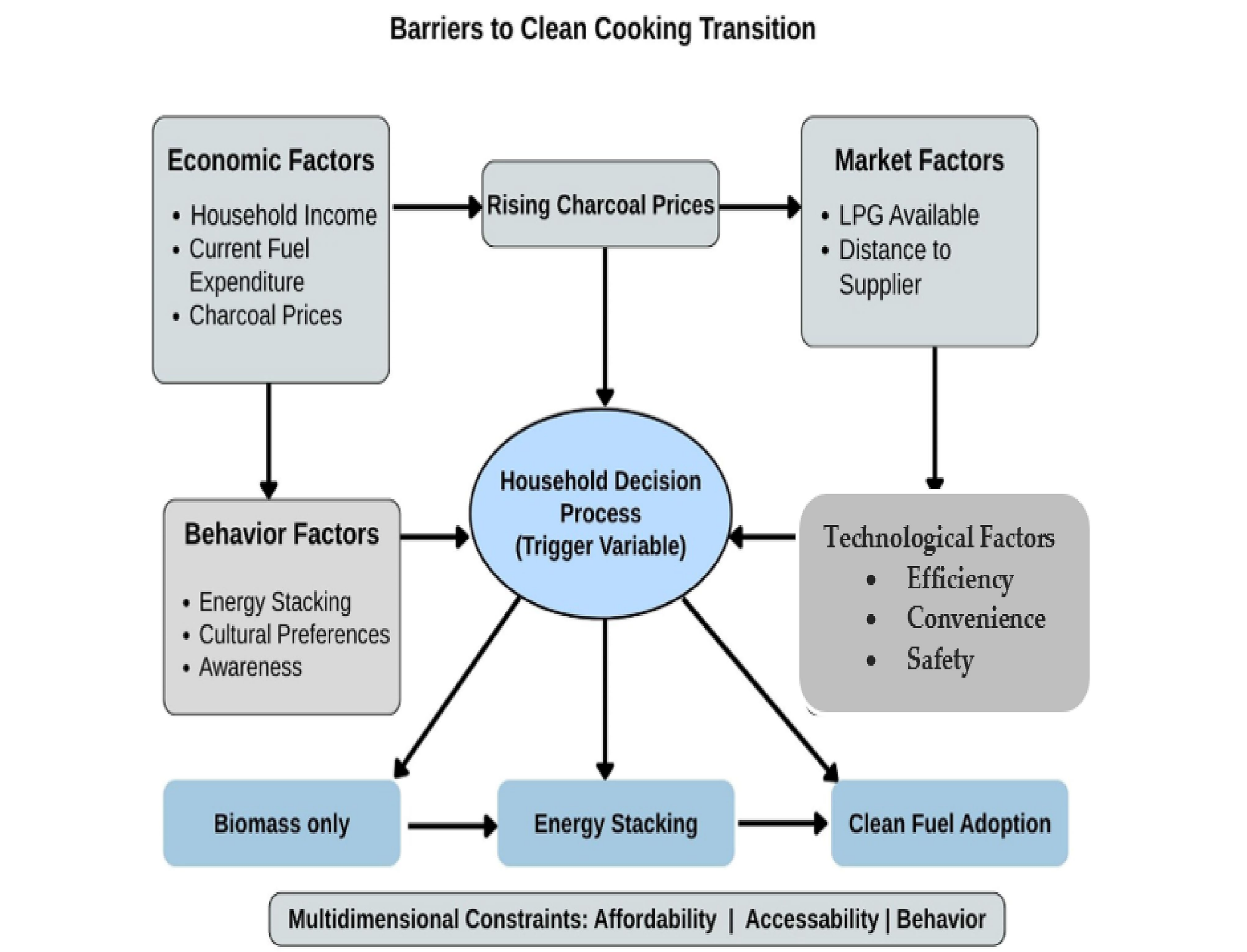

FIGURE 1
Conceptual framework adapted from the author's literature review based on Dai et al. (2025), Janikowska et al. (2024), Mandal (2026), and Mukanema et al. (2026).

inclusion of economic, market, behavioral, technological, and socio-demographic factors in our framework.

2 Methodology

2.1 Study area

This study was conducted in four major urban centers in Malawi, and these are Lilongwe, Blantyre, Mzuzu, and Zomba. These cities represent the country's primary urban agglomerations, characterized by rapid population growth driven largely by rural–urban migration. Each city exhibits distinct socio-economic conditions, yet all share a common heavy reliance on biomass fuels, particularly charcoal, for household cooking. These cities serve as central nodes in charcoal distribution networks linking rural production zones to urban demand. The diversity across these locations, varying levels of clean cooking adoption, fuel pricing dynamics, and infrastructural development provide a suitable context for examining how structural, economic, and behavioral factors interact to shape household energy stacking behavior and clean cooking transitions in urban Malawi. Figure 2 shows the study areas in Malawi.

2.2 Research design and data

The study adopted a quantitative cross-sectional research design using household survey data collected from urban Malawi during the 2024 Consumer Market Research (2024 CMR), with a focus on Lilongwe, Blantyre, Mzuzu and Zomba. The analysis focused on household cooking energy choices in contexts where charcoal was the dominant fuel but clean alternatives such as liquefied petroleum gas (LPG) were available. The unit of analysis was the household. A total of 1,613 households were included in the final sample after data cleaning and validation.

Households in each city were selected using a multi-stage stratified sampling design. Enumeration areas were first randomly drawn from official census lists, after which households within each selected area were systematically sampled using a random starting point and a fixed sampling interval. Prior to data collection, oral informed consent was obtained from each household head or primary cook following an explanation of the study objectives, voluntary participation, and confidentiality safeguards. Data were collected through face-to-face interviews conducted by trained enumerators using structured questionnaires administered on mobile devices. The household survey achieved a response rate of 87.3%, with non-response mainly attributable to refusals (8.1%) and the inability to contact eligible respondents after three visits (4.6%). The final sample comprised 1,613 households.

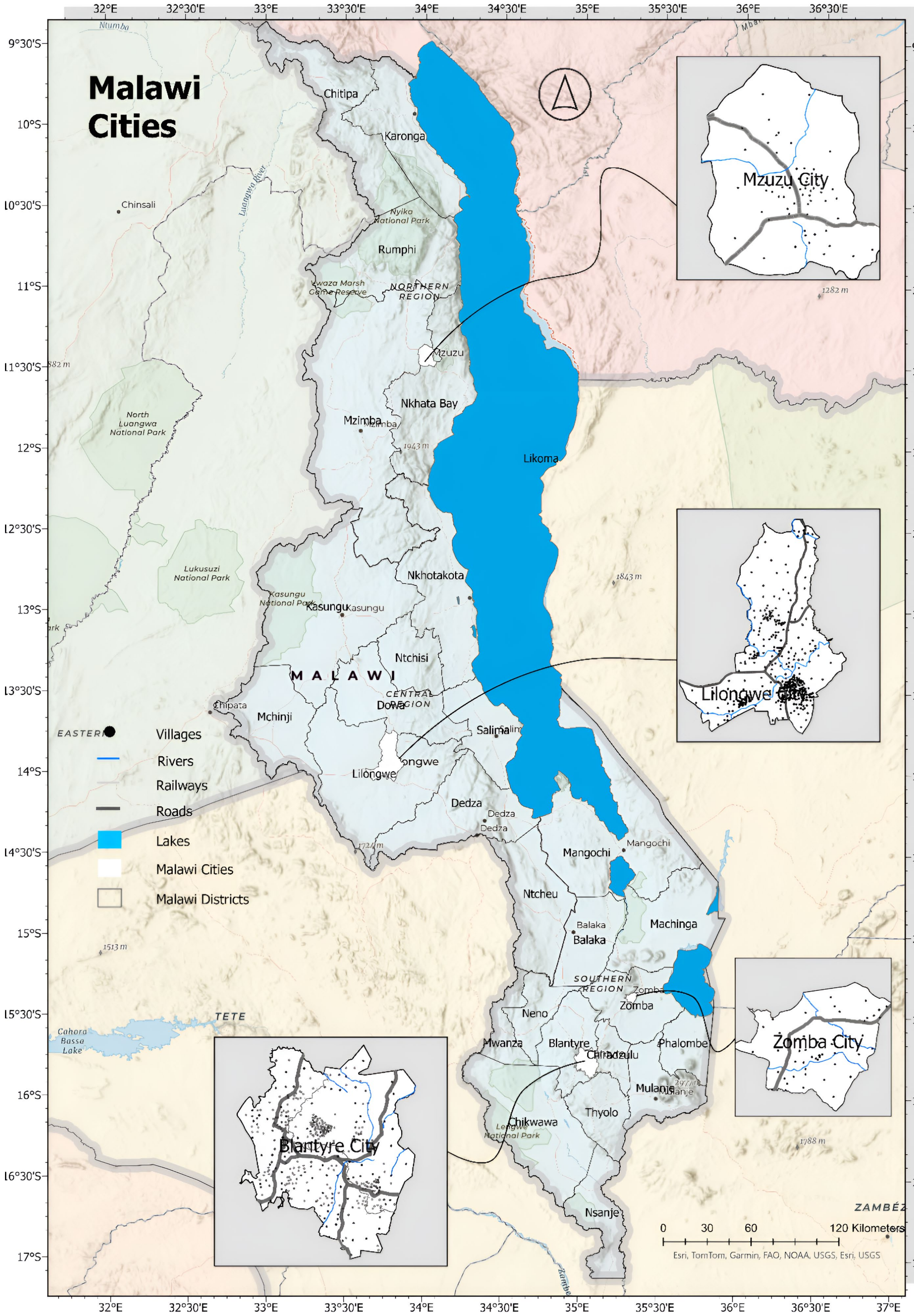

FIGURE 2
Map of Malawi showing study locations.

These respondents were entirely separate from the 225-348 charcoal sellers surveyed for the complementary market analysis, as the household and seller surveys employed distinct sampling frames, target populations, and data collection instruments.

Although this study is primarily cross-sectional, descriptive comparisons are made using data from a Consumer Market Research (CMR) survey conducted in 2022. The 2022 survey used the same sampling frame and questionnaire but surveyed a different sample of households (n = 1,512). Consequently, comparisons between the 2022 baseline and the 2024 survey reflect changes across two independent cross-sectional samples rather than the same households over time. All inferential analyses, including the multinomial regression and marginal effects, are based exclusively on the 2024 data.

2.3 Sampling design

A multi-stage stratified sampling design was employed to select households across the four urban centers. In the first stage, enumeration areas (EAs) were randomly selected from the official census sampling frame maintained by the Malawi National Statistical Office. Selection was stratified by city and socioeconomic status (low-, medium-, and high-income areas), using housing density and infrastructure characteristics as stratification criteria. A total of 120 EAs were selected, with 30 EAs drawn from each city. In the second stage, field enumerators conducted household listings within each selected EA to establish an updated sampling frame. Households were then selected through systematic random sampling using a randomly determined starting point and a fixed sampling interval based on the total number of listed households in each EA. The target sample size was 1,600 households (i.e., 400 households per city), which was determined to provide sufficient statistical power to detect a 10-percentage-point difference in clean fuel adoption at a 95% confidence level and 80% statistical power, assuming a design effect of 1.5. The final achieved sample comprised 1,613 households.

To ensure that estimates were representative of the urban populations in the four cities, sampling weights were calculated based on the inverse probability of selection at each sampling stage and applied in all descriptive and econometric analyses. Sampling weights are particularly important because the four cities differ substantially in population size, i.e., Lilongwe has approximately 1.1 million residents, while Zomba has approximately 105,000, yet each city was allocated a roughly equal number of households. Without weighting, households in smaller cities would be overrepresented relative to their share of the urban population. The constructed weights correct for this imbalance, ensuring that results reflect the actual population distribution across the four cities.

2.4 Variable specification

The dependent variable is cooking fuel transition, modeled as a categorical outcome with three mutually exclusive states: (0) exclusive biomass use, (1) energy stacking, and (2) clean fuel adoption. This classification reflects the energy transition pathway in household cooking practices, which typically occurs incrementally rather than through abrupt switching from traditional to modern fuels (Cellini et al., 2025; Medina et al., 2019; Mukanema et al., 2026; Sharma and Rahman, 2025; Sovacool and Geels, 2016).

To avoid conceptual overlap between variables, it is important to distinguish between the dependent variable classification and behavioral predictors. In this study, "energy stacking" in the dependent variable refers specifically to a household's current cooking fuel use status, defined by the simultaneous use of multiple fuels at the time of the survey. In contrast, the explanatory variable "habitual fuel stacking" captures a behavioral tendency toward the use of multiple cooking fuels over a broader reference period. Specifically, habitual fuel stacking was measured by asking respondents: "Over the past 12 months, how often have you used more than one type of fuel for cooking?" with responses recorded on a five-point scale (never, rarely, sometimes, often, always). This measure reflects generalized or habitual multi-fuel use over the preceding year, rather than the household's current categorical fuel status at the time of the survey. This temporal and conceptual distinction (i.e., current state versus past-year behavioral tendency) ensures that the explanatory variable is constructed independently of the dependent variable classification and eliminates concerns of tautological bias in the model.

The explanatory variables are constructed independently of the dependent variable and are grouped into economic, market, behavioral, technological, and socio-demographic constructs. Table 1 presents the variable definitions and expected signs.

TABLE 1 Variable definition and expected signs.

Variable category	Variable	Description	Expected sign
Dependent variable	Cooking fuel transition	0 = Biomass, 1 = Stacking, 2 = Clean fuel	—
Core variable	Charcoal price	Cost of charcoal per unit	+
Economic	Income	Monthly household income	+
	Affordability	Perceived affordability of LPG	+
	Willingness to pay	Maximum willingness to pay for clean fuel	+
Market	LPG availability	Availability of LPG in the area	+
	Distance to supplier	Distance to nearest LPG supplier	–
Behavioral	Habitual fuel stacking	Household's generalized tendency or frequency of using multiple cooking fuels over a defined reference period, independent of current cooking fuel transition status.	– / ±
Technological	Efficiency	Perceived efficiency of LPG	+
	Convenience	Ease of use of LPG	+
	Safety	Perceived safety of LPG	+
Socio-demographic	Household size	Number of household members	–
	Education	Education level of household head	+
	Gender	Gender of household head	±

City of residence is included as a set of dummy variables (fixed effects) to account for unobserved heterogeneity across locations. Lilongwe serves as the omitted reference category. The coefficients for Blantyre, Mzuzu, and Zomba therefore represent differences in cooking fuel transition probabilities relative to Lilongwe, holding other factors constant.

2.5 Econometric model

The study employed a multinomial logistic regression (MNL) model to estimate the probability that a household belongs to a particular cooking fuel transition category. The dependent variable *Yi* takes three mutually exclusive outcomes:

- *P* Y*i* = 0: exclusive biomass use (reference category)
- Y*i* = 1: fuel stacking
- Y*i* = 2: exclusive clean fuel use

Given household *i* and a vector of explanatory variables X*i*, the probability of observing outcome *j* is specified as:

$$P\left(Y_i = j|\mathrm{X}_i\right) = \frac{\exp\left(\mathrm{X}_i'\beta_j\right)}{\sum_{k=0}^{2}\exp\left(\mathrm{X}_i'\beta_k\right)}, \quad j = 0,1,2$$

Where:

- $P\left(Y_i = j \mid \mathrm{X}_i\right)$ is the probability that household *i* belongs to cooking fuel category *j*;
- $\times_i$ is a vector of explanatory variables, including household income, fuel prices, education, household size, location, and other socioeconomic characteristics;
- β_j is the vector of coefficients associated with outcome category *j*.

To identify the model, the coefficient vector for the reference category (exclusive biomass use) is normalized to zero (β_0=0) Consequently, the estimated probabilities for the non-reference categories are:

$$P\left(Y_i = j \mid \mathrm{X}_i\right) = \frac{\exp\left(\mathrm{X}_i'\beta_j\right)}{1+\sum_{k=1}^{2}\exp\left(\mathrm{X}_i'\beta_k\right)}, \quad j = 1,2$$

And the probability of the reference category is:

$$P\left(Y_i = 0 \mid \mathrm{X}_i\right) = \frac{1}{1+\sum_{k=1}^{2}\exp\left(\mathrm{X}_i'\beta_k\right)}$$

To account for heterogeneous responses to fuel price changes, an interaction term between charcoal price and household income was included among the explanatory variables.

2.6 Hypotheses

The study tested six hypotheses derived from the conceptual framework:

- H1 (price effect): rising charcoal prices increased the likelihood of transitioning away from exclusive biomass use but did not necessarily lead to full adoption of clean fuels.
- H2 (economic constraints): economic factors (income, affordability, and willingness to pay) positively influenced the likelihood of clean fuel adoption.
- H3 (market accessibility): market factors (LPG availability and proximity to suppliers) increased the likelihood of clean fuel adoption.
- H4 (behavioral constraints): behavioral factors (cultural preferences and energy stacking practices) reduced the likelihood of full transition to clean fuels.
- H5 (technology perception): positive perceptions of clean cooking technologies (efficiency, convenience, and safety) increased the likelihood of adoption.
- H6 (interaction effect): the effect of charcoal price on clean fuel adoption was moderated by household income, such that higher-income households were more responsive to rising charcoal prices compared to lower-income households.

2.7 Addressing potential endogeneity

While the multinomial logistic regression provides useful insights into associations between household characteristics and cooking fuel transitions, potential endogeneity may affect causal interpretation. This section briefly outlines key concerns and robustness checks undertaken.

2.7.1 Sources of endogeneity

Three main sources of endogeneity are considered. First, reverse causality may arise, particularly for household income, which may both influence and be influenced by clean cooking adoption through fuel cost savings, leading to potential upward bias in its estimated effect. Second, omitted variable bias may occur due to unobserved factors such as environmental awareness, risk preferences, or local policy interventions that jointly influence both fuel choices and key regressors such as willingness to pay, prices, and access. Third, self-selection may bias estimates because households are not randomly assigned to income levels, fuel prices, or LPG availability, and may instead sort into locations consistent with their energy preferences.

2.7.2 Robustness and analytical approach

Given the cross-sectional nature of the data, causal identification is not claimed and results are interpreted as associations. However, robustness checks were conducted to assess sensitivity to potential endogeneity.

Given the cross-sectional nature of the data, causal identification is not claimed and results are interpreted as associations. However, robustness checks were conducted to assess sensitivity to potential endogeneity. An exploratory instrumental variable approach was implemented for charcoal price using distance to charcoal production areas as an instrument; results are broadly consistent but are treated as suggestive due to data limitations. Similarly, propensity score matching (PSM) was applied to compare clean fuel adopters and non-adopters with similar observable characteristics; the estimated ATT aligns with the main findings, indicating limited bias from observable selection. Overall, while these checks support the robustness of the results, potential bias from unobserved confounders and reverse causality cannot be fully ruled out. Therefore, the findings should be interpreted as associational rather than causal, and policy implications are framed accordingly.

Overall, while these checks support the robustness of the results, potential bias from unobserved confounders and reverse causality cannot be fully ruled out. Therefore, the findings should be interpreted as associational rather than causal, and policy implications are framed accordingly.

2.8 Estimation strategy

Model estimation was conducted using maximum likelihood techniques. Statistical significance was evaluated at conventional levels ($p < 0.05$), and model fit was assessed using pseudo-R^2 and likelihood ratio tests. Marginal effects were estimated to quantify the change in the probability of each transition outcome associated with changes in explanatory variables. All analyses incorporate sampling weights to adjust for differential selection probabilities across cities and enumeration areas.

3 Results

The results offer an overview of household cooking energy use, price dynamics, and transition patterns in urban Malawi. Findings indicate a gradual but incomplete shift toward cleaner fuels, with continued reliance on biomass alongside limited uptake of alternatives. Despite rising charcoal prices, transitions remain partial, with households adjusting through substitution and energy stacking. Energy use patterns vary significantly across households, influenced by differences in economic capacity, infrastructure access, and behavioral preferences (Gould et al., 2026).

3.1 Sample characteristics

The study was based on a sample of 1,613 households distributed across the four major urban centers of Malawi: Lilongwe, Blantyre, Mzuzu, and Zomba. The sample was relatively evenly distributed, with each city contributing approximately one-quarter of the total respondents. Blantyre and Mzuzu each accounted for 25.2% of the sample, Zomba accounted for 25.1%, and Lilongwe contributed 24.4%, as shown in Table 2. This balanced distribution ensured that the results captured variation across different urban contexts within the four cities studied.

The descriptive statistics show that the sample comprised 1,613 urban households distributed across Lilongwe (24.4%), Blantyre (25.2%), Mzuzu (25.2%), and Zomba (25.1%). The average respondent age was 36 years, and 79.4% of respondents were female. Household income sources were distributed across formal employment (39.7%) and business or self-employment activities (38.6%), with the remaining households engaged in other income-generating activities. In terms of infrastructure access, 70.9% of households reported having electricity connections.

Energy use data show that charcoal remained the dominant cooking fuel, used by 82.8% of households in 2024 CMR compared to 85.8% at 2022 baseline (2022 BL). Firewood was used by 37.6% of households, while electricity was used by 33.7%, and LPG by 7.2%. For water heating, charcoal was used by 62.2% of households, followed by firewood (36.0%), electricity (25.0%), and LPG (2.9%). The data also show that 37.4% of households used clean fuels for at least 50% of their cooking activities in 2024 CMR, compared to 32.5% at 2022 BL.

TABLE 2 Sampling distribution by location.

City	Sample size	Percentage (%)
Blantyre	407	25.2
Mzuzu	407	25.2
Zomba	405	25.1
Lilongwe	394	24.4
Total	1,613	100.0

The sample is representative of urban households in Lilongwe, Blantyre, Mzuzu, and Zomba, but not of rural Malawi.

Charcoal price data show a consistent increase over time, with average prices rising from MK 176/kg at 2022 BL to MK 340/kg and MK 497/kg in 2024 CMR for charcoal with dust, and from MK 185/kg to MK 348/kg and MK 507/kg over the same period for charcoal without dust. There was variation across cities, with higher prices observed in Lilongwe relative to other locations. In addition, 97.9% of households reported awareness of alternative cooking energy sources, and awareness of LPG increased to 84.8%. Despite access to electricity and high levels of awareness, the data show continued use of biomass fuels alongside modern energy sources within the same households.

3.2 Cooking energy and water heating use patterns

The results in Table 3 indicate that biomass fuels continue to be the primary source of cooking energy among urban households. Charcoal was used by 82.8% of households in 2024 CMR, representing only a slight decline from 85.8% at 2022 BL. Firewood use increased marginally from 36.3 to 37.6%, indicating continued dependence on traditional fuels. In contrast, there was a gradual increase in the use of cleaner energy sources. Electricity usage increased from 29.9% at 2022 BL to 33.7% in 2024 CMR, while LPG usage increased more than twofold from 2.9 to 7.2% over the same period.

These patterns indicate that while the use of cleaner fuels is increasing, the transition remains partial, with households continuing to rely on charcoal alongside alternative fuels. The persistence of charcoal use, even among households with access to electricity or LPG, reflects the coexistence of multiple fuels within the household energy mix.

A similar pattern in Table 4 was observed in the use of energy for heating water. Charcoal remained the dominant fuel, with usage increasing slightly from 59.7% at 2022 BL to 62.2% in 2024 CMR. Firewood use also increased marginally from 35.7 to 36.0%. At the same time, there was a noticeable increase in the use of electricity for heating water, which rose from 20.3% at 2022 BL to 25.0% in 2024 CMR. LPG usage increased from 1.4% at 2022 BL to 2.9% in 2024 CMR, although this remained relatively low compared to biomass fuels.

The results indicate that the transition to cleaner fuels is also limited in non-cooking energy uses, with biomass fuels continuing to dominate household energy consumption across multiple functions.

3.3 Adoption of clean cooking fuels, stoves, and technology use

The proportion of households using clean cooking solutions for at least 50% of their cooking activities increased from 32.5% at 2022 BL to 37.4% in 2024 CMR. While this represents a statistically significant improvement, the magnitude of change remains modest relative to the overall reliance on biomass fuels as shown in Table 5.

TABLE 3 Energy sources used for cooking (%).

Energy source	2022 BL (%)	2024 CMR (%)
Charcoal	85.8	82.8
Firewood	36.3	37.6
Electricity	29.9	33.7
LPG	2.9	7.2

TABLE 4 Energy sources used for heating water (%).

Energy source	2022 BL (%)	2024 CMR (%)
Charcoal	59.7	62.2
Firewood	35.7	36.0
Electricity	20.3	25.0
LPG	1.4	2.9

TABLE 5 Adoption of clean cooking solutions (%).

Indicator	2022 BL (%)	2024 CMR (%)
Clean fuel use (≥50%)	32.5	37.4
Electricity	26.0	28.2
LPG	2.1	4.9

TABLE 6 Use of charcoal stoves (%).

Stove Type	2022 BL (%)	2024 CMR (%)
Jiko	83.7	78.1
Improved charcoal stoves	<1	5.6
Others	<1	<1

Electricity accounted for the largest share of clean fuel use, while LPG adoption remained relatively limited. This indicates that the transition to clean cooking is uneven across different fuel types, with electricity playing a more prominent role than LPG.

The results in Table 6 show that traditional charcoal stoves (jiko) remained the most widely used cooking technology, used by 78.1% of households in 2024 CMR, although this represents a decline from 83.7% at 2022 BL. The use of improved and alternative stoves increased modestly, including newer technologies such as the UpEnergy SmartHome stove, which was used by 5.6% of households.

3.4 Charcoal market dynamics and structural change

The following subsections present data on charcoal market dynamics, including price trends and seller characteristics. While the main analysis focuses on household fuel choices, these market patterns help explain price signals and supply constraints affecting households. Supplementary seller data provide supply-side context on access and pricing, but are not included in the main inferential analysis, which is centered on household adoption decisions.

3.4.1 Charcoal price trends

The results show a substantial increase in charcoal prices over time. The mean price of charcoal increased from MK 176/kg at 2022 BL to MK 497/kg in 2024 CMR (with dust), while prices without dust increased from MK 185/kg to MK 507/kg. This represents nearly a threefold increase over the study period. There was also significant variation across cities, with Lilongwe recording the highest prices in 2024 CMR, followed by Blantyre and Mzuzu, while Zomba recorded comparatively lower prices. Despite these substantial price increases, charcoal remained widely used, indicating that households did not fully substitute away from biomass fuels.

3.4.2 Knowledge and awareness of energy systems

The findings show a mixed pattern of declining supply-chain awareness alongside rising knowledge of alternative energy sources. Overall, awareness of charcoal and firewood origins fell from 77.0 to 69.5%, while those with no knowledge increased from 20.6 to 30.5%, indicating reduced visibility of supply chains. Trends vary by city: Lilongwe improved (71.1 to 84.6%), Blantyre declined sharply (91.2 to 67.3%), Mzuzu showed a slight drop, and Zomba maintained very high awareness (100%).

3.4.2.1 Household awareness

Among the 1,613 household respondents, 97.9% reported awareness of alternative cooking energy sources, and awareness of LPG reached 84.8%. Electricity remained the most recognized option, rising from 87.3 to 92.9%. Awareness of briquettes rose from 9.4 to 26.7%, sustainable charcoal from 1.8 to 24.9%, and pellets from 0.7 to 10.2%. Awareness of kerosene declined slightly from 8.7 to 7.6%, though it increased in Mzuzu. Gasifiers emerged at 5.8%, mainly in Mzuzu. Under prompted conditions, household awareness was even higher: 99.6% for electricity and 93.3% for LPG. Meanwhile, households with no knowledge of alternatives fell from 7.6 to 4.0%, and mentions of "other" options declined, suggesting clearer recognition of specific fuels.

3.4.2.2 Seller awareness

Among charcoal sellers (n = 225–348; see Supplementary material), awareness of LPG increased from 13.2% at 2022 BL to 73.8% in 2024 CMR. LPG was viewed by sellers as the most marketable alternative fuel (70.9%).

3.5 Inferential analysis results

3.5.1 Multinomial logistic regression results

Relative to exclusive biomass use (the reference category), charcoal price was positively associated with both energy stacking and clean fuel adoption, with a larger coefficient for energy stacking ($\beta = 0.842$) than for clean fuel adoption ($\beta = 0.215$). This suggests that increases in charcoal prices were more strongly associated with partial transitions away from biomass than with complete adoption of clean fuels.

Statistical significance is indicated by asterisks, where ***, **, and * denote significance at the 1, 5, and 10% levels, respectively. Coefficients without asterisks, including charcoal price for clean fuel adoption, awareness, convenience and safety for energy stacking, and gender for both outcomes, are not statistically significant at the 10% level and should therefore be interpreted with caution.

Economic variables exert the strongest influence on clean fuel adoption. Household income has a greater effect on clean fuels (β = 0.785) than on energy stacking (β = 0.326), while affordability shows the largest overall impact (β = 0.963). Willingness to pay is also more strongly associated with clean fuel adoption (β = 0.672) than with energy stacking (β = 0.298), underscoring the importance of financial capacity for full transition. Market access variables reinforce this pattern. LPG availability is more strongly linked to clean fuel adoption (β = 0.854) than to energy stacking (β = 0.215), while distance to suppliers has a larger negative effect on clean fuels (β = −0.902) compared to energy stacking (β = −0.433). This suggests that access barriers are particularly restrictive for complete transition. Behavioral factors show strong negative effects. Cultural preference has a larger negative impact on clean fuels (β = −1.124) than on energy stacking (β = −0.512), while existing energy stacking behavior has the strongest negative association overall (β = −1.356), reinforcing continued biomass use. Technological perceptions, i.e., efficiency (β = 0.491), convenience (β = 0.533), and safety (β = 0.472), positively influence adoption, especially for clean fuels. Socio-demographic effects are moderate, with household size negatively associated (β = −0.615) and education positively associated (β = 0.601). The interaction between charcoal price and income is positive (β = 0.742), indicating stronger responses among higher-income households.

3.5.2 Marginal effects

Distance to suppliers increased the probability of biomass use (0.118) while reducing clean fuel adoption (−0.066), confirming that physical access remains an important barrier to transition. Cultural preference increased reliance on biomass (0.135) and reduced clean fuel adoption (−0.087), highlighting the persistence of behavioral constraints. Existing fuel stacking behavior had one of the strongest effects, increasing the probability of biomass dependence (0.164) while reducing the likelihood of clean fuel adoption (−0.108), suggesting that established fuel-use habits reinforce continued reliance on traditional fuels. Technological perceptions showed relatively modest positive effects on clean fuel adoption, including efficiency (0.037), convenience (0.039), safety (0.035), and awareness (0.025), compared to economic and market factors. Education increased the probability of clean fuel adoption (0.048), while willingness to pay (0.061) and the interaction between charcoal price and income (0.053) further reinforced the importance of household financial capacity in facilitating transition. Gender had only a small positive effect on clean fuel adoption (0.017), indicating limited influence relative to other determinants. Overall, the marginal effects confirm that affordability, willingness to pay, market accessibility, and income-conditioned responses to charcoal price increases are more influential drivers of clean fuel adoption than technological perceptions or demographic characteristics.

TABLE 7 Model diagnostics and goodness-of-fit.

Statistic	Value
Number of observations	1,613
Log-likelihood	−1,284.56
LR Chi-square	1,032.78
Pseudo R^2	0.287
AIC	2,615.12
BIC	2,742.33
Mean VIF	2.31
Max VIF	4.87

3.5.3 Model diagnostics

The model diagnostics as in Table 7 indicate that the model adequately fits the data. The pseudo R^2 value of 0.287 suggests moderate explanatory power, while the likelihood ratio statistic indicates overall model significance. The variance inflation factor values remain below critical thresholds, indicating no severe multicollinearity among explanatory variables.

Multicollinearity diagnostics showed a mean VIF of 2.31 and a maximum VIF of 4.87. Although the maximum VIF approaches the conventional threshold of 5.0, it remains within acceptable limits and below the more conservative threshold of 10.0. The relatively high VIF is expected because the model includes an interaction term between charcoal price and household income alongside the two constituent variables. To reduce non-essential multicollinearity, charcoal price and household income were mean-centered before constructing the interaction term as a robustness check. The centered specification produced substantively similar results, confirming that multicollinearity does not materially affect the interpretation of the model.

Figure 3 provides a visual summary of the marginal effects associated with clean fuel adoption. Affordability (0.089), LPG availability (0.063), willingness to pay (0.061), the charcoal price × income interaction (0.053), and education (0.048) emerged as the strongest positive drivers of clean fuel adoption. Conversely, existing energy stacking behavior (−0.108), cultural preferences (−0.087), and distance to suppliers (−0.066) were the strongest barriers. The figure reinforces the conclusion that economic and market accessibility factors play a more prominent role in shaping household energy transitions than demographic characteristics alone.

4 Discussion

Our estimates should be interpreted as associations, not causal effects, due to potential endogeneity of price and income, including reverse causality, omitted variable bias, and self-selection. While we have conducted robustness checks (instrumental variable exploration and propensity score matching; see Supplementary material), the cross-sectional nature of the data precludes strong causal claims.

The findings show that the transition to clean cooking in the four urban centers studied in Malawi is complex and shaped by interacting economic, market, behavioral, and technological factors, rather than price signals alone. Household energy choices reflect multiple

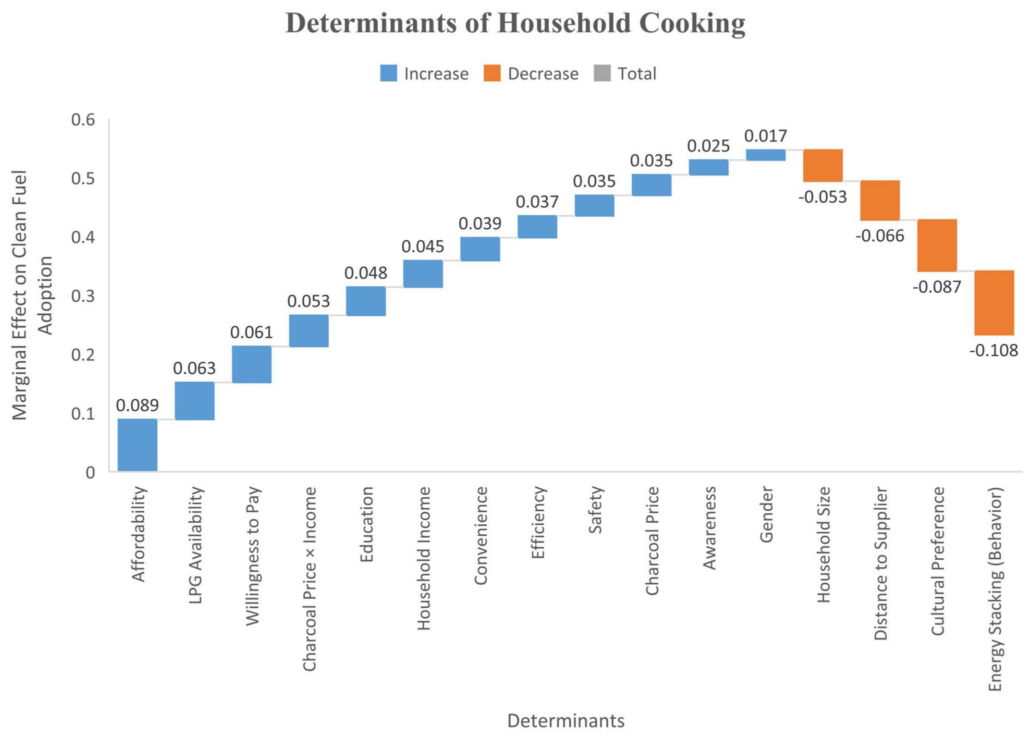

FIGURE 3
Key determinants of household cooking fuel transition.

constraints and preferences. Rising charcoal prices have not triggered a complete shift to clean fuels but have instead reinforced energy stacking, where households combine fuels. This challenges the traditional energy ladder model, which assumes a linear transition, and supports the energy stacking theory (Ntiyakunze and Stage, 2025). Overall, households tend to optimize fuel use within existing constraints rather than fully replacing biomass with cleaner energy sources.

4.1 Price dynamics and partial energy transition (H1)

The analysis shows that charcoal price plays a significant but limited role in driving clean cooking transitions. Prices increased sharply from MK 176/kg at 2022 BL to MK 497/kg in 2024 CMR, nearly threefold, yet charcoal remained dominant, used by 82.8% of households. Regression results indicate that rising prices are associated with movement away from exclusive biomass use, but the effect is much stronger for energy stacking than for full adoption of clean fuels. Marginal effects confirm this asymmetry: while higher prices reduce reliance on biomass alone, only a small share leads to complete transition. These findings support H1, showing that charcoal price acts more as a transition pressure than a mechanism. Households respond to price increases by adjusting their fuel mix rather than abandoning charcoal entirely. This challenges the neoclassical expectation of straightforward substitution toward cleaner alternatives. Instead, households adapt incrementally within existing constraints, using energy stacking to balance cost and uncertainty. The results align with evidence from low-income settings, where price-driven transitions are rarely linear. Rather than moving steadily up an energy ladder, households diversify fuel use to maintain flexibility and manage risks related to income variability and supply insecurity. In this context, energy stacking is not a failed transition but a rational and adaptive strategy that helps households cope with changing economic conditions while maintaining reliable access to cooking energy.

4.2 Economic constraints and adoption capacity (H2)

The results strongly support H2, showing that economic capacity is central to clean cooking adoption. Household income and affordability are among the strongest predictors are among the strongest predictors of clean fuel adoption, with large marginal effects, indicating that transition depends less on rising charcoal prices and more on households' ability to afford both upfront and recurring costs, particularly for LPG. In the four urban centers studied, adopting LPG requires purchasing a stove, cylinder, and accessories, followed by ongoing refill expenses. For low-income households, these costs are constrained by limited and irregular incomes, as well as liquidity challenges. In contrast, charcoal can be purchased in small, flexible quantities, making it easier to integrate into daily budgets despite price increases. This explains continued reliance on biomass and supports evidence that adoption depends on both relative prices and the ability to mobilize cash when needed (Sun et al., 2025). Willingness to pay further highlights the gap between preference and actual adoption. While households may favor LPG, affordability constraints prevent this from translating into effective demand. This has important policy implications: awareness alone is insufficient to drive adoption. Instead, financial barriers must be addressed through reduced entry

TABLE 8 Multinomial logit regression results for cooking fuel transition outcomes (reference category: exclusive biomass use, Y = 0).

Variables	Energy stacking (Y = 1) vs. Exclusive biomass use (Y = 0) Coef. (SE)	Clean fuel adoption (Y = 2) vs. Exclusive biomass use (Y = 0) Coef. (SE)
Charcoal price	0.842 (0.115)***	0.215 (0.132)
Household income	0.326 (0.142)**	0.785 (0.168)***
Affordability	0.411 (0.121)***	0.963 (0.154)***
Willingness to pay	0.298 (0.134)**	0.672 (0.149)***
LPG availability	0.215 (0.127)*	0.854 (0.163)***
Distance to supplier	−0.433 (0.118)***	−0.902 (0.141)***
Cultural preference	−0.512 (0.136)***	−1.124 (0.172)***
Energy stacking (behavior)	−0.685 (0.121)***	−1.356 (0.165)***
Awareness	0.174 (0.119)	0.338 (0.141)**
Efficiency	0.221 (0.123)*	0.491 (0.147)***
Convenience	0.198 (0.128)	0.533 (0.152)***
Safety	0.156 (0.117)	0.472 (0.139)***
Household size	−0.287 (0.131)**	−0.615 (0.148)***
Education	0.245 (0.129)*	0.601 (0.153)***
Gender (male = 1)	0.102 (0.115)	0.214 (0.132)
Charcoal price × Income	0.318 (0.144)**	0.742 (0.168)***

The multinomial logit (MNL) model uses exclusive biomass use (Y = 0) as the reference (base) category. Coefficients reported for Energy Stacking (Y = 1) and Clean Fuel Adoption (Y = 2) represent the change in the log-odds of belonging to each outcome category relative to households that rely exclusively on biomass fuels. Standard errors are reported in parentheses. *, **, and *** indicate statistical significance at the 10, 5, and 1% levels, respectively.

TABLE 9 Marginal effects of key variables on cooking fuel transition.

Variables	Biomass (0)	Energy stacking (1)	Clean fuel (2)
Charcoal price	−0.124	0.089	0.035
Household income	−0.086	0.041	0.045
Affordability	−0.152	0.063	0.089
Willingness to pay	−0.097	0.036	0.061
LPG availability	−0.097	0.034	0.063
Distance to supplier	0.118	−0.052	−0.066
Cultural preference	0.135	−0.048	−0.087
Energy stacking (behavior)	0.164	−0.056	−0.108
Awareness	−0.042	0.017	0.025
Efficiency	−0.058	0.021	0.037
Convenience	−0.061	0.022	0.039
Safety	−0.054	0.019	0.035
Household size	0.082	−0.029	−0.053
Education	−0.073	0.025	0.048
Gender (male = 1)	−0.026	0.009	0.017
Charcoal price × Income	−0.081	0.028	0.053

costs, flexible payment options, and consumer financing. Overall, economic factors are fundamental determinants of transition capacity in the four urban centers studied.

4.3 Market accessibility and supply constraints (H3)

The findings strongly support H3, showing that market accessibility is a key determinant of clean fuel adoption. LPG availability is positively associated with adoption, while distance to supplier has a strong negative effect (Table 8). This indicates that even when households are willing and financially able to adopt LPG, transition depends heavily on physical accessibility, convenience, and supply reliability. This shifts the explanation from household demand to energy market structure. Clean fuels cannot be widely adopted where distribution networks are weak, refill points are distant, transport costs are high, or supply chains are unreliable. In the four urban centers studied, these constraints significantly limit LPG uptake, even amid rising awareness and policy support. The negative effect of supplier distance captures both direct transport costs and broader transaction burdens associated with accessing fuel that is not readily available nearby. Descriptive results reinforce this interpretation. Despite high awareness of alternative fuels and relatively widespread electricity access, LPG use remains low (Tables 5, 9), showing that awareness alone is insufficient when supply-side constraints persist. This aligns with regional evidence that clean cooking transitions are more constrained by weak supply systems than by consumer resistance (Sadath and Acharya, 2025). The findings imply that policies focused only on restricting charcoal supply are unlikely to succeed without parallel investment in LPG infrastructure (Gould et al., 2026). This includes expanding distribution networks, increasing retail points, and improving refill accessibility. Without these improvements, households remain dependent on biomass even when economic conditions or prices favor switching.

4.4 Behavioral persistence and energy stacking (H4)

Notably, the magnitude of behavioral constraints exceeds that of price signals. For clean fuel adoption, cultural preference ($\beta = -1.124$) and existing energy stacking practices ($\beta = -1.356$) have substantially larger absolute coefficients than charcoal price ($\beta = 0.215$, not statistically significant). This suggests that behavioral factors are more powerful barriers to full transition than rising fuel costs, reinforcing the inadequacy of price-based policies alone.

The behavioral dimension provides strong explanatory power and clear support for H4. Both cultural preference and existing energy-stacking practices are negatively associated with full clean fuel adoption, with large coefficients in Table 8. This indicates that household fuel choices are shaped more by cooking routines, food preferences, and risk management strategies than by cost or awareness alone. These findings help explain why biomass remains widely used even among households with access to modern fuels. As shown in Tables 5, 6, 9, many households combine charcoal with electricity or LPG rather than fully substituting fuels. This reflects the multifunctional nature of energy use, where different fuels are used for different cooking tasks, heating needs, and meal types. Charcoal often remains preferred for practical, economic, and cultural reasons. Consequently, energy stacking should be understood not as an incomplete transition but as a deliberate strategy that preserves flexibility, familiarity, and resilience to uncertainty. The results align with literature challenging the energy ladder model, which assumes a linear shift from traditional to modern fuels with rising income. Instead, evidence from low- and middle-income settings shows that fuel stacking is the dominant pattern (Debebe et al., 2025a; Derebe et al., 2025b). The findings from the four urban centers studied reinforce this, showing a hybrid transition in which biomass persists alongside cleaner options. This supports the energy stacking framework, which argues that households optimize fuel portfolios rather than fully switching fuels (Gill-Wiehl et al., 2025; Onakomaiya et al., 2026). Importantly, the strong negative effect of existing stacking behavior suggests that once households diversify fuels, this pattern can itself hinder full transition. Stacking becomes self-reinforcing, reducing pressure to abandon biomass entirely and thereby sustaining partial rather than complete adoption of clean cooking fuels.

4.5 Technological perceptions and adoption readiness (H5)

The results support H5, showing that technological perceptions positively influence clean cooking adoption, though their effects are more moderate than economic and market factors. Positive views of efficiency, convenience, and safety increase the likelihood of adopting clean fuels (Table 8). This indicates that households do recognize the functional benefits of modern cooking technologies such as LPG. However, these perceptions are not strong enough to drive adoption on their own. While many households value the speed, cleanliness, and convenience of modern fuels, these advantages are often outweighed by affordability and access constraints. Thus, technological perceptions act more as enabling conditions than decisive drivers of transition. They can increase readiness to adopt but only when economic and supply barriers are manageable. Safety is particularly important. Concerns about LPG safety are widely documented and can discourage uptake where trust in equipment and suppliers is limited (Dianda et al., 2025; Sharma and Rahman, 2025; Siagian and Hartono, 2025). The positive effect of safety perceptions in this study suggests that trust-building measures, improved standards, and consumer education could support adoption. Awareness must also be interpreted in context. Although awareness of clean fuels is high, it does not translate into adoption when access and affordability remain limited. This explains the coexistence of high awareness and persistent biomass dependence. Overall, information and positive perceptions are necessary but insufficient without supportive economic and infrastructural conditions (Gould et al., 2026).

4.6 Income-conditioned price effects and household heterogeneity (H6)

The interaction between charcoal price and income strongly supports H6 and adds nuance to the price effect. The positive interaction coefficient in Table 8 shows that higher-income households are more responsive to rising charcoal prices than lower-income households, indicating that price effects are conditioned by purchasing power. For poorer households, higher charcoal prices do not facilitate a shift to clean fuels; instead, they may increase energy insecurity, reduce consumption, or deepen reliance on cheaper biomass options. For better-off households, however, the same price increases make LPG relatively more attractive because the financial threshold for switching is already attainable. This explains why aggregate price increases do not lead to widespread clean fuel adoption: those most affected are often least able to transition. The findings highlight that price-based policies alone are insufficient and may be inequitable, benefiting mainly households already capable of switching. Rising charcoal prices may be welfare-reducing for the poorest households. Rather than shifting to clean fuels, low-income households respond to price increases by reducing energy consumption, switching to cheaper and lower-quality biomass (e.g., agricultural waste), or spending a larger share of their limited income on cooking fuel. This can increase energy insecurity, reduce nutritional outcomes (if less cooking is done), and exacerbate exposure to household air pollution from lower-quality fuels. Price-based policies alone therefore risk harming the most vulnerable without achieving clean cooking objectives. This aligns with evidence that fuel substitution is shaped by income heterogeneity, access constraints, and vulnerability to price shocks (Sharma and Rahman, 2025; Tang et al., 2025; Vicent et al., 2025). The results also reinforce the value of the multinomial framework, which distinguishes between exclusive biomass use, energy stacking, and clean fuel adoption. Households do not respond to price changes in a binary way; instead, they shift across different transition states depending on their economic capacity and available options.

4.7 Visual interpretation of marginal effects on clean fuel adoption

Figure 3 provides a visual summary of the marginal effects associated with household cooking fuel transition and highlights the relative importance of the key determinants of clean fuel adoption. The figure shows that affordability (0.089), LPG availability (0.063), willingness to pay (0.061), the interaction between charcoal price and household income (0.053), and education (0.048) are among the strongest positive drivers of clean fuel adoption. These findings suggest that household transitions towards cleaner fuels are primarily influenced by economic capacity, market accessibility, and the ability of households to respond to increasing biomass fuel costs. This finding is consistent with previous studies that identify affordability, income, and access to modern energy infrastructure as critical determinants of clean cooking adoption in developing countries.

In contrast, existing energy stacking behavior (−0.108), cultural preferences (−0.087), and distance to suppliers (−0.066) emerge as the strongest barriers to clean fuel adoption, indicating that behavioral factors and market access constraints continue to reinforce reliance on traditional biomass fuels. These results support the growing body of literature challenging the traditional energy ladder hypothesis and instead emphasizing fuel stacking as a persistent and rational household strategy under conditions of economic uncertainty, supply constraints, and diverse cooking requirements.

Technological attributes such as convenience (0.039), efficiency (0.037), safety (0.035), and awareness (0.025) also contribute positively to adoption decisions, although their effects are comparatively smaller than those associated with affordability and market access. This suggests that while households recognize the benefits of cleaner cooking technologies, perceived advantages alone are insufficient to drive widespread adoption when financial and supply-side barriers remain unresolved. Similar findings have been reported in studies across Sub-Saharan Africa, where awareness campaigns and technology promotion efforts have often generated interest in clean cooking solutions but achieved limited adoption in the absence of accessible and affordable fuel supply systems.

Overall, Figure 3 reinforces the central finding of this study that clean cooking transitions in urban Malawi are driven more strongly by economic and market-system factors than by technological perceptions alone. The results further support the argument that households respond to a combination of affordability, accessibility, and behavioral considerations, resulting in gradual adjustments in fuel portfolios rather than complete substitution away from biomass fuels. These findings provide additional evidence that policies aimed at accelerating clean cooking transitions should prioritize reducing affordability constraints, strengthening supply chains, improving market access, and supporting commercially viable business models capable of delivering clean cooking fuels at scale.

4.8 Broader implications for theory and policy

Taken together, the findings show that the clean cooking transition in the four urban centers studied is constrained by interacting factors that limit the effectiveness of charcoal price increases as a policy tool. While charcoal price triggers adjustment, economic factors (household income, affordability, willingness to pay) and market factors (LPG availability, distance to supplier) determine households' ability to respond, and behavioral, technological, and socio-demographic factors shape their willingness to do so. This layered structure explains the non-linear transition and continued reliance on biomass despite rising awareness and modest gains in clean fuel use. The study makes three key contributions. First, it shows that rising biomass prices encourage energy stacking rather than full substitution, challenging simple price-based explanations of household energy behavior. Second, it demonstrates that affordability and accessibility are not secondary barriers but core structural determinants of adoption. Third, it reinforces the energy stacking framework, highlighting that households in low-income urban settings balance cost, culture, convenience, and risk rather than choosing a single fuel (Nandwani and Jain, 2026). From a policy perspective, the findings suggest that charcoal price increases or supply restrictions alone are insufficient to drive transition. More effective strategies should combine affordability support, improved LPG distribution, expanded local access, and safety and awareness interventions that recognize persistent multi-fuel use. Without addressing these constraints, price increases will continue to produce partial rather than sustained transitions. This aligns with broader evidence from Sub-Saharan Africa, where clean cooking progress remains slow under weak markets and limited purchasing power.

4.9 Study limitations

4.9.1 Clean fuel categorization

In this study, the clean fuel adoption category combined households using electricity and LPG. However, electricity constituted the majority of clean fuel use (28.2%) compared to LPG (4.9%) (Table 5). Consequently, the effects of LPG-specific variables, such as fuel availability and distance to suppliers, should be interpreted with caution, as a substantial proportion of households classified as clean fuel users rely on electricity and are therefore not directly affected by LPG distribution constraints. Future studies should distinguish between different clean fuel types to better capture fuel-specific adoption dynamics.

4.9.2 Endogeneity

As noted earlier in the Discussion, the estimated relationships should be interpreted as associations rather than causal effects because of the potential endogeneity of key variables, particularly charcoal prices and household income. Although robustness checks, including instrumental variable exploration and propensity score matching, were undertaken, the possibility of unobserved confounding factors cannot be entirely excluded.

4.9.3 Generalizability

The study sample was designed to be representative of households in the four major urban centres of Lilongwe, Blantyre, Mzuzu, and Zomba. Accordingly, the findings may not be directly generalizable to other urban areas in Malawi or to rural populations, where energy access conditions, fuel markets, and household cooking practices may differ substantially.

4.9.4 Female predominance in the sample

Women constituted 79.4% of respondents because the survey prioritized interviewing the household member primarily responsible for cooking, who is typically female in Malawian households. While this approach captures the perspectives of those most directly involved in cooking fuel decisions, it underrepresents male viewpoints and may limit the generalizability of the findings. Future research could examine potential gender differences in household fuel transition behavior.

5 Conclusion and policy implications

This study investigated why rising charcoal prices fail to drive clean cooking transitions in the four urban centers studied, using survey data from 1,613 households across four major cities. The findings show that the relationship between charcoal price increases and clean fuel adoption is neither linear nor automatic. Despite charcoal prices rising nearly threefold, from MK 176/kg at 2022 BL to MK 497/kg in 2024 CMR, charcoal remains the dominant cooking fuel, used by 82.8% of households. Although higher prices are associated with reduced exclusive biomass use, the effect is significantly stronger for energy stacking (β = 0.842) than for full clean fuel adoption (β = 0.215). This supports the energy stacking framework and challenges the traditional energy ladder model, indicating that households diversify rather than fully substitute fuels.

Economic factors are the most important determinants of transition. Affordability (β = 0.963) and household income (β = 0.785) strongly influence clean fuel adoption, suggesting that financial constraints, rather than lack of awareness, are the primary barrier. The positive interaction between charcoal prices and income (β = 0.742) further indicates that higher-income households are more responsive to price increases, while poorer households remain reliant on biomass or shift to cheaper alternatives, potentially worsening energy insecurity. Market constraints also play a critical role. LPG availability (β = 0.854) promotes adoption, while distance to suppliers (β = −0.902) significantly limits it. These findings highlight the importance of supply-side factors, showing that weak distribution networks and unreliable supply chains restrict uptake even where demand exists. This is reflected in the descriptive results: despite high awareness of LPG (84.8%) and relatively widespread electricity access (70.9%), only 7.2% of households use LPG.

Behavioral factors further explain the persistence of biomass use. Cultural preferences (β = −1.124) and established energy stacking practices (β = −1.356) reduce the likelihood of full transition, indicating that cooking habits, food preferences, and risk management strategies shape fuel choices. Energy stacking should therefore be seen as a rational and adaptive strategy rather than a transitional failure. Finally, perceptions of efficiency, convenience, and safety positively influence adoption but have a more limited effect. These factors increase readiness to adopt clean fuels but are insufficient without improvements in affordability and accessibility. Overall, the findings demonstrate that price signals alone cannot drive clean cooking transitions; instead, coordinated interventions addressing economic, market, and behavioral barriers are essential.

From a policy perspective, the findings indicate that clean cooking transitions cannot be achieved through charcoal price increases alone but require integrated interventions that address affordability, accessibility, and behavioral barriers. Because the clean fuel category in this study comprises both electricity and LPG users, with electricity accounting for the majority of clean fuel adoption, policy measures should support both pathways rather than focusing exclusively on LPG. For electricity, this includes tariff subsidies, grid reliability upgrades, and connection fee waivers. For LPG, this includes cylinder subsidies, distribution network expansion, and refill affordability measures. Efforts should therefore reduce the costs of clean cooking technologies through targeted subsidies and innovative financing mechanisms, while improving access through strengthened LPG distribution networks and more reliable electricity infrastructure. Given the prevalence of energy stacking, policies should support the gradual integration of clean fuels alongside existing cooking practices rather than expecting immediate fuel switching. Public awareness campaigns, safety assurance measures, and consumer support services can further enhance acceptance and confidence in clean cooking technologies. However, the combined treatment of LPG and electricity within a single clean fuel category limits fuel-specific policy interpretation, particularly regarding LPG availability and supplier distance effects. Future research should therefore disaggregate clean fuel types to better understand the distinct drivers of LPG and electricity adoption. Overall, stronger institutional coordination, sustainable financing, and integration of clean cooking into broader urban and energy planning frameworks are essential for accelerating clean cooking transitions in the four urban centers studied.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/Supplementary material.

Ethics statement

The studies involving humans were approved by the Malawi National Commission for Science and Technology. The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because the study design incorporated the informed consent during the interview with the respondents.

Author contributions

SC: Methodology, Conceptualization, Formal analysis, Investigation, Validation, Visualization, Software, Writing – review & editing, Supervision, Resources, Writing – original draft, Data curation, Project administration, Funding acquisition. BT: Supervision, Validation, Conceptualization, Writing – review & editing, Visualization. HC: Methodology, Formal analysis, Writing – review & editing, Data curation, Investigation.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsc.2026.1850587/full#supplementary-material

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