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Fuel Diversification as a Risk Management Strategy: Household Cooking Energy Choices Under Uncertainty in Urban Malawi

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Abstract

Clean cooking transitions in Sub-Saharan Africa remain limited despite increasing access to modern energy, highlighting the need to extend traditional demand-side approaches by incorporating risk and uncertainty into household decision-making. This study examines household energy choices under uncertainty in urban and peri-urban Malawi and reconceptualizes fuel diversification, or energy stacking, as a rational risk management strategy. Using cross-sectional data from 3015 households collected in 2026, the study uses binary logistic regression models to estimate the determinants of fuel diversification. The results show that exposure to uncertainty significantly increases the likelihood of energy stacking. Electricity unreliability ($p < 0.01$), charcoal price variability ($p < 0.05$), income volatility, and past fuel shortages are all positively associated with diversification behavior. In contrast, stable and higher incomes reduce reliance on multiple fuels. Household size significantly increases the number of fuels used ($p < 0.01$), reflecting higher energy demand and risk exposure. The findings demonstrate that energy stacking is a deliberate risk mitigation strategy consistent with risk diversification theory and highlight that improving reliability, stabilizing prices, and reducing market uncertainty are critical for accelerating clean cooking transitions.

Keywords: clean cooking; energy stacking; fuel diversification; energy transition; risk and uncertainty; household energy demand; Malawi

1. Introduction

1.1. Research Background

Access to clean and modern energy for cooking remains one of the most critical yet underachieved components of sustainable development, with far-reaching implications for public health, environmental sustainability, gender equality, and inclusive economic growth [1,2]. Despite global commitments under Sustainable Development Goal 7 (SDG7) [3,4], an estimated 2.1 billion people worldwide continue to rely on traditional technologies as well as biomass fuels such as firewood and charcoal for cooking [5]. The combustion of these fuels in inefficient stoves generates high levels of household air pollution, which has been identified as a leading risk factor for respiratory infections, cardiovascular diseases, and premature mortality, particularly among women and children [3,6–10]. In addition, unsustainable biomass harvesting contributes significantly to deforestation, land degradation, and greenhouse gas emissions, exacerbating climate change and undermining ecosystem resilience [11–13]. These interconnected challenges position clean cooking



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transitions as a central pillar of both development and climate agendas. The academic discourse on household energy transitions has evolved considerably over time. Early theoretical frameworks, particularly the “energy ladder” model, suggested that households would transition linearly from traditional biomass fuels to modern energy sources as incomes increase [14–16]. However, empirical evidence across diverse contexts has consistently challenged this assumption, demonstrating that households often engage in “fuel stacking,” whereby multiple fuels are used simultaneously to meet different cooking and energy needs [17–19]. This behavior reflects a rational response to uncertainty, price volatility, supply reliability, and cultural preferences, rather than a failure to adopt modern energy [20–22]. Consequently, energy transitions are increasingly understood as nonlinear, multidimensional processes shaped by the interaction of socio-economic, infrastructural, and institutional factors [23–25]. This study is grounded in risk diversification theory, which explains how households allocate resources across multiple options to minimize exposure to uncertainty [26–28].

While much of the literature on clean cooking adoption has focused on demand-side factors such as income, education, and cultural preferences [29], growing evidence highlights the critical role of energy market conditions [30]. In many low-income contexts, the availability, affordability, and reliability of clean fuels are shaped by the structure and performance of energy markets rather than household characteristics alone [31,32]. Limited distribution networks, high transaction costs, and underdeveloped financing mechanisms constrain access to clean cooking solutions, even where demand exists [33]. These structural constraints manifest through price volatility, unreliable supply, and income instability, which directly shape household decision-making under uncertainty [34,35]. The study therefore focuses on how households respond to uncertainty arising from price variability, unreliable electricity supply, income volatility, and past fuel shortages. This approach is consistent with established methods in energy and development economics, where household-level behavioral responses are prioritized over direct estimation of structural supply-side variables, as demonstrated in life cycle assessment studies of cooking fuels [36], analyses of agricultural energy transitions [37], and examinations of domestic energy poverty [38].

Clean fuels such as LPG and ethanol require robust infrastructure, including storage facilities, transportation systems, distribution networks, and retail points. In many developing countries, these systems are fragmented or underdeveloped [32], leading to inconsistent availability of alternative fuels, high prices, and limited geographic coverage [33,39]. Distance to fuel suppliers and the absence of last-mile delivery mechanisms further constrain access, particularly in peri-urban and rural areas [40]. Moreover, private sector participation in clean cooking markets is often hindered by high upfront investment costs, regulatory uncertainties, and limited access to finance [41], resulting in low market density and weak competition [42,43]. Beyond structural market constraints, household-level behavioural factors, including risk aversion, innovation resistance, and time preferences, further limit the uptake of clean cooking technologies, even when physical access is available [10]. These factors collectively contribute to market failures that limit the diffusion of clean cooking technologies.

Evidence from Sub-Saharan Africa highlights persistent structural constraints in clean cooking transitions. Studies from Kenya and South Africa demonstrate that improved electricity access does not necessarily translate into clean cooking adoption due to affordability and reliability challenges [6,34,44,45]. Similarly, evidence from Zambia and Tanzania shows that supply-side constraints, including limited distribution networks and weak market systems, restrict access to modern fuels [44,46]. In contrast, countries such as Mozambique and Ethiopia continue to exhibit high dependence on biomass fuels, driven by affordability

constraints and entrenched consumption patterns. Across these contexts, uncertainty in prices, supply reliability, and household income emerge as consistent barriers to sustained transitions toward clean cooking [45,47–49].

A significant proportion of the earlier clean cooking and household energy transition literature interpreted fuel stacking as a transitional phenomenon or an intermediate stage along the traditional “energy ladder” [18]. Under this perspective, moving up the ladder toward modern fuels such as electricity and LPG has been viewed as the expected outcome of economic development [14–16]. Under this perspective, the simultaneous use of multiple fuels was generally viewed as evidence that households had not fully transitioned to modern energy systems due to persistent income limitations, infrastructural barriers, weak market development, or behavioral constraints [50,51]. The energy ladder framework assumed that households would progressively abandon traditional biomass fuels in favor of cleaner and more modern energy sources as income, urbanization, education, and access to modern infrastructure improved [14,15]. Consequently, the continued reliance on charcoal, firewood, or other biomass fuels alongside electricity or LPG was often interpreted as a temporary, irrational, or suboptimal outcome within the broader transition process [52].

Emerging evidence from Sub-Saharan Africa and other developing regions suggests that fuel diversification is strongly influenced by price volatility, unreliable electricity supply, fluctuating incomes, supply disruptions, seasonal changes, and varying cooking requirements rather than simply reflecting incomplete modernization [20,26,34]. Scenario analyses from Nigeria, for example, project that cooking fuel choices will continue to be shaped by economic and environmental constraints under different future scenarios [26]. Similar patterns have been explored in the context of African informal settlements, where the food–energy nexus provides a lens for understanding household cooking journeys [27]. Studies increasingly show that household energy choices are shaped by multiple interacting factors. For example, targeted poverty alleviation programs have been shown to promote clean cooking fuel adoption in China [53], national energy policies such as Brazil’s “Fuel of the Future” law influence sectoral transitions [54], and the portfolio effects of renewable energy integration affect power system stability [55]. Collectively, these studies demonstrate that household and national energy decisions are embedded within broader policy, economic, and market contexts. This emerging body of literature therefore reconceptualizes energy stacking not as a failure of transition but as a rational and adaptive response to uncertainty. Building on this perspective, the present study explicitly conceptualizes fuel diversification as a household risk management strategy within unstable and uncertain energy environments.

Beyond these cases, additional evidence from the region further reinforces the centrality of market conditions [29]. In many Sub-Saharan African countries, the adoption of clean cooking technologies has been constrained by fragmented distribution systems, limited private sector engagement, and weak market linkages, despite strong government promotion of improved cookstoves [30,32,33]. Across the region, persistent macroeconomic instability and supply disruptions have affected LPG fuel availability, leading to inconsistent supply and price volatility, which undermine consumer confidence and adoption [40–42]. In South Africa, although electricity access is nearly universal, the continued use of solid fuels in low-income settlements has been attributed to affordability constraints and uneven access to reliable and affordable energy services, particularly in informal settlements [6]. Similar patterns of persistent solid fuel use despite electricity access have been documented across Sub-Saharan Africa, including Tanzania [44] and Zambia [46].

Similarly, in Malawi’s regional context, studies from Nigeria, often used as a comparative benchmark, show that weak distribution networks, high upfront costs, and limited access to credit significantly constrain LPG adoption, particularly outside major urban

centers [56,57]. Across these diverse contexts, a consistent pattern emerges: clean cooking transitions are not solely determined by household preferences or income levels but are strongly influenced by energy market conditions [31,41,42]. These country-level experiences collectively reinforce that uncertainty in prices, supply reliability, and market access remains a central barrier to clean cooking transitions across the region [45,49]. Despite extensive evidence across countries, existing studies have not sufficiently examined how households respond to uncertainty in energy access, which this study addresses.

Malawi presents a particularly compelling case for examining how households respond to uncertainty in clean cooking energy access. The country is characterized by one of the highest levels of biomass dependence globally, with charcoal and firewood accounting for the majority of household cooking energy [58–60]. Despite concerted efforts by the Government of Malawi and development partners to promote cleaner cooking technologies, adoption of modern fuels such as LPG and electricity remains limited [40,61,62]. National policy frameworks, including the 2018 Malawi National Energy Policy and the Malawi SDG7 Cleaner Cooking Energy Compact, have set ambitious targets to accelerate clean cooking transitions. For instance, the Compact aims to distribute over 2 million improved biomass cookstoves by 2025 as part of a broader target of 5 million by 2030. While these initiatives demonstrate strong policy commitment, they have largely focused on technology dissemination rather than addressing systemic market constraints [40,62].

Empirical evidence indicates that access to clean cooking fuels in Malawi remains extremely low, with only 5.1% of urban households and 0.5% of rural households having access [58,59,61]. Although there has been a statistically significant increase in the use of alternative energy sources from 32.5% at baseline to 37.9% in 2024, the scale of progress remains modest. Electricity and LPG have shown some growth, but their adoption is constrained by structural factors. Electricity, for example, remains the most commonly used alternative energy source, yet its use for cooking is limited by reliability issues, appliance availability, and cost considerations [6,34,46]. Similarly, LPG adoption has increased but remains low due to supply constraints, limited distribution networks, and affordability barriers [40–42]. At the same time, traditional technologies such as the Malawi Ceramic Jiko and the three-stone fire continue to dominate, supported by well-established biomass supply systems and reliable market networks [60]. A critical limitation of existing research in Malawi is its predominant focus on demand-side determinants, often neglecting the role of supply chain and distribution constraints [40,49,62]. In reality, the availability of clean fuels is highly uneven, with significant disparities between urban, peri-urban, and rural areas [41]. Supplier presence is often concentrated in major cities, leaving large segments of the population underserved [42]. Distribution networks are limited, resulting in high transportation costs and reduced accessibility [40]. Distance to fuel providers further increases the cost and inconvenience of adopting clean fuels, particularly for low-income households [62]. In addition, the absence of accessible financing mechanisms such as consumer credit, leasing models, or pay-as-you-go (PAYGO) systems limits both household adoption and private sector expansion [49]. These factors contribute to low market density and weak competition, further constraining the development of clean cooking markets.

This study examines how households adapt their cooking energy choices under conditions of uncertainty, reconceptualizing fuel diversification as a risk management strategy rather than a transitional inefficiency [19,20]. It focuses on how exposure to key sources of uncertainty, including price variability, electricity reliability, income volatility, and past fuel shortages, shapes fuel diversification behavior [63]. This perspective extends traditional demand-side approaches by incorporating risk dynamics [34,36] and offers a more comprehensive understanding of the structural barriers to clean cooking transitions [37,64]. The contribution of this study is threefold.

First, it advances the literature by situating household decision-making within broader market conditions of clean cooking adoption, thereby addressing a critical gap in existing research. Second, it provides robust empirical evidence from Malawi, offering context-specific insights into the functioning of clean cooking markets [58–60]. Third, it generates policy-relevant findings that can inform interventions aimed at improving energy market conditions, including fuel supply systems, distribution infrastructure, and expanding access to financing mechanisms for clean cooking solutions [40,41,61].

1.2. Conceptual Framework- Risk-Based Energy Choice Model Under Uncertainty

The conceptual framework guiding this study provides a risk-based reinterpretation of household energy behavior by demonstrating that fuel diversification is a rational adaptation to uncertainty rather than a transitional inefficiency [17,18], thereby extending existing energy transition frameworks [19,20]. The dependent variable, household fuel diversification behavior, is measured as both the number of fuels used and the probability of stacking. It is influenced by key risk-related independent variables, including price variability, electricity reliability, income volatility, household size, and past fuel shortages [34,37,38].

These variables capture different dimensions of uncertainty: price fluctuations increase cost risk [56,65]; unreliable electricity introduces supply instability [26,58]; and income volatility constrains sustained use of modern fuels [27], with evidence from both African and Asian contexts confirming this pattern [53,57,59,61]. Household size further amplifies exposure to these risks through increased energy demand [40], while past fuel shortages contribute to adaptive learning that reinforces diversification behavior [49,62]. Market-related factors, including supplier availability and distribution networks, are treated as contextual conditions influencing uncertainty but are not directly included in the econometric estimation [29,30,32,33]. The framework therefore focuses on key dimensions of uncertainty, namely, price variability, electricity reliability, income volatility, and supply disruptions, which shape household decision-making under conditions of risk [26,27,53]. Figure 1 shows the conceptual framework.

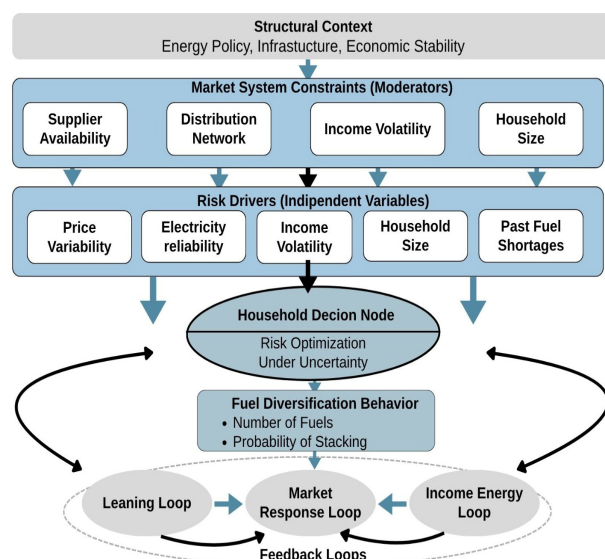


Figure 1. Conceptual framework for risk-based energy choice.

These market-related conditions influence household behavior indirectly by shaping the broader uncertainty environment within which energy decisions are made. For example, weak supplier networks, limited fuel distribution systems, and poor market accessibility contribute to fuel price variability, unreliable availability of alternative fuels, and higher transaction costs [31,39]. Rather than estimating these structural market variables directly

at the household level, the econometric analysis focused on proximate manifestations of market uncertainty experienced by households, including perceived price fluctuations, electricity reliability, income instability, and past fuel shortages [6,44], which more directly influence household fuel diversification behavior [46].

To further elaborate, the framework emphasizes that these uncertainty factors operate simultaneously rather than independently, shaping household energy decisions through cumulative and interacting effects [54,55,66,67]. This expanded perspective highlights that fuel diversification emerges not from isolated constraints but from the combined influence of market instability, economic vulnerability, and supply unreliability within the broader energy system [28,45]. These uncertainty factors interact to shape household expectations about future energy access, influencing both short-term fuel choices and long-term energy strategies [49]. As uncertainty increases, households rationally diversify their energy portfolios to minimize exposure to supply, price, and income shocks [19,26].

1.3. Contribution to Knowledge

These findings contribute to the clean cooking literature by introducing a risk-based framework that reconceptualizes energy stacking as a rational response to uncertainty rather than a transitional inefficiency. Using data from 3015 households in urban and peri-urban Malawi, the study demonstrates that uncertainty factors, including price variability, unreliable electricity supply, income volatility, and past fuel shortages, significantly influence fuel diversification behavior. The analysis extends existing energy transition frameworks by integrating risk and uncertainty into household energy decision-making and provides empirical evidence linking uncertainty to sustained fuel diversification. The findings highlight that improving energy reliability, stabilizing fuel prices, and reducing market uncertainty are critical for accelerating clean cooking transitions.

2. Methodology

2.1. Study Design and Analytical Framework

This study employed a quantitative cross-sectional research design to examine household energy choices under conditions of uncertainty in urban and peri-urban Malawi. The analytical framework was grounded in a reconceptualization of energy stacking as a rational response to risk, drawing from household utility theory and the risk management literature. Unlike traditional energy ladder models, which assume a linear progression from biomass to modern fuels [68,69], this study adopted a behavioral-economic perspective in which households optimize energy portfolios under uncertainty [70]. In this context, diversification of cooking fuels was interpreted as a strategy to hedge against multiple forms of risk, including price volatility, unreliable supply, and income instability.

This approach builds on the established energy stacking literature [54,55] while extending it by explicitly incorporating uncertainty as a central explanatory dimension [37,38]. In this study, clean cooking energy sources refer to modern cooking fuels and technologies associated with lower household air pollution emissions, improved combustion efficiency, and reduced environmental and health impacts [64]. These include electricity, liquefied petroleum gas (LPG), ethanol, biogas, and other modern low-emission cooking technologies consistent with international clean cooking frameworks. In contrast, polluting or traditional cooking fuels refer to biomass-based and high-emission energy sources such as charcoal, firewood, crop residues, and traditional biomass stoves, which are associated with elevated indoor air pollution, inefficient combustion, and adverse environmental and health outcomes [60]. The study therefore examines household diversification and transition patterns across both clean and polluting cooking energy sources within the context of uncertainty, affordability constraints, and energy system instability in urban Malawi.

The framework conceptualized households as risk-aware decision-makers who allocate energy choices across multiple fuels to minimize vulnerability to shocks [28]. This aligns with economic theories of risk diversification, which suggest that agents spread exposure across alternatives when faced with uncertainty [71,72]. In the context of Malawi's energy system characterized by fluctuating charcoal prices, unreliable electricity supply, and irregular income streams, fuel diversification was therefore hypothesized to be a rational and adaptive behavior rather than an inefficient or transitional state. The empirical strategy was designed to test this hypothesis by linking observed household fuel use patterns to measurable indicators of risk and uncertainty.

In addition to the primary data collected through the 2026 National Consumer Survey dataset (N = 3015), this study incorporated secondary data from the Malawi Cooking and Heating Fuel (MCHF) Consumer Market Research surveys conducted at baseline (2020), midline (2022), and endline (2024). The MCHF datasets, derived from repeated cross-sectional surveys of urban households, provide important longitudinal insights into trends in cooking fuel use, charcoal prices, energy awareness, and adoption of alternative cooking energy sources over time. The econometric analysis presented in this study is based exclusively on the 2026 National Consumer Survey dataset, while the MCHF datasets were used solely for descriptive analysis, contextual interpretation, and trend comparison. The integration of the MCHF datasets enabled triangulation of findings by linking the cross-sectional econometric results with broader temporal patterns related to price variability, electricity reliability, fuel supply dynamics, and household cooking energy behavior in urban Malawi.

2.2. Study Context and Data Source

The empirical analysis was based on data collected through the 2026 National Consumer Energy Survey, implemented between January and March 2026. The survey was designed to generate nationally relevant insights into household energy use, with a particular focus on cooking practices, fuel combinations, and market conditions. Data collection was concentrated in urban and peri-urban areas, where households are more likely to have access to multiple energy options, including electricity, charcoal, LPG, and other fuels. These areas provided a suitable context for examining diversification behavior, as households operate within more dynamic and heterogeneous energy markets compared to rural settings. The survey instrument captured detailed information on household demographics, cooking fuel use, energy expenditure, perceptions of fuel prices, electricity reliability, and past experiences with fuel shortages. In addition, data were collected on income patterns and variability, allowing for the construction of proxies for economic uncertainty. The dataset therefore enabled a comprehensive analysis of how different dimensions of risk influence household energy choices.

2.3. Sample Design and Distribution

The study analyzed data from 3015 completed household interviews distributed across eight districts representing Malawi's four administrative regions, as presented in Table 1. The survey was implemented by the authors in both urban and peri-urban areas to capture diverse household energy-use experiences and cooking practices across different socio-economic and geographic contexts. The sampling framework was developed using population statistics from the National Statistical Office (NSO) Malawi [73], covering a total population of 2,623,875 across the selected districts. Based on this framework, an initial target sample of 3104 households was drawn. Following data cleaning, verification, and removal of incomplete responses, the final dataset used for econometric analysis comprised 3015 valid household observations. This design enhanced comparability across regions

and reduced potential biases associated with uneven spatial distribution. The selected districts included Karonga and Mzuzu in the Northern Region, Kasungu and Lilongwe in the Central Region, Blantyre and Zomba in the Southern Region, and Salima and Mangochi in the Eastern Region.

Table 1. Sample Distribution of Surveyed Households (N = 3015).

Region	District/City	Number of Households (N)	Percentage (%)
Northern Region	Karonga	377	12.5
	Mzuzu	377	12.5
Central Region	Kasungu	377	12.5
	Lilongwe	377	12.5
Southern Region	Blantyre	377	12.5
	Zomba	377	12.5
Eastern Region	Salima	377	12.5
	Mangochi	376	12.5
Total		3015	100

The relatively large sample size enhanced the statistical reliability of the findings and provided a robust basis for econometric analysis. The inclusion of both urban and peri-urban households allowed the study to capture variations in market access, infrastructure, and exposure to uncertainty.

2.4. Data Collection Procedures

Data were collected using structured questionnaires administered by trained enumerators. The survey instrument was designed to capture both objective and perception-based measures of energy use and uncertainty. Enumerators were trained extensively prior to field deployment to ensure consistency in data collection and understanding of survey instruments.

Data collection was conducted using digital tools, which improved accuracy and minimized data entry errors. Specifically, enumerators used Samsung Galaxy Tab A8 tablets (Samsung Electronics Co., Ltd., Suwon, South Korea) running the SurveyCTO Collect mobile application (version 2.80; <https://www.surveycto.com>). Field supervisors conducted regular quality checks using the SurveyCTO Server (version 2.80) to ensure adherence to data collection protocols.

The primary respondents were household heads or main cooking decision-makers, ensuring that the data accurately reflected actual energy use practices. Information collected included the number and types of fuels used, frequency of use, perceived price changes, electricity reliability, and experiences with fuel shortages. This approach ensured that the dataset captured both behavioral outcomes and underlying risk perceptions.

2.5. Variable Definition and Measurement

The dependent variable in this study captured fuel diversification behavior, operationalized as both a count variable (number of fuels used) and a binary indicator (whether a household used multiple fuels). This dual specification allowed the analysis to capture both the extent and likelihood of diversification [28], consistent with previous studies on energy stacking [74,75]. The key independent variables were defined to reflect different dimensions of uncertainty. Price variability was measured based on reported fluctuations in charcoal prices, capturing exposure to market instability. Electricity reliability was proxied by the frequency of power outages and perceived consistency of supply, reflecting market conditions risk. Income volatility was constructed using reported variability in household income sources, representing economic uncertainty. Household size was included as a

proxy for consumption pressure and risk exposure, while past fuel shortages captured households' prior experiences with supply disruptions, which may influence current behavior. Control variables included education level, employment status, gender of the household head, and location (urban versus peri-urban) [38,76], all of which have been shown to influence energy choices in previous studies [46].

The dependent variable in this study captures household cooking energy diversification behavior, measured based on the number and combination of cooking fuels reportedly used by households during the 30 days preceding the survey. Households were classified as practicing fuel diversification or fuel stacking if they reported simultaneous use of two or more cooking fuels within the reference period. The survey instrument collected information on both primary and supplementary cooking fuels used for routine household cooking activities. This approach recognizes that households may rely on multiple fuels concurrently rather than exclusively transitioning from one fuel to another. The 30-day reference period was selected to capture recent and active household cooking energy practices while minimizing long-term recall bias.

The independent variables used in the econometric analysis were primarily derived from household-level responses collected through the 2026 National Consumer Energy Survey (NCES), which was designed and implemented directly by the authors for this study. Several variables were intentionally measured using perception-based indicators because the study examines household decision-making under conditions of uncertainty, where behavior is shaped by both actual market conditions and household perceptions of risk. For example, price variability was measured using respondents' reported experiences of fluctuations in charcoal prices, while electricity reliability was measured based on reported frequency and consistency of power supply interruptions. Income volatility captured perceived instability in household income streams, and fuel shortage history reflected respondents' past experiences with disruptions in fuel availability. In addition to these perception-based measures, secondary descriptive datasets from the Malawi Urban Cooking Energy Consumer Market Research (MCHF) surveys were used to provide independent contextual evidence on broader market trends, including observed charcoal price changes, awareness levels, and energy adoption patterns over time. However, these external indicators were used solely for descriptive and trend analysis and were not directly incorporated into the econometric estimations.

The selection of independent variables was guided by the conceptual framework, risk diversification theory, and the previous empirical literature on household energy choice and energy stacking behavior [17,18,20,54]. Variables were specifically selected to capture key dimensions of uncertainty affecting household energy decisions, including price variability, electricity reliability, income volatility, household demand pressure, and past fuel shortages. Additional market-related factors such as supplier availability, distribution systems, and accessibility were initially considered during model development. However, these variables were treated as broader contextual conditions influencing household uncertainty rather than direct household-level determinants and were therefore not included in the final econometric estimation. Variable selection was further informed by data completeness, theoretical relevance, and model performance considerations, including avoidance of multicollinearity and over-specification. These variables were excluded from the final econometric specification because reliable household-level measures capturing supplier density, physical market accessibility, and distribution network performance were not consistently available across all surveyed locations. Moreover, these factors operate primarily as broader structural conditions influencing household exposure to uncertainty rather than as direct behavioral determinants. Their effects are therefore captured indirectly

through household-level measures of perceived price variability, electricity reliability, and fuel shortage experiences included in the regression analysis (Table 2).

Table 2. Measurement and Coding of Key Uncertainty Variables.

Variable	Survey Question/Measurement	Coding Used in Regression
Charcoal Price Variability	Households were asked whether charcoal prices in their area had changed frequently or unpredictably over the previous 12 months.	1 = Frequent/unpredictable price changes reported; 0 = Stable/predictable prices
Income Volatility	Respondents were asked whether household income fluctuated significantly or was difficult to predict over the previous 12 months.	1 = Unstable/irregular income; 0 = Stable income
Electricity Reliability	Respondents assessed the reliability of electricity supply based on frequency of outages and interruptions experienced.	1 = Reliable supply; 0 = Unreliable/frequent outages
Past Fuel Shortages	Households were asked whether they experienced shortages or inability to access preferred cooking fuels during the previous 12 months.	1 = Experienced shortages; 0 = No shortages reported

2.6. Analytical Strategy and Econometric Specification

The empirical analysis was conducted in two stages. First, descriptive statistics were used to characterize household cooking energy use patterns and fuel diversification. Second, econometric models were applied to identify the determinants of diversification behavior.

Fuel diversification intensity, measured by the number of cooking fuels used, was analysed using Poisson and negative binomial regression models, with model choice informed by the presence of overdispersion [77–79]. A binary logistic regression model was also estimated to assess the likelihood of adopting diversified cooking fuels. Table 3 summarizes the variables used in the regressions.

Table 3. Summary of Variables.

Variable	Type	Description
Fuel diversification	Dependent	Binary (1 = multiple fuels, 0 = single fuel)
Number of fuels	Dependent	Count of fuels used
Price variability	Independent	Perceived charcoal price fluctuations
Electricity reliability	Independent	Frequency of outages
Income volatility	Independent	Variability in income sources
Household size	Independent	Number of household members
Fuel shortage history	Independent	Past experience with fuel shortages
Education	Control	Highest level attained
Employment status	Control	Employment category
Location	Control	Urban/peri-urban

The logistic regression model was specified as: $\text{logit}(P_i) = \ln(P_i/(1 - P_i)) = \beta_0 + \beta_1\text{PriceVar}_i + \beta_2\text{Reliability}_i + \beta_3\text{IncomeVol}_i + \beta_4\text{HHSIZE}_i + \beta_5\text{Shortage}_i + \epsilon_i$. The corresponding probability function is given by: $P_i = 1/(1 + \exp(-(\beta_0 + \beta_1\text{PriceVar}_i + \beta_2\text{Reliability}_i + \beta_3\text{IncomeVol}_i + \beta_4\text{HHSIZE}_i + \beta_5\text{Shortage}_i)))$, where P_i represents the probability that a household engages in fuel diversification (i.e., uses multiple fuels). All coefficients (β_1 – β_5) are interpreted as the marginal effects of uncertainty-related variables on the log-odds of fuel diversification.

All analyses were conducted using Stata/MP 18.0 (StataCorp LLC, College Station, TX, USA). Count and logistic models were estimated using the *poisson*, *nbg*, and *logit* commands, and marginal effects were computed using the *margins* command. Data cleaning and validation were performed in Stata and cross-checked using the *tidyverse* package (version 2.0.0) in R.

The methodological approach adopted in the findings contributed to the literature by explicitly integrating risk and uncertainty into the analysis of household energy choices.

Rather than treating energy stacking as a transitional or suboptimal outcome, the study framed it as a rational and adaptive strategy employed by households to manage uncertainty. This perspective provided a more nuanced understanding of household behavior and offered important implications for policy, particularly in designing interventions that address not only affordability and access but also reliability and market stability. Market-related factors such as supplier availability and distribution networks are treated as contextual conditions influencing uncertainty but are not directly included as explanatory variables in the econometric models. These factors shape the uncertainty environment within which households make energy decisions, rather than being directly estimated in the model.

Although the regression analysis identifies significant associations between household fuel diversification behavior and indicators of uncertainty such as perceived price variability, electricity reliability, and past fuel shortages, the cross-sectional nature of the data limits the ability to establish definitive causal relationships. Potential reverse causality may exist, whereby households already practicing fuel stacking become more sensitive to fuel price fluctuations and supply disruptions. Similarly, some reported shortages may reflect broader structural conditions associated with energy insecurity that simultaneously influence diversification behavior. To assess robustness, additional sensitivity checks using alternative model specifications and variable combinations were conducted, and the direction and statistical significance of the key relationships remained broadly consistent. The findings should therefore be interpreted as evidence of strong associations consistent with the conceptual framework rather than definitive causal effects.

2.7. Ethical Considerations and Informed Consent

All procedures involving human participants were conducted in accordance with ethical standards of the National Commission for Science and Technology (NCST), Malawi, under approval No. IP.11/22/742. Prior to data collection, informed consent was obtained from all participants. Respondents were fully informed about the purpose of the study, the voluntary nature of participation, their right to withdraw at any time without penalty, and the confidentiality of their responses. No personally identifiable information was collected, and all data were anonymized to ensure participant privacy and data protection. The study complied with relevant national and institutional ethical guidelines for research involving human subjects.

3. Results

3.1. Sample Characteristics and Household Structure

The results revealed that household energy decisions were embedded within specific demographic and socio-economic structures. Across the surveyed districts, the sample was dominated by female respondents, reflecting gendered roles in cooking and energy management. At the district level, for example, 69.6% of respondents in Karonga were female, compared to 30.4% male, reinforcing the centrality of women in household energy decision-making. Age distribution further showed that the majority of respondents were within economically active groups, with 39.5% aged 18–30 years, 31.5% aged 31–40 years, 21.5% aged 41–50 years, and 7.5% aged 50 years or older, indicating that energy choices were largely made by economically active populations. Household sizes were relatively large: approximately 55.3% of households had three to five members, while roughly 28.7% had six or more members, implying higher aggregate energy demand and exposure to energy-related risks. Overall, the demographic profile suggests that household energy demand is both structurally high and decision-making is strongly gendered, with implications for how energy transitions are adopted and sustained.

3.2. Cooking Demand and Behavioral Patterns

Analysis of the MCHF data (2020, 2022, and 2024) shows that household energy demand remained consistently high across all districts, although cooking frequency patterns shifted over time. At the aggregate level, the proportion of households cooking daily declined from 47.8% at baseline to 38.2% in 2024. In contrast, those cooking most days increased substantially from 7.8% to 22.0%, indicating a shift toward slightly less frequent but still regular cooking. Households cooking half the time decreased marginally from 9.9% to 8.8%, while those cooking only 1–2 days per week rose from 19.7% to 22.0%. The share of households that never cooked remained relatively low overall, despite minor fluctuations. City-level trends reveal notable variation in these patterns. In Lilongwe, daily cooking declined from 65.1% to 52.9%, accompanied by increases across all less frequent cooking categories and a reduction in households that never cooked. Blantyre experienced the most pronounced decline in daily cooking, falling from 46.4% to 20.6%, alongside significant increases in households cooking occasionally (1–2 days per week) and half the time. In Mzuzu, daily cooking rose slightly from 37.1% to 39.5%, while the share of households cooking most days surged from 6.7% to 32.6%. At the same time, less frequent cooking declined, and the proportion of households that never cooked dropped sharply. In Zomba, daily cooking fell from 42.7% to 25.2%, while those cooking most days more than doubled, and occasional cooking increased; however, the share of households that never cooked also rose. Overall, the findings suggest that although cooking demand remains high, households are adjusting cooking frequency, likely in response to evolving energy access, affordability constraints, and changing household dynamics.

3.3. Reasons for Choosing a Particular Clean Cooking Fuel

The aggregated results across all surveyed urban and peri-urban districts revealed that household cooking energy choices were predominantly driven by economic and energy market-related factors, with strong consistency observed across regions as shown in Table 4.

Table 4. Reason for technology and fuel choice.

Please Rank Responses (Up to Three) Mentioned Above in Order of Importance										
RESPONSE	LL		BT		MZ		ZA		TOTAL	
	BL	2024 CMR	BL	2024 CMR	BL	2024 CMR	BL	2024 CMR	BL	2024 CMR
Cooks faster	37.8	43.9	55.7	33.2	49.6	38.1	36.0	43.1	44.8	39.5
Fuel efficient	22.2	22.7	15.2	19.5	14.5	22.8	31.7	17.1	20.9	20.5
Affordable	20.1	16.3	19.8	27.2	11.6	28.5	20.6	7.2	18.0	19.8
Cheap fuel	3.2	7.7	1.5	3.0	7.0	2.2	5.3	18.3	4.3	7.8
Modern	5.0	7.1	2.8	11.7	8.4	2.0	3.4	5.4	4.9	6.6
Cleaner to use	5.6	5.6	2.6	6.5	1.4	1.0	11.1	11.1	5.2	6.1
No smoke	2.4	4.6	0.3	5.7	2.9	3.5	5.0	10.1	2.7	6.0
Portable	1.1	2.3	1.3	6.2	-	0.2	5.3	7.7	1.9	4.1
Safe to use	1.9	3.1	-	2.7	0.3	0.5	3.7	5.7	1.5	3.0
Accessible	5.0	2.6	1.8	2.7	2.0	1.2	5.8	3.7	3.7	2.6
Durable	1.1	2.3	-	2.7	0.6	0.2	2.1	3.0	1.0	2.1
Other	4.2	1.8	0.8	3.7	4.9	1.0	2.1	0.0	3.0	1.6
Total respondents	378	392	388	401	345	404	378	404	1489	1601

The values presented in Table 4 represent the percentage of respondents identifying specific factors influencing their cooking fuel and technology choices. Respondents were asked to rank up to three reasons in order of importance. The abbreviations and acronyms used in the table are provided in the Abbreviations and Acronyms section of the manuscript.

Cooking speed was the most frequently reported reason for fuel and technology choice across all districts and survey periods, accounting for 39.5% of total responses.

Fuel efficiency accounted for 20.5% of responses, while affordability accounted for 19.8%. Perceptions of fuels as cheap accounted for 7.8% of responses. Other reported factors included technologies being modern (6.6%), cleaner to use (6.1%), and smoke-free (6.0%). Portability accounted for 4.1% of responses, accessibility for 2.6%, safety for 3.0%, and durability for 2.1%. Across cities, cooking speed remained consistently among the highest-ranked factors, particularly in Blantyre (55.7%) and Mzuzu (49.6%) during the baseline survey. Fuel efficiency and affordability also remained consistently reported across all locations and survey periods.

3.4. Fuel Use Patterns and Technology Adoption

Households relied on multiple fuels and technologies rather than a single dominant source, confirming widespread energy stacking (Table 5). Charcoal remained the primary cooking fuel across all districts, while electricity and LPG were used more selectively. The share of households using alternative energy sources increased from 32.5% at baseline to 37.9% in 2024 (+5.4 percentage points), driven by modest gains in electricity (26.0% to 28.2%) and LPG (2.1% to 4.9%).

Table 5. Regional Comparative Profile of Household Cooking Energy Characteristics in Malawi.

Category	Northern	Central	Southern	Eastern
Setting	Mixed (rural–urban)	Mixed (semi-urban–urban)	Predominantly urban	Predominantly rural
Female respondents (%)	55–60%	55–58%	57%	59–69%
Dominant age group	31–40 years	31–40 years	31–40 years	31–40 years
Secondary education (%)	40–50%	41–43%	40–48%	50–56%
	45–55% earning MWK	51–64% earning MWK	50–56% earning MWK	59–66% earning MWK
Monthly income (%)	100,000–500,000 (~\$60–\$300)	100,000–500,000 (~\$60–\$300)	100,000–500,000 (~\$60–\$300)	100,000–500,000 (~\$60–\$300)
Cooking ≥ 3 times/day (%)	60–75%	58–72%	50–54%	60–80%
Primary cooking fuel (%)	Charcoal 55–68%; Electricity 20–35%	Charcoal 45–58%; Electricity 37–53%	Electricity 50–54%; Charcoal 35–45%	Charcoal 58–66%; Firewood 20–30%
Electricity use for cooking (%)	20–35%	37–53%	50–54%	6–41%
Charcoal dependence (%)	60–75%	55–70%	40–55%	58–66%
Fuel reliability/no shortages (%)	35–48%	29–57%	36–42%	70%
Electricity awareness (%)	88–94%	93–96%	90–98%	84–89%
LPG awareness (%)	45–58%	55–70%	68–80%	40–55%
Perceived affordability of clean fuels (%)	35–45%	53–58%	64–67%	27%
Energy use pattern	Energy stacking dominant	Energy stacking dominant	Energy stacking dominant	Strongest energy stacking behavior

Regional patterns show broadly similar demographic characteristics across areas, with households mainly composed of adults aged 31–40, a majority of female respondents, moderate secondary education levels, and incomes largely within the MWK 100,000–500,000 (~\$58–289) range. Cooking intensity was consistently high, with most households preparing meals multiple times daily. In contrast, energy use patterns varied across regions. Charcoal remained the dominant fuel everywhere, especially in rural areas, while electricity use was more common in urban settings. The Southern region demonstrated relatively higher electricity uptake, whereas the Eastern region relied more heavily on biomass fuels. However, no region achieved a full transition to clean energy. Fuel reliability and affordability perceptions also differed: biomass supply was more stable in rural areas, while modern fuels were perceived as more affordable in urbanized regions. Awareness of electricity was high across all regions, and LPG awareness ranged from moderate to high. Overall, households continued to rely on multiple fuels and technologies, confirming the persistence of energy stacking as a dominant household strategy.

Electricity use increased from 26.0% to 28.2% and LPG from 2.1% to 4.9%, with total alternative energy use rising from 32.5% to 37.9%. Traditional stoves remained dominant,

i.e., the Malawi Ceramic Jiko declined from 83.7% to 78.1%, the Chitetezo Mbaula remained stable (7.4% to 7.7%), and three-stone fire systems were widely used. Across cities, electricity use was highest in Blantyre (54.2%), followed by Zomba (50.0%), Mzuzu (45.7%), and Lilongwe (37.6%). Charcoal reliance remained high. Awareness of electricity and LPG was very high in Blantyre, Lilongwe, and Mzuzu and high in Zomba, while LPG awareness ranged from moderate to high. Charcoal prices per kilogram ranged from MWK 341–370 (~\$0.19–0.21) in Zomba to MWK 741–770 (~\$0.42–0.44) in Lilongwe, with Blantyre (MWK 511–541; ~\$0.29–0.31) and Mzuzu (MWK 503–523; ~\$0.29–0.30) falling within the mid-range. Households used a combination of fuels. Building on these national and regional patterns, Table 6 presents a cross-city comparison of urban cooking energy dynamics, highlighting how these trends manifest within Malawi’s major urban centers.

Table 6. Cross-City Comparative Patterns of Cooking Energy Use in Urban Malawi.

Theme	Blantyre	Lilongwe	Mzuzu	Zomba	Overall Pattern
Electricity Use (%)	Highest (54.2%)	Lower (37.6%)	Moderate (45.7%)	High (50.0%)	Widely present but not dominant
Charcoal Reliance	High	Very high	High	High	Remains central across all cities
Awareness (Electricity & LPG)	Very high	Very high	Very high	High	Awareness not a binding constraint
LPG Awareness	Moderate–high	High	High	Moderate	Increasing but uneven
Charcoal Price (MWK/kg)	Mid-range (\$0.29–\$0.31)	Highest (\$0.42–\$0.44)	Mid-range (\$0.29–\$0.30)	Lowest (\$0.19–\$0.21)	Significant inter-city variation
Energy Use Pattern	Mixed fuels	Mixed fuels	Mixed fuels	Mixed fuels	Energy stacking dominant

Across all cities, electricity is used for cooking but remains a supplementary energy source, while charcoal continues to be the dominant fuel. LPG use is present but limited, and overall energy use is characterized by multiple-fuel combinations rather than single-fuel reliance. Awareness of electricity and LPG is high across all cities, with only minor variation in LPG awareness between locations. Inter-city differences are mainly observed in the intensity of electricity use and the structure of fuel markets. Lilongwe records relatively lower electricity use, while Blantyre and Zomba show comparatively higher levels. Charcoal prices vary considerably across cities, with the highest levels observed in Lilongwe and the lowest in Zomba, while Mzuzu and Blantyre fall in the mid-range. Despite these variations, charcoal remains central to household cooking practices in all cities. Overall, urban households consistently rely on a combination of fuels, indicating persistent energy stacking across all four cities.

3.5. Willingness to Pay and Market Behavior

The results showed strong and increasing willingness among households to adopt improved cooking technologies. At baseline, 87.7% of households expressed willingness to purchase improved stoves, indicating a high initial level of acceptance. This willingness was accompanied by a steady increase in the mean willingness to pay (WTP), which rose from MWK 9062 (~\$5.18) at baseline to MWK 14,391 (~\$8.22) in 2022 and further to MWK 18,293 (~\$10.45) in 2024, reflecting a growing valuation of improved cooking technologies over time. City-level variation was also observed, with WTP highest in Lilongwe (MWK 22,396; ~\$12.79), followed by Zomba, Blantyre, and Mzuzu, indicating spatial differences in purchasing capacity and market demand. In addition, payment preferences shifted toward cash-based transactions, increasing from 63.9% at baseline to 71.5% in 2024, suggesting a gradual movement toward more direct and immediate purchasing behavior.

3.6. Regression Results: Determinants of Electricity Use for Cooking

The econometric results in Table 7 provided detailed insights into the determinants of electricity use for cooking. It is important to acknowledge that household electricity access and ownership of electric cooking appliances are necessary enabling conditions

for the adoption of electric cooking technologies. Their inclusion in the regression model therefore reflects foundational infrastructural requirements rather than purely behavioral or preference-driven determinants. As expected, these variables demonstrated strong associations with electric cooking adoption and contributed substantially to model performance. However, the analysis further highlights that beyond access-related factors, broader socio-economic and behavioral determinants such as affordability, reliability of supply, awareness of clean cooking technologies, and prevailing energy stacking practices also significantly shape household cooking energy decisions. The interpretation of the model therefore places greater emphasis on these complementary determinants to better understand the wider dynamics influencing clean cooking transitions in urban Malawi. The logistic regression results showed that electricity access, reliability, appliance ownership, and income were all statistically significant predictors of electricity use.

Table 7. Logistic Regression Results (Electricity Use for Cooking).

Variable	Coefficient (β)	Odds Ratio	<i>p</i> -Value
Electricity access	1.42	4.14	0.000
Reliability	1.18	3.26	0.000
Appliance ownership	1.65	5.21	0.000
Income	0.37	1.45	0.002
Household size	−0.28	0.76	0.004
Cooking frequency	0.22	1.25	0.010
Education	0.19	1.21	0.018
Gender	0.05	1.05	0.412

The results further showed that household size had a negative association with electricity use, while access and appliance ownership had the strongest positive effects.

3.7. Marginal Effects and Model Diagnostics

The marginal effects analysis showed that appliance ownership had the strongest positive effect on the probability of electricity use for cooking, increasing the likelihood by 0.36. This was followed by electricity access, which increased the probability by 0.31, and reliability of supply, which increased it by 0.27, highlighting the importance of infrastructure and household assets in shaping adoption behavior. Income also had a positive but smaller effect, increasing the probability of electricity use by 0.09, while cooking frequency had a modest positive effect of 0.05. In contrast, household size had a negative effect, reducing the probability of electricity use by 0.07. Model diagnostics indicated strong explanatory power of the regression model. The analysis was based on 3015 observations and produced a log-likelihood value of −1245.67. The model achieved a pseudo R^2 of 0.312, and the likelihood ratio test (Chi-square = 412.5) was statistically significant, confirming overall model fit. The classification accuracy was 74.6%, indicating that the model reliably predicts household electricity use for cooking.

3.8. Market Conditions and Market Constraints

The results in Table 8 consistently showed that market-related factors influenced energy outcomes. Descriptive findings and contextual analysis indicated that fuel supply systems, accessibility, and distribution networks were important structural conditions shaping household energy outcomes and broader patterns of fuel diversification. Weak distribution networks and limited supplier access were associated with lower uptake of clean fuels, while households continued to rely on charcoal due to its widespread availability and established market systems. Market-related factors strongly shape household energy outcomes, with availability, accessibility, and distribution systems emerging as key

determinants of adoption. Weak supply networks and limited supplier access constrain the uptake of clean fuels, while charcoal remains widely used due to its established market presence and availability.

Table 8. Trends in Household Cooking Energy and Market Conditions (2020–2026).

Indicator	2020 (Baseline)	2022 (Midline)	2024 (MCHF Endline)	2026 (National Survey)	Trend
Households using alternative energy (%)	32.5%	35%	37.9%	40%+	Gradual increase
Electricity use for cooking (%)	26.0%	27–29%	28.2–33.7%	33–35%	Slow growth
LPG use (%)	2.1%	3–4%	4.9%	5–7%	Emerging but low
Charcoal reliance (%)	85–90%	83%	82.8%	80%+	Slight decrease but dominant
Charcoal price (MWK/kg)	176 (~\$0.10)	340 (\$0.19)	500+ (~\$0.29+)	High/volatile	Significant increase
Awareness of electricity (%)	90–95%	96%	98.6%	98%+	Very high
Awareness of LPG (%)	34%	70%+	84.8%	85%+	Strong increase
Energy stacking behavior	High	High	High	Very high	Persistent
Electricity reliability	Low	Low–moderate	Moderate	Still unreliable	Constraint persists

Analysis of secondary data from the MCHF surveys (2020, 2022, 2024) and the 2026 National Consumer Survey shows gradual changes in household energy use over time. There is a steady increase in the use of alternative energy sources, including electricity and LPG, although growth remains limited relative to charcoal, which continues to dominate household cooking across all survey periods. Electricity access has expanded over time, but its use for cooking remains lower than access levels. Awareness of alternative energy sources has also increased substantially across the study period. The 2026 survey confirms persistent use of multiple fuels, with electricity more common in urban areas and charcoal widely used across all locations. Overall, the findings indicate gradual but incomplete energy transitions characterized by persistent energy stacking and continued reliance on charcoal despite improvements in access and awareness. These findings are consistent with risk diversification theory, where households adopt multiple fuels to hedge against uncertainty in energy access.

4. Discussion

4.1. Introduction to the Discussion

This study examines household energy choices in urban and peri-urban Malawi using a risk-based lens, arguing that energy stacking is a rational response to uncertainty rather than a transitional stage of the energy ladder [18]. Households build diversified energy portfolios to manage price volatility, unreliable supply, income instability, and demand pressures [19]. Table 4 shows affordability (38–45%) and accessibility (30–40%) dominate decisions, while Table 8 shows biomass, especially charcoal, remains dominant despite high awareness of electricity and LPG [44,63], confirming that knowledge alone is insufficient [60]. Econometric results (Table 7) show electricity access (OR = 4.14), reliability (OR = 3.26), and appliance ownership (OR = 5.21) increased use but do not eliminate charcoal. This supports rejection of the energy ladder [14,15] and aligns with energy stacking theory [17,80], showing energy choices reflect adaptive risk management under uncertainty [16,37,38,64].

4.2. Price Variability (Charcoal Trends) as a Driver of Risk-Based Energy Decisions

The findings provide strong evidence that price variability, particularly within charcoal markets, significantly influences household energy diversification behavior in urban Malawi. Analysis of charcoal price trends reveals substantial inter-city variation, with prices ranging from MWK 341–370 in Zomba to MWK 741–770 in Lilongwe, reflecting spatial differences in fuel market conditions, transportation costs, supply chains, and access to

charcoal production areas across urban centers in Malawi. Despite these variations, charcoal remains a central component of household cooking energy portfolios across all cities.

The persistence of charcoal use alongside other energy sources suggests that households respond to price uncertainty through fuel diversification strategies rather than complete substitution away from biomass fuels [19,21]. Despite this variation, households do not abandon charcoal; instead, it remains central to their energy portfolios, indicating diversification rather than substitution. This is reinforced in Table 4, where affordability is the dominant determinant of energy choice (38–45%) [22]. Cost is therefore a structural feature of energy systems, but it is dynamic, shaped by fluctuating prices and constrained liquidity. Households continuously adjust energy use based on short-term purchasing power [34,35]. When charcoal prices rise in Lilongwe, households may rely more on electricity but retain charcoal as a fallback [36]; when electricity is unreliable or costly, they revert to charcoal.

Charcoal price patterns across urban Malawi reveal substantial spatial variation in fuel costs, reflecting differences in transportation distances, supply chains, market access, and proximity to charcoal production areas. Charcoal prices were highest in Lilongwe (MWK 741–770 per kilogram; ~\$0.42–~\$0.44), followed by Blantyre (MWK 511–541; ~\$0.29–~\$0.31) and Mzuzu (MWK 503–523; ~\$0.29–~\$0.30), while Zomba recorded comparatively lower prices (MWK 341–370; ~\$0.19–~\$0.21). These geographic differences highlight the uneven structure of charcoal markets across cities rather than instability alone.

In addition to these spatial differences, households also reported experiencing fluctuations in charcoal prices over time [21], particularly in larger urban centers where demand pressures and transport costs are higher [26]. The combined effect of spatial price variation and perceived temporal price fluctuations contributes to uncertainty in household energy expenditures and influences fuel diversification behavior [27].

Charcoal's persistence reflects structural advantages, including informal fuel supply systems and small, flexible purchases suitable for low-income households [32,33]. This challenges the energy ladder model [39] and supports evidence that energy transitions are driven more by risk and uncertainty than relative prices [23,24]. Studies from Tanzania, Kenya, and Mozambique similarly show resilient charcoal demand due to accessibility and efficient supply systems [25,44]. Price variability also reflects spatial inequalities in availability of alternative fuels, transport costs, and regulation (Table 5), interacting with income volatility and reliability to reinforce energy stacking. Overall, price uncertainty, not price level, drives diversification and explains slow clean cooking transitions [35,36,43].

4.3. Electricity Reliability as a Binding Constraint in Clean Energy Transitions

The findings provide strong empirical evidence that electricity reliability is a key constraint in the transition toward clean cooking fuels in urban Malawi. Although electricity access and awareness are high across regions, reliability rather than access determines actual cooking adoption [29], challenging assumptions that infrastructure expansion alone drives energy transitions [30,31]. Descriptive results show variation in electricity use across cities, with higher uptake in Blantyre (54.2%) and Zomba (50.0%) compared to Lilongwe (37.6%). However, electricity is not a dominant cooking fuel in any city. Instead, it is used alongside charcoal and other fuels, reinforcing energy stacking and showing that access alone cannot displace traditional fuels [17,80]. Econometric results confirm the importance of reliability, with a strong and statistically significant effect on electricity use for cooking ($\beta = 1.18$, OR = 3.26, $p < 0.001$). Despite this, electricity does not replace charcoal.

Risk management theory explains this: in contexts of frequent outages, households maintain multiple fuels as insurance against supply disruptions [26,27]. Regional patterns support this [53], with the Eastern region reporting about 70% of households with no biomass shortages, where charcoal and firewood dominate. Less reliable electricity regions

show greater diversification, indicating perceived reliability is more important than access. These findings align with Sub-Saharan African evidence that unreliable electricity limits cooking adoption of clean cooking fuels despite access [6,34]. Households use electricity opportunistically while retaining traditional fuels as backups [46]. Although appliance ownership increases electricity use (OR = 5.21), investment depends on expectations of reliable supply, creating a feedback loop [37,38]. Malawi's energy-intensive cooking further limits electricity's practicality.

Overall, the results distinguish access from reliability, showing that reliability determines usability and that policy must address supply stability to achieve clean cooking transitions. These findings are consistent with evidence from Sub-Saharan Africa, where households respond to energy market instability by maintaining multiple fuel options as a coping mechanism [20,44]. This supports the argument that energy stacking reflects rational decision-making under uncertainty rather than incomplete transitions [19,21].

4.4. Income Volatility and the Affordability–Adoption Paradox

The results show that income dynamics, particularly income volatility rather than income level alone, play a key role in shaping household energy choices and sustaining fuel diversification [37,38]. While energy transition theory often emphasizes rising income as a driver of clean fuel adoption [14,15], the findings here suggest a more complex relationship in which unstable and irregular income streams limit sustained use of modern energy technologies, even among households with moderate earnings [16,65]. Price fluctuations increase cost risk [56,58], unreliable electricity introduces supply instability [26], and income volatility constrains sustained use of modern fuels [27], with similar findings reported across multiple developing country contexts [53,57,59].

Descriptive evidence shows that most households fall within the MWK 100,000–500,000 income range, indicating moderate purchasing power [40,61]. However, income is often irregular due to informal and seasonal livelihoods, meaning energy decisions are influenced more by income stability and timing than by average income levels [49,62]. This contributes to persistent reliance on multiple fuels. Econometric results confirm a positive association between income and electricity use for cooking ($\beta = 0.37$, OR = 1.45, $p = 0.002$), but the effect is relatively modest compared to electricity access (OR = 4.14) and appliance ownership (OR = 5.21), indicating that income alone is not a dominant driver.

Despite rising income, energy stacking persists across all income groups, showing that higher earnings do not translate into full substitution away from biomass fuels [50,51]. This pattern reflects an “affordability–adoption paradox,” where households demonstrate willingness and partial ability to adopt clean energy but are unable to sustain exclusive use due to income instability [52]. This is supported by rising willingness to pay for improved stoves, which increased from MWK 9062 to MWK 18,293, indicating strong latent demand that does not fully translate into consistent adoption [65,76]. From a theoretical perspective, this aligns with consumption smoothing and precautionary behavior under uncertainty, where households maintain a portfolio of fuels with different cost structures [26,27]. Electricity and LPG require more fixed or upfront payments, while charcoal allows flexible, incremental purchasing, making it essential during income shortfalls [41,42].

Although willingness to pay for improved cooking technologies increased substantially over time, actual adoption and sustained exclusive use of clean cooking fuels remained comparatively limited [76]. This suggests that stated willingness to pay may not necessarily translate directly into observed adoption behavior under conditions of uncertainty. One possible explanation is hypothetical bias, where respondents express higher willingness to pay in survey settings than they may realistically commit under actual market conditions. In addition, households may face liquidity constraints, irregular income flows,

competing expenditure priorities, and uncertainty regarding future electricity costs, fuel prices, and supply reliability, all of which reduce the likelihood of sustained clean cooking adoption despite positive stated preferences [53,65]. The findings therefore suggest that willingness to pay reflects latent demand and positive consumer attitudes toward clean cooking technologies, while actual adoption decisions remain constrained by broader economic and market uncertainties [34–36]. The findings identify important associations between uncertainty-related factors and household fuel diversification behavior; however, the cross-sectional nature of the data limits the ability to directly observe behavioral change over time or establish causal learning processes. References to behavioral adaptation and adjustment should therefore be interpreted as observed associations and patterns consistent with adaptive household responses to uncertainty rather than definitive causal evidence of dynamic learning effects.

Affordability, identified as the main driver of energy choice (38–45%), therefore reflects liquidity constraints rather than price alone. This distinction between perceived and actual affordability explains continued biomass use. These findings align with evidence from developing countries showing that income volatility, not just income level, drives energy choices and encourages fallback to biomass during financial stress [37,38]. Overall, income volatility reinforces energy stacking as a risk management strategy and highlights the need for financial flexibility mechanisms to support sustained clean energy adoption [65,76].

4.5. Household Size, Demand Pressure, and Energy Portfolio Decisions

The results show that household size is a significant structural determinant of household fuel diversification behavior, influencing energy choices through increased cooking demand, operational cooking requirements, and greater exposure to energy-related uncertainty [46]. The descriptive findings presented in Section 3.1 indicate that household sizes across the surveyed districts were relatively large, with approximately 55.3% of households comprising three to five members and about 28.7% consisting of six or more members. At the same time, the results in Section 3.2 show that cooking intensity remained consistently high across all regions, with most households cooking daily or multiple times per day. Regional comparisons in Table 5 further show that between 50% and 80% of households reported cooking three or more times per day, particularly in the Eastern and Northern regions. These findings collectively indicate substantial and continuous household cooking demand, which increases pressure on household energy systems and influences reliance on multiple fuels and technologies [17,80].

The econometric results presented in Table 7 further confirm a statistically significant negative relationship between household size and electricity use for cooking ($\beta = -0.28$, OR = 0.76, $p = 0.004$), indicating that larger households are less likely to rely primarily on electricity-based cooking systems. The marginal effects analysis in Section 3.7 also shows that an increase in household size reduces the probability of electricity use for cooking by 0.07. At the same time, the descriptive results consistently show persistent energy stacking behavior across all regions and cities. Table 5 identifies energy stacking as the dominant household energy pattern across all regions, while Table 6 shows that all major urban centers, including Blantyre, Lilongwe, Mzuzu, and Zomba, relied on mixed-fuel combinations rather than single-fuel systems. Charcoal remained central to household cooking practices across all cities despite increasing electricity awareness and modest growth in electricity use. Together, these findings suggest that larger households diversify cooking fuels rather than transitioning exclusively toward electricity.

The relationship between household size and fuel diversification appears strongly linked to the practical and operational realities of cooking for larger families. Larger households generally require greater cooking volumes, longer cooking durations, and multiple

cooking activities occurring simultaneously, particularly during peak meal preparation periods. In such contexts, reliance on a single stove or cooking technology may not provide sufficient heating intensity, cooking space, or flexibility to meet household cooking needs efficiently [46]. As a result, households combine different fuels and technologies to manage cooking demand more effectively. For example, electricity may be used for quick cooking tasks, reheating, or boiling, while charcoal and biomass fuels are retained for prolonged cooking activities or preparation of larger meals. These operational dynamics are reflected in the descriptive results, where cooking speed emerged as the most important determinant of cooking fuel and technology choice, accounting for 39.5% of total responses in Table 4. Fuel efficiency (20.5%) and affordability (19.8%) were also among the most highly ranked considerations. These findings suggest that households prioritize cooking systems that provide sufficient capacity, flexibility, and efficiency under conditions of high cooking demand [19,22].

Household size also increases exposure to energy-related risks and supply disruptions, reinforcing incentives for maintaining diversified energy portfolios. Larger households face greater vulnerability to electricity outages, fuel shortages, and fluctuations in fuel prices because interruptions in cooking energy have immediate implications for food preparation and household welfare [26,27]. The results in Section 3.8 further show persistent electricity reliability challenges alongside continued dependence on charcoal across all survey periods. In response to these uncertainties, households maintain multiple fuels as a form of self-insurance against supply disruptions and market instability. Similar patterns have been observed in other Sub-Saharan African contexts. In Zambia, for instance, household energy choices are significantly shaped by gender dynamics, with female-headed households exhibiting different cooking fuel profiles compared to male-headed households [46]. While Ng'ombe et al. [46] focus primarily on gender gaps, their findings also suggest that household composition and size influence energy stacking behavior, consistent with the broader pattern observed in the present study.

4.6. Past Fuel Shortages, Learning Effects, and Behavioral Adaptation

The findings highlight the important role of past fuel shortages and supply disruptions in shaping current household energy behavior. Although not directly quantified in the descriptive tables, the conceptual framework and supporting evidence suggest that households incorporate past experiences into their decision-making, leading to adaptive strategies that prioritize reliability and risk reduction [26,27,53]. Regional patterns in Table 5 provide indirect evidence of this, particularly in the Eastern region, where about 70% of households report no fuel shortages and reliance on charcoal and firewood remains high. In contrast, regions with more variable electricity supply tend to show greater fuel diversification, with households maintaining biomass fuels as backup sources. This indicates that perceived reliability, shaped by historical experience, strongly influences fuel choice.

From a theoretical perspective, this behavior aligns with risk management and adaptive learning theories, where households adjust strategies based on past disruptions to minimize future risk [19–21].

In this context, maintaining multiple fuels functions as “self-insurance” against unreliable energy systems. The persistence of energy stacking, even where modern fuels are available, reflects behavioral inertia reinforced by past experiences rather than purely cost or access factors for the consumers. Evidence from Sub-Saharan Africa similarly shows that households retain traditional fuels to hedge against supply disruptions [44] and that LPG users often revert to biomass when supply is interrupted, underscoring the importance of reliability and trust in sustaining adoption [49]. Overall, these findings suggest that energy transitions are path-dependent, shaped by historical conditions, meaning that effective

interventions must address not only current constraints but also entrenched behavioral patterns formed over time [37,38,64].

5. Policy Recommendations

The findings of this study provide important insights for policy design aimed at accelerating clean cooking transitions in urban and peri-urban Malawi. Central to these findings is the role of uncertainty in shaping household energy decisions, indicating that policy interventions must move beyond traditional demand-side approaches and address systemic market risks. Improving the reliability of electricity supply, stabilizing energy prices, and reducing uncertainty in fuel availability are critical to enabling households to transition toward cleaner cooking solutions. Without addressing these structural constraints, households are likely to continue relying on diversified fuel portfolios as a rational risk management strategy.

Stabilizing energy prices, particularly for charcoal and alternative fuels, is essential to reducing cost-related uncertainty. Fluctuations in charcoal prices and inconsistent pricing of clean fuels undermine household confidence in adopting modern energy solutions. Policy measures should therefore focus on enhancing market transparency, strengthening regulatory oversight of fuel supply systems, and promoting competition within clean cooking markets. These interventions would contribute to more predictable pricing environments, allowing households to make longer-term energy investment decisions.

Improving accessibility to clean cooking fuels requires strengthening supply chains and expanding distribution networks. Limited supplier presence and weak last-mile delivery systems continue to constrain access, particularly in peri-urban areas. Policies that incentivize private sector participation, support the expansion of retail networks, and improve logistics infrastructure can significantly enhance the availability of LPG and electricity-based cooking solutions. Increasing market density and reducing transaction costs will be critical to scaling adoption.

Addressing affordability constraints also requires expanding access to consumer financing mechanisms. Income volatility and liquidity limitations prevent many households from adopting clean cooking technologies despite awareness and willingness to pay. Financing models such as pay-as-you-go (PAYGO) systems, microcredit schemes, and appliance financing can lower upfront costs and enable gradual payment structures. These mechanisms are particularly important in enabling access to electric cooking technologies, which often require higher initial investment.

In addition, promoting enabling technologies, particularly electric cooking appliances, is necessary to support the transition toward modern energy systems. Targeted policy measures, including subsidies, tax reductions, and reduced import duties on clean cooking appliances, can improve affordability and stimulate market growth. Supporting local distribution and after-sales service systems will further enhance adoption and sustained use.

Finally, an integrated policy approach is required to align clean cooking, electrification, and climate objectives. Clean cooking transitions cannot be achieved in isolation but must be embedded within broader energy and development strategies. A market systems approach that simultaneously addresses infrastructure, affordability, reliability, and private sector incentives will be essential for long-term sustainability. Future research should build on these findings by examining the dynamics of uncertainty through longitudinal and experimental studies, with particular focus on how households respond to changes in prices, reliability, and income stability over time.

6. Conclusions

This study examined household cooking energy choices under conditions of uncertainty in urban and peri-urban Malawi and reconceptualized fuel diversification, or energy stacking, as a rational household risk management strategy rather than a transitional inefficiency. Using cross-sectional survey data from 3015 households collected through the 2026 National Consumer Energy Survey, the study demonstrates that uncertainty-related factors significantly shape household cooking energy behavior. The findings show that electricity reliability, charcoal price variability, income volatility, household size, and past fuel shortages all contribute to persistent fuel diversification behavior among households.

The descriptive results revealed that charcoal remains the dominant cooking fuel across all regions and cities despite increasing awareness and gradual growth in the use of electricity and LPG. Electricity use for cooking increased modestly from 26.0% at baseline to between 33% and 35% in 2026, while LPG use increased from 2.1% to approximately 5–7% over the same period. However, more than 80% of households continued to rely on charcoal, confirming that clean cooking transitions remain incomplete and characterized by widespread energy stacking. Across all urban centers, including Blantyre, Lilongwe, Mzuzu, and Zomba, households consistently relied on combinations of fuels rather than exclusive dependence on a single energy source. Charcoal prices also showed substantial variation across cities, ranging from approximately MWK 341–370 per kilogram in Zomba to MWK 741–770 per kilogram in Lilongwe, reinforcing the role of market uncertainty in shaping household energy choices.

The econometric results further confirmed that electricity reliability and infrastructure-related factors strongly influence clean cooking adoption. Electricity access significantly increased the likelihood of electricity use for cooking ($OR = 4.14, p < 0.001$), while reliability of supply also had a strong positive effect ($OR = 3.26, p < 0.001$). Appliance ownership emerged as the strongest predictor ($OR = 5.21, p < 0.001$), highlighting the importance of enabling household assets in clean cooking transitions. In contrast, larger households were significantly less likely to rely primarily on electricity for cooking ($OR = 0.76, p = 0.004$), suggesting that higher cooking demand reinforces diversification behavior and continued reliance on biomass fuels. The results also showed that willingness to pay for improved cooking technologies increased substantially over time, rising from MWK 9062 at baseline to MWK 18,293 in 2024. Nevertheless, this growing willingness to pay did not translate into complete adoption of modern cooking fuels, indicating that affordability constraints, unreliable supply, and income instability continue to limit sustained transitions away from biomass fuels.

The findings therefore challenge the traditional energy ladder hypothesis, which assumes that households progressively abandon traditional fuels as income and access improve. Instead, the results support the energy stacking framework and risk diversification theory by demonstrating that households deliberately maintain diversified energy portfolios to reduce vulnerability to supply disruptions, unreliable electricity, fluctuating fuel prices, and unstable incomes. Under conditions of uncertainty, households use multiple fuels simultaneously as a coping and risk management strategy rather than as evidence of incomplete modernization.

From a policy perspective, the findings suggest that expanding access to clean cooking technologies alone is insufficient to achieve sustained transitions toward modern energy use. Accelerating clean cooking transitions in Malawi will require integrated interventions that address electricity reliability, stabilize clean fuel supply systems, improve affordability, strengthen distribution networks, and expand access to flexible financing mechanisms such as pay-as-you-go models and consumer credit systems. Without addressing the broader structural and market uncertainties shaping household energy decisions, households

are likely to continue relying on diversified fuel portfolios dominated by charcoal and other biomass fuels. The study therefore contributes to the clean cooking and energy transition literature by providing empirical evidence that uncertainty and risk management considerations are central to understanding household cooking energy behavior in Sub-Saharan Africa.

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Abbreviations

3As	Affordability, Accessibility, and Acceptability
BL	Baseline Survey
BT	Blantyre
CMR	Consumer Market Research
ESMAP	Energy Sector Management Assistance Program
LPG	Liquefied Petroleum Gas
LL	Lilongwe
MCHF	Malawi Cooking and Heating Fuel Program
MNL	Multinomial Logistic Regression
MWK	Malawi Kwacha
MZ	Mzuzu
NSO	National Statistical Office
OR	Odds Ratio
SDG	Sustainable Development Goal
SE	Standard Error
USD	United States Dollar
WHO	World Health Organization
WTP	Willingness to Pay
ZA	Zomba

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