Understanding the Complementarity and Substitutability of Cooking Fuels in Developing Countries: Evidence from 2020/21 Tanzania National Panel Survey

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Abstract
Increasing access to alternative energy sources in developing countries might be a potential for multiple energy consumption rather than switching from traditional to modern ones. This study aims to examine the complementarity and substitutability of cooking fuels and factors influencing households' choices of such fuels. Two categories of cooking energy were considered: traditional (dirty) fuels - firewood, charcoal and kerosene; and modern (cleaner) fuels - Liquefied Petroleum Gas (LPG) and electricity. Based on a nationally representative sample of 5,199 households from the Tanzania National Panel Survey (NPS) of 2020/21, results from a Multivariate Probit model indicate that there is strong substitutability between traditional and modern fuels. Moreover, substitutability exists between solid fuels, while cleaner sources complement each other. Households' cooking energy decisions were observed to be influenced by demographic and socioeconomic factors. In light of these findings, the study recommends appropriate policy packages for fastening energy transition in developing countries.

Keywords: *Cooking fuel choices; Energy transition; Energy ladder; Energy stacking; Tanzania*

JEL : *C31, D12, Q42*

1. Introduction

Majority of the households in developing countries heavily depend on solid biomass to meet their cooking energy needs. About 2.7 billion people worldwide use traditional sources of energy, while some 1.2 billion still live without access to electricity, of which 590 million are from Sub-Saharan Africa (International Energy Agency, 2022). Heavily relying on traditional fuels has been linked with adverse environmental and health effects (Batinge et al., 2019; Twumasi et al., 2021). According to estimates, household air pollution from cooking energy smoke accounts for the deaths of 3.2 million

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people annually, including about 237,000 under five deaths (World Health Organization, 2024). Besides, increased dependence on firewood triggers environmental destruction such as loss of biodiversity and soil erosion (Makonese et al., 2018). Similarly, unsustainable harvest of wood products accelerates deforestation and degradation of forests and lands which negatively affect economic growth (Assa et al., 2015).

Concerning environmental and health problems, the use of traditional energy, such as residues from plants and animals increases the work burden, especially for women and children. These groups are exposed to pollution from indoor cooking smoke due to spending a lot of hours near cooking fires. In addition, the long hours spent in firewood collection by women and children have been shown to have both short-run and long-run consequences in their education outcomes (Karimu et al., 2016). Moreover, consumption of dirty fuels has been associated with deaths, especially for pregnant women in many African countries. It is estimated that about 500,000 premature deaths are observed from households that consume solid fuels in Africa (International Energy Agency, 2022).

The Sustainable Development Goal 7 (SDG-7) which ensures access to clean, modern, affordable, reliable and sustainable energy for all by 2030, has been regarded as a key policy for socio-economic and human development. Developing countries have been striving to help their communities shift from traditional to cleaner and environmentally friendly sources of energy. The usage of modern energy has brought positive effects on society and the economy, though the transition from one form of energy to another is complex. Energy transition may involve moving from entirely using traditional energy to consumption of an energy mix (i.e., both traditional and modern) or a complete transition from traditional to modern energy. Generally, the majority of households in the Least Developed Countries (LDCs) tend to complement different sources of cooking energy, for instance, traditional fuel like firewood may be used in combination with intermediate sources like kerosene and modern sources such as electricity (Imran & Ozcatalbas, 2020). In Tanzania, around 90% of the households depend on wood and charcoal as their primary cooking energy, while the remaining 10% mainly consume LPG, electricity and other sources (URT, 2024). The use of charcoal has been responsible for deforestation of about 23,308 hectares, around 20% of closed woodland (Doggart & Meshack, 2017). Various measures were in place to increase access to modern energy services especially in rural areas, including the establishment of the Rural Energy Agency (REA) in 2005. Following such initiatives, the country has been recording a substantial increase in the proportion of population with access to electricity. For instance, in 2020, REA reported that about 78.4% of the population was connected to electricity (NBS, 2020). The National Development Plan 2021/22 – 2025/26 targets to increase electricity connectivity to 85% by 2026. Conversely, households using electricity as the primary source of cooking energy remained below 1%

(NBS, 2022). The government of Tanzania has recently launched the National Clean Cooking Strategy (2024 – 2034). The strategy aims to ensure that 80% of Tanzanians transit to clean cooking by 2034 (URT, 2024). Moreover, the country has potential for utilizing other sources of fuel following the natural gas discovery in Mtwara and Lindi regions. The estimated volume of natural gas deposits is approximately 57.54 trillion cubic feet (EWURA, 2022). Currently, a total of 1,511 households in Mtwara, Lindi and Dar es Salaam have been connected to natural gas (URT, 2024).

Regarding households switching from traditional to clean cooking energy, factors for the fuel choices has become more relevant from the policy perspective (Assa et al., 2015). Worldwide, policymakers relate households' cooking energy choices with the fuel's affordability and availability (Jan et al., 2012). This is especially for rural households who have limited choices for cooking energy (Nnaji et al., 2012). On the other hand, urban dwellers have a wider alternative, and modern commercial energy sources are relatively more available and accessible; therefore, a greater potential for fuel switching (Assa et al., 2015). However, the presence of alternative energy sources could be regarded as a potential for multiple energy consumption rather than switching from traditional to modern and cleaner energy (Baiyegunhi & Hassan, 2014). Following multiple fuel consumption practices in developing countries, most studies have examined the determinants of the main cooking energy choice (Imran & Ozcatalbas, 2020; Karimu et al., 2016; Sana et al., 2020), whereas little attention has been paid to the factors for energy switching and multiple fuel usage. The objective of this study is therefore to; (i) explore the determinants of cooking energy choices, and (ii) examine the complementarity and substitutability of energy choices among Tanzanian households

The rest of the paper is organized as follows, section 2 outlines the methodology used in this study, section 3 describes results and discussion, and the last section presents conclusions and policy implications.

2. Material and Methods

2.1 Theoretical Framework

Energy transition theories explain how the households switch from inferior and dirty to modern and cleaner fuels. Two theories have been developed to explain the household's energy transition patterns. First, the energy ladder hypothesis which describes the behavior of a utility-maximizing consumer on choices for cooking fuel. Based on this theory, households switch from a primitive fuel to a more advanced fuel as income increases. Although there is an argument on whether the household income is a single determinant of the movement along the energy ladder (Gupta & Köhlin, 2006), most empirical studies have shown to support the energy ladder hypothesis (Masera & Navia, 1997; Mwaura et al., 2021; Pallegedara et al., 2021). On the other hand, the energy-stacking hypothesis assumes transition in cooking energy takes place through the usage of multiple fuels instead of a single fuel at a time (Masera & Navia, 1997). The household may switch back to a traditional fuel even after shifting to the modern ones, as specific fuels might be preferred for specific tasks (Pachauri et al., 2004).

This study explores the energy transition pattern followed by the Tanzanian communities by using the framework suggested by Hassen (2015) and Twumasi et al. (2021). It relies on the household's decisions on choosing the cooking energy based on various households' and energy characteristics. The framework is modeled by using a random utility framework. The household decides whether to (i) stick on traditional energy (ii) switch from traditional to modern energy sources or (iii) use both traditional and modern sources. A model is developed with an assumption that that μ_j^t represents the utility received by the household for stacking on energy (j) which is a traditional source (t), μ_j^m represents the benefit household gets for switching from traditional to modern energy (m). Therefore, the household may decide to stick on a traditional fuel if and only if:

$$Y_{ij}^* = U_{ij-}^t U_{ij}^m > 0 \ (1)$$

In addition, the household might decide to shift from traditional to modern energy or use multiple energy if and only if,

$$Y_{ij}^* = U_{ij-}^m U_{ij}^t \geq 0 \ (2)$$

Whereby Y_{ij}^* shows the latent benefits received by the household for using either type of energy source. This latent variable is also modeled as;

$$Y_{ij}^* = X_{ij}\beta_{j+} \varepsilon_{ij} \quad (3)$$

$$\varepsilon_{ij} = \alpha_j + \eta_{ij} \ (4)$$

Where X_{ij} represents the observed characteristics of household i and energy source j [$j =$ firewood F, charcoal C, kerosene K, LPG G and electricity E], β_j is the vector for unknown parameters for the jth energy use. Equation (3) has the composite error term ε_{ij} which is formed from two components; one consists of unobserved characteristics (α_j) and the other includes observed individual household characteristics (η_{ij}).

Since the net benefit received by the household for consuming either traditional, modern, or mixed energy sources is unobservable (latent), another equation is needed to map an observable binary variable that reflects the usage of energy sources j. This can be presented in equation 5.

$$Y_{ij} = \begin{cases} 1 \ if \ Y_{ij}^* > 0 \\ 0 \ if \ Y_{ij}^* \leq 0 \end{cases} \ (5)$$

Moreover, if we assume the error terms are identically and independently distributed across the households' decisions on cooking energy for both traditional and modern energy, five Equations would represent five separate energy adoption models, of which the first three would represent traditional energy adoption while the rest would be used to estimate the modern energy adoption. This approach assumes that the choices between traditional and modern energy are not correlated. However, a household may adopt two or more energy sources simultaneously. Furthermore, switching to modern energy use is more likely to cause a correlation between the unobservable error terms of two or more decisions because the usage of one energy might induce the application or non-application of another energy source. Therefore, the choice of one energy source depends on the usage or non-usage of the other.

If this is the case, then the household makes two discrete decisions that are interrelated, first, decides whether to shift to a modern (or package of modern) energy source(s). Secondly, he/she further decides to stop using (dis-adopt) traditional (or package of traditional) energy source(s). Estimation by using a single Equation approach could cause bias and inefficiency in the estimated parameters if the interdependence is observed and/or if unobserved heterogeneity is correlated among the energy consumption decisions. Since choices for fuels are interrelated, both non-linear and linear seemingly unrelated simultaneous Equations (SURE) are the best models for explaining the relationships. These models comprise several regression Equations, of which every Equation has its own dependent variable and may have different sets of explanatory variables. The SURE model allows correlation among the unobserved disturbances of a set of linear regression models. Moreover, since the binary dependent variables of cooking fuel choice were used in a set of estimated Equations, a specific form of SURE- a Multivariate Probit method (MVP) was employed. Thus, the energy choice models presented in equation 3 are linear regression Equations with different dependent variables, explanatory variables and error terms which are allowed to be correlated across the energy choice equations. The interdependence of choices between consumptions and non-consumptions of energy sources is determined by the signs and significance of the off-diagonal elements of the variance-covariance matrix Σ of the MVP model, presented as;

$$\Sigma = \begin{bmatrix} 1 & \rho FC & \rho FK & \rho FG & \rho FE \\ \rho CF & 1 & \rho CK & \rho CG & \rho CE \\ \rho KF & \rho KC & 1 & \rho KG & \rho KE \\ \rho GF & \rho GC & \rho GK & 1 & \rho GE \\ \rho EF & \rho EC & \rho EK & \rho EG & 1 \end{bmatrix} \quad (6)$$

where $\rho_{jj'}$ is the correlation coefficient (rho) of the residuals ε_{ij} and $\varepsilon_{ij'}$ of the regression equations of which dependent variables are the choices of energy j [$j =$ firewood F, charcoal C, kerosene K, LPG G and electricity E]

2.2 Source of data

This study used the fifth wave of the Tanzanian National Panel Survey (NPS) which took place from December 2020 to January 2022. The survey contains a nationally representative sample of 5,893 households; where, 1,184 households are from *extended panel*, and 4,709 households from the *refresh panel* (NBS, 2022). This survey was selected primarily because it represents the most recent wave, providing up-to-date data reflective of current conditions. Apart from being the recent wave, this survey was selected because it offers a larger sample size compared to previous rounds. Since some of the cooking fuels are typically consumed by a small number of households, it is possible to estimate fuel choice models when larger sample is used. In addition, earlier waves, i.e., 1-3, despite containing valuable data, utilized a different sampling framework that could not be seamlessly integrated with the fifth wave. This lack of compatibility between the sampling designs hindered our ability to merge these datasets effectively, necessitating our focus on the most recent wave.

NPS collects various information on households, agriculture, community, livestock and fisheries by using questionnaires. The survey offers comprehensive information on household income and consumption (including energy choices and usage). After compiling and cleaning the dataset, 694 households were excluded due to various missing information, thus the final sample remained for analysis consisted of 5,199 households. Further details about the design and methodology for data collection are provided in the survey's main report (NBS, 2022); and the dataset is freely available online: https://microdata.worldbank.org/index.php/catalog/5639.

2.3 Empirical specification of the model

The choice of cooking energy consumed by the household depends on various household and energy characteristics. In this paper, selection of the variables to form energy choice models was based on previous studies. Household head characteristics such as sex was included in (Karimu et al., 2016; Liao et al., 2019; Soltani et al., 2019), age (Baiyegunhi & Hassan, 2014, p. 31; Liao et al., 2019, p. 106; Soltani et al., 2019, p. 3), education (Pallegedara et al., 2021; Twumasi et al., 2021) and occupation (Baiyegunhi & Hassan, 2014; Liao et al., 2019). Other studies included the dependency ratio (Nwaka et al., 2020; Sana et al., 2020; Sharma, 2019; Wassie et al., 2021), family wealth status (Ishengoma & Igangula, 2021; Nwaka et al., 2020; Sana et al., 2020), location (Assa et al., 2015; Khundi-Mkomba, 2021; Nwaka et al., 2020) and house ownership (Baiyegunhi & Hassan, 2014; Khundi-Mkomba, 2021). From the theoretical model presented in Equation 3, a set of empirical models for cooking energy choices can be presented as follows;

$$EC_{ij} = \beta_{oj} + \beta_{1j}sex + \beta_{2j}midage + \beta_{3j}oldage + \beta_{4j}secondary + \beta_{5j}tertiary + \beta_{6j}agr + \beta_{7j}dependency + \beta_{8j}poorer + \beta_{9j}middle + \beta_{10j}rich + \beta_{11j}richest + \beta_{12j}rural + \beta_{13j}ownhouse + \varepsilon_{ij} \quad (7)$$

Where, EC_{ij} is the household $i's$ choice on using cooking energy source j, βs and ε are parameters and error term of the model, respectively. A detailed description of the variables included in the models is provided in Table 1 below;

Table 13: Description of the Variables Used in Analysis.

Variable	Description
Dependent variables	Household cooking energy choice (Energy consumption over the past 30 days)
use_firewood	1 if the household consumed firewood, 0 otherwise
use_charcoal	1 if the household consumed charcoal, 0 otherwise
use_kerosene	1 if the household consumed kerosene, 0 otherwise
use_LPG	1 if the household consumed gas, 0 otherwise
use_electricity	1 if the household consumed electricity , 0 otherwise
Independent variables	Household characteristics
sex	Gender of the household head (1 if a male, 0 if a female)
	Characteristics of the household head
midage	1 if age is between 36 and 59 years, 0 otherwise
oldage	1 if age is 60 years and above, 0 otherwise
secondary	1 if the highest educational level is secondary, 0 otherwise
tertiary	1 if the highest educational level is tertiary, 0 otherwise
agr	1 if the household main occupation for the past 12 months is agriculture, 0 otherwise
	Characteristics of the household
dependency	Determined by the total number of household members with age between 0 and 14; and 65 and above, divide by the number of members aged between 15 and 64.
poorest	1 if the household is in the poorest group, 0 otherwise
poorer	1 if the household is in the poorer group, 0 otherwise
middle	1 if the household is in the middle group, 0 otherwise
rich	1 if the household is in the rich group, 0 otherwise
richest	1 if the household is in the richest group, 0 otherwise
rural	Household residence (1 if the household lives in rural area, 0 otherwise)
ownhouse	House ownership (1 if the household owns a house, 0 otherwise)

3. Results and Discussion

3.1 Descriptive results

Summary statistics of the variables included in the analysis is presented in Table 2. Results indicate that firewood was the most consumed source of cooking energy (57%), followed by charcoal (43%), LPG (14%) kerosene (13%) and electricity (8%). Majority (75%) of the households were male-headed, and about 30% were young adults of age between 15 and 35 years, 52% were middle-aged, while 18% of households headed by old aged heads. Regarding education, majority (84%) had primary education with few got secondary (12%) or tertiary (4%) education. Dependency ratio ranged between 0 and 10 with an average of 0.93. Nearly half of the households (48%) engaged in agriculture as the main occupation for the past 12 months. About 60% of the households were living in rural areas, while 68% were living in their own houses. Furthermore, the disaggregation of summary statistics based on location (see appendix A1) indicates that there was a big disparity in energy choices and socio-economic characteristics of the households (level of education, occupation, dependency ratio and wealth) between rural and urban areas.

Table 14: Summary Statistics of the Variables Used in the Analysis

Variable	Units	Obs.	Mean	Std. dev.	Min	Max
use_firewood	1 or 0	5,199	0.57	0.49	0	1
use_charcoal	1 or 0	5,199	0.43	0.50	0	1
use_kerosene	1 or 0	5,199	0.13	0.33	0	1
use_gas	1 or 0	5,199	0.14	0.35	0	1
use_electricity	1 or 0	5,199	0.08	0.38	0	1
sex	1 or 0	5,199	0.75	0.43	0	1
midage	1 or 0	5,199	0.52	0.50	0	1
oldage	1 or 0	5,199	0.18	0.38	0	1
secondary	1 or 0	5,199	0.12	0.33	0	1
tertiary	1 or 0	5,199	0.04	0.19	0	1
dependency	Ratio	5,199	0.93	0.87	0	10
agr	1 or 0	5,199	0.48	0.50	0	1
poorest	1 or 0	5,199	0.18	0.38	0	1
poorer	1 or 0	5,199	0.19	0.39	0	1
middle	1 or 0	5,199	0.20	0.40	0	1
rich	1 or 0	5,199	0.21	0.41	0	1
richest	1 or 0	5,199	0.22	0.42	0	1
rural	1 or 0	5,199	0.60	0.49	0	1
ownhouse	1 or 0	5,199	0.68	0.47	0	1

Source: Authors computation based on NPS (2020/21)

The unconditional probability of household consuming firewood was 57% (see Table 3), this was reduced up to 12% conditional on using it in combination with charcoal. The probability of using firewood was 8%, 1% and 2% conditional on using it with kerosene, LPG and electricity, respectively. This implies that firewood is less likely to be consumed with other fuels. The unconditional probability of a household consuming charcoal was 43%, and it was reduced when consumed with other dirty fuels (17% and 19%) than clean ones (20% and 29%). It implies that charcoal is more likely to be consumed with clean fuels than other traditional fuels. The unconditional probability of using kerosene was 13%. This was increased when it is consumed with other fuels, suggesting that kerosene is a fuel that was rarely consumed as a single source, it is mostly consumed in combination with other sources (Doggart et al., 2020), and mostly charcoal. The unconditional probability of a household consuming LPG was 14%. However, it was reduced to 6% and 13% when LPG was used with firewood only, and kerosene only respectively. Probability of consuming LPG increases when used in combination with charcoal only (62%), electricity only (83%), firewood and electricity (49%), charcoal and electricity (59%), kerosene and electricity (55%); and charcoal, kerosene and electricity (54%). Electricity was unconditionally consumed by 8% households, dropped to 2% when consumed with firewood, but raised to 29%, 21%, and 83% when consumed with charcoal, kerosene and LPG respectively. These results imply that electricity is less likely to be consumed with firewood but more likely to be consumed with other sources such as charcoal and LPG. Moreover, since electricity is relatively expensive, households are more likely to consume it with other sources of fuels.

Table 3: Unconditional and Conditional Probability of Energy Choices.

	Firewood	**Charcoal**	**Kerosene**	**Gas**	**Electricity**
One source (unconditional)	0.57***	0.43***	0.13***	0.14***	0.08***
Source with F	1	0.12***	0.08***	0.01***	0.02***
Source with C	0.17***	1	0.19***	0.20***	0.29***
Source with K	0.35***	0.65***	1	0.15***	0.21***
Source with LPG	0.06***	0.62***	0.13***	1	0.83***
Source with E	0.07***	0.72***	0.15***	0.68***	1
Source with F & C	1	1	0.13***	0.06***	0.08***
Source with F & K	1	0.20***	1	0.02***	0.03***
Source with F & LPG	1	0.49***	0.12***	1	0.72***
Source with F & E	1	0.49***	0.13***	0.49***	1
Source with C & K	0.11***	1	1	0.19***	0.29***
Source with C & LPG	0.05***	1	0.17***	1	0.84***
Source with C & E	0.05***	1	0.19***	0.59***	1
Source with K & LPG	0.05***	0.83***	1	1	0.78***
Source with K & E	0.06***	0.88***	1	0.54***	1
Source with LPG & E	0.04***	0.63***	0.12***	1	1
Source with F, C & K	1	1	1	0.06**	0.11**
Source with F, C & LPG	1	1	0.14**	1	0.67***
Source with F, C & E	1	1	0.16***	0.45***	1

Source with F, K & LPG	1	0.63	1	1	0.8
Source with F, K & E	1	0.62	1	0.50	1
Source with F, LPG & E	1	0.46***	0.11**	1	1
Source with C, K & LPG	0.05**	1	1	1	0.73***
Source with C, K & E	0.04**	1	1	0.54***	1
Source with C, LPG & E	0.03***	1	0.15***	1	1
Source with K, LPG & E	0.04***	0.81***	1	1	1
Source with F, C, K & LPG	1	1	1	1	0.40
Source with F, C, K & E	1	1	1	0.33	1

Note: Statistical significance at 1%, 5% and 10% are denoted by *, ** and *** respectively
F = firewood, C = charcoal, K = kerosene, G = LPG and E= electricity
Source: Authors computation based on NPS (2020/21)

3.2 Regression results

Regression analysis was conducted to examine the determinants of households' cooking energy decisions as well as the interdependencies of such decisions. The analysis was done first by including the pool of all households and secondly, by conducting a separate analysis for rural and urban households. This was due to the fact that rural and urban areas differ in terms of energy usage, availability and affordability which might affect households' energy consumption decisions. Thus, Tables 4 and A2 present results based on such groups. The Wald chi-square (χ^2) statistics was used to test the fitness of the MVP model. Results from the pooled, rural and urban dataset suggests that models were correctly specified and selected explanatory variables are relevant in explaining the household's cooking energy decisions. The likelihood ratio test confirms the existence of a correlation between household's decisions on fuel choices.

From the regression analysis, results show that sex of the household head influences choices on all fuel consumption. Overall, the gender of the household head had an influence on the choices of all fuels except firewood. Results show that a female headed household is more likely to consume charcoal and clean sources of fuel. The likelihood of choosing charcoal, LPG and electricity increases by 11%, 23% and 12% respectively, when the household is headed by a female. Unfolding the results further reveals that, choices for charcoal consumption by female heads are predominantly in rural areas, while in urban areas, female headed households are more likely to consume modern fuels (see Appendix A2). The fact that females spend more time for cooking as compared to males might induce their choices of clean fuels to save their time and health. The influence of the gender of the household head was also observed by Karimu et al. (2016) and Soltani et al. (2019).

The age of the household head had a strong influence on fuel decisions. Results indicate that the households with middle- and adult-aged heads were more likely to choose firewood or kerosene, and less likely to choose charcoal and LPG as compared to households headed by young adults. For instance, middle aged household head was more likely to choose firewood and kerosene by 29% and 14% respectively, and less likely to choose charcoal and LPG by 11% and 12% respectively, than households headed by young adults. This means that young adults had higher probability of choosing charcoal and LPG than middle and old adults. This result was also reflected in rural areas, where young adults were more likely to choose charcoal, while firewood and kerosene were more likely to be consumed by middle and old adults. Similarly, middle and old adults in urban areas preferred firewood and kerosene, while young adults were more likely to consume clean fuel (i.e., LPG). Results suggest that while solid fuels are most preferred in rural areas, charcoal is mostly consumed by young adults, while firewood is typically preferred by middle and old adults.

Regarding education of the household head, results show that there is a shift from traditional to modern fuels when the household head attains a higher education level. Specifically, having a secondary education decreases the likelihood of choosing firewood and kerosene by 31% and 13% respectively; while the likelihood of choosing LPG and electricity increases by 41% and 35% respectively. Moreover, attaining tertiary education reduces the likelihood of consuming all traditional fuels, and increases the likelihood of choosing LPG and electricity by more than one fold and by 72% respectively. In rural areas, having a secondary education increases the likelihood of consuming charcoal, LPG, and electricity, while tertiary education strongly increases the likelihood of choosing modern fuels. Similarly, all traditional fuels are less consumed, while modern are likely to be consumed by secondary and tertiary educated households. The fact that modern fuels are less reliable and relatively less available in rural areas, attaining higher level of education will only make a household shift to from firewood to a better solid fuel (charcoal). On the other hand, in urban areas, households with secondary and tertiary educated heads will completely transit to modern fuels as they are aware of the pros and cons of every fuel and availability and reliability is not a problem. Higher educated households are less likely to choose traditional cooking fuels (firewood, charcoal and kerosene) and more likely to choose modern fuels i.e. LPG and electricity. This implies that having a household head with at least a secondary education may help the household to refrain from dirty fuel usage. In addition, a complete transition from traditional to modern energy requires not only a tertiary education but also easy availability and accessibility of modern sources. Education impact on the transition to cleaner energy was also observed by Twumasi et al. (2021), Pallegedara et al., (2021) and Mukhadi et al. (2021).

The results show that the dependency ratio has influence on the choices of households on firewood and modern fuels. Results from pooled regression show that households with higher dependency ratio are more likely to choose firewood and less likely to choose any of the modern fuel. Specifically, households with bigger dependency ratio were more likely to choose firewood by a factor of 0.199 (20%), and less likely to prefer LPG and electricity by 16% and 14% respectively. As for rural areas, households with more dependents were more likely to choose firewood and less likely to choose charcoal, LPG and electricity, while in urban areas either firewood or charcoal was selected by households with many dependents, and modern fuels were likely to be consumed by households with fewer dependents. Family planning initiatives may be among the policy components for accelerating transition to clean cooking energy (Ifegbesan et al., 2016; Khundi-Mkomba, 2021; Lokina & Lwiza, 2018; Mukhadi et al., 2021; Soltani et al., 2019; Wassie et al., 2021).

Employment in agriculture also strongly influences decisions on cooking fuels. The family whose household head engaged in agriculture as the main occupation was more likely to choose firewood as the cooking fuel, as observed by (Liao et al., 2019) and less likely to choose charcoal, kerosene, LPG and electricity. Results show that household heads engaged in agriculture as the main occupation increased their choice of firewood by 86%, whereas the likelihood of choosing other sources of fuel were reduced. This result was also reflected in both rural and urban households. The engagement in agricultural activities may increase accessibility for agricultural residuals which can be used as firewood.

Results show that the likelihood of choosing firewood decreases as the household ascends to higher wealth status. However, graduating to a wealthier group increases the likelihood of choosing charcoal and kerosene. Graduating to a poorer household reduces the likelihood of choosing firewood by 29% and raises the probability of choosing charcoal by 43%. However, being a rich household only reduces the probability of choosing firewood (by 1.6 fold), and increases the probability of choosing the rest of the fuels. Further disaggregation of the dataset between rural and urban areas, results indicate that wealthier groups are more likely to choose modern fuels. Interestingly, the consumption of modern fuels by wealthier households is accompanied by charcoal and kerosene in rural areas, and only charcoal in urban areas. The fact that LPG is less likely to be consumed with kerosene, the availability and reliability increase the likelihood of its consumption and a reduction in consumption of kerosene in urban areas. Moreover, LPG and electricity were chosen by the top 60% and 40% households respectively. This results are in line with the studies by (Khundi-Mkomba, 2021; Sana et al., 2020; Soltani et al., 2019).

Concerning location, the findings indicate that the location of the household is a strong predictor of cooking fuel choices. Rural households were more likely to choose firewood (by 72%) and less likely to choose the rest of the fuels. This was due to easy availability, accessibility and affordability of firewood in rural areas (Ifegbesan et al., 2016; Wassie et al., 2021). Moreover, agriculture is the main activity in rural areas, which assures the families engaging in this activity a reliable source of cooking energy. On the other hand, in urban areas, the engagement in other activities apart from agriculture helps the household shift to other sources of fuel.

Lastly, house ownership has an influence on households' decisions on cooking fuel. Households that were living in their own houses were more likely to consume firewood and kerosene by 69% and 10% respectively, and less likely to choose the rest of the fuels. Specifically, rural dwellers who were living in their own houses were more likely to consume firewood and kerosene, and less likely to consume charcoal and electricity. Similarly, urban dwellers who were living in their own houses were more likely to consume firewood and less likely to consume LPG and electricity. Normally, households that live in their own houses are free to use any source of energy, even if it is not environmentally and health-friendly. Moreover, they have spaces for setting up traditional stoves (Khundi-Mkomba, 2021), unlike the rented houses of which due to some restrictions, tenants end up using charcoal and modern fuels.

Table 4: Determinants of the Households' Cooking Energy Decisions.

	Firewood	Charcoal	Kerosene	LPG	Electricity
sex of the hh head	0.03	-0.11**	0.10*	-0.23***	-0.12***
	(0.06)	(0.05)	(0.06)	(0.07)	(0.07)
Middle aged hh head	0.29***	-0.11**	0.14*	-0.12*	0.00
	(0.06)	(0.05)	(0.06)	(0.07)	(0.07)
Old adult	0.32***	-0.13*	0.31***	-0.14	0.06
	(0.08)	(0.07)	(0.08)	(0.10)	(0.10)
Secondary	-0.31***	-0.02	-0.13*	0.41***	0.35***
	(0.07)	(0.07)	(0.07)	(0.07)	(0.07)
Tertiary	-0.50***	-0.20*	-0.24**	1.03***	0.72***
	(0.14)	(0.11)	(0.12)	(0.11)	(0.11)
Dependency	0.20***	-0.03	0.01	-0.16***	-0.14***
	(0.03)	(0.02)	(0.03)	(0.04)	(0.04)
Agriculture	0.86***	-0.62***	-0.43***	-0.36***	-0.51***
	(0.06)	(0.05)	(0.06)	(0.08)	(0.09)

	Firewood	Charcoal	Kerosene	LPG	Electricity
Poorer	-0.29***	0.43***	0.03	0.30	-0.24
	(0.10)	(0.08)	(0.10)	(0.31)	(0.29)
Middle	-0.65***	0.93***	0.28***	0.64**	0.31
	(0.09)	(0.08)	(0.09)	(0.28)	(0.26)
Rich	-1.14***	1.25***	0.29***	1.50***	1.20***
	(0.09)	(0.08)	(0.10)	(0.27)	(0.25)
Richest	-1.63***	1.34***	0.40***	2.27***	2.37***
	(0.10)	(0.09)	(0.10)	(0.27)	(0.25)
Rural	0.72***	-0.50***	-0.40***	-0.22***	-0.24***
	(0.05)	(0.05)	(0.06)	(0.07)	(0.07)
Own house	0.69***	-.25***	0.10*	-0.14**	-0.32***
	(0.05)	(0.05)	(0.06)	(0.06)	(0.06)
Constant	-0.48***	-0.13	-1.27***	-2.06***	-1.74***
	(0.11)	(0.10)	(0.12)	(0.29)	(0.25)
	ρCF	-0.70***		ρGC	-0.19***
		0.02			0.03
	ρKF	-0.03		ρEC	-0.02
		0.03			0.04
	ρGF	-0.18***		ρGK	-0.17***
		0.04			0.04
	ρEF	-0.20***		ρEK	-0.16***
		0.04			0.04
	ρKC	0.06**		ρEG	0.71***
		0.03			0.02
Number of Observations		5199			
Model test-Wald $\chi^2(65)$		4716.63			
Log likelihood		-7733.77		Prob > χ^2	= 0.00
Likelihood ratio test $\chi^2(10)$		1594.58		Prob > χ^2	= 0.00

Note: p = rho = correlation coefficient, F = firewood, C = charcoal, K = kerosene, G = gas, E = electricity. Statistical significance at 1%, 5% and 10% are denoted by *, ** and *** respectively, standard errors in parentheses
Source: Author computation based on NPS (2020/21)

Regarding the relationship between energy choices, the signs of correlation coefficients shown in Tables 4 indicate the type of relationship that exists between cooking fuels. It is observed that there was a strong negative and significant correlation between charcoal and firewood [ρCF = -70%], and it was revealed in both rural and urban areas. This negative correlation suggests that firewood and charcoal are substitute energy sources. Ascending to a higher wealth group is among the contributing factors for the households to substitute firewood for charcoal. Results also indicate that there is substitutability between firewood and modern fuels; between kerosene and modern fuels; and between charcoal and LPG in both rural and urban areas. Moreover, a significant positive correlation between charcoal and kerosene usage was revealed particularly in urban area [ρKC= 6%]. However, unlike results from descriptive statistics, MVP indicates a significant negative correlation between charcoal and LPG [ρGC= -19%] in pooled data and in urban area. However, there were mixed results in rural and urban areas regarding the consumption of charcoal with modern fuels. Charcoal and electricity were complement in rural areas [ρGC= 13%], but substitute in urban area with both LPG and electricity, [ρGC = -29%], [ρEC = -7%], respectively. Likewise, there is a significant negative relationship between kerosene and modern fuels in rural and urban areas, implies that kerosene is considered as a substitute for modern cooking fuels. In urban areas, the supply of modern energy is relatively higher compared to rural areas, thus we can suggest that the substitutability of kerosene for modern energy might not only be caused by household affordability but also the availability of modern cooking energy. On the other hand, LPG and electricity had a strong positive and significant correlation [ρEG= 71%] and was revealed in both rural and urban households. Generally, the findings suggest that there is substitutability among traditional energy sources as well as between traditional and modern energy sources, while complementarity exists between modern energy sources.

The findings from this study corroborate with both the energy ladder and energy-stacking hypotheses. Results indicate that households switch from a traditional/dirty fuel to a more advanced fuel as income increases, consistent with the energy ladder hypothesis. Moreover, the argument that household wealth is not the only factor for energy switching was observed. Apart from wealth, other factors such as sex, level of education and occupation of the household head, dependency ratio and household ownership also influenced energy transition. Besides, energy-stacking was observed particularly in rural areas, where charcoal was jointly consumed with modern fuels due to its relatively less accessibility, affordability and reliability of modern fuels than in urban areas.

4. Conclusion and Policy Implications

This study examined the complementarity and substitutability of cooking fuels and the determinants of households' energy choices in Tanzania. Both descriptive and inferential analyses were presented in this paper.

Results from conditional and unconditional probability indicate that households were more likely to choose firewood as a single source, and kerosene in combination with other fuels, implying that while firewood is the traditional fuel mostly consumed as a single source, kerosene is mostly consumed with other sources. Moreover, the regression analysis shows that the choice of traditional fuels was negatively correlated with the choice of modern sources, implying that traditional fuels are likely to be substituted when the household decides to switch to low-carbon emitting fuels. However, energy stacking was observed in rural areas where an insufficient supply of modern fuels exists, as charcoal was used in complement with electricity. Adequate supply of modern fuels reduces the complementarity between traditional and modern energy, and therefore ensures a complete transition.

Results indicate that female headed households were more likely to transit to clean cooking energy than those headed by males. These findings shed light on the importance of mainstreaming gender in modern energy transition efforts. Elevating the participation of women particularly in male-headed household decision making may accelerate energy transition. It was also observed that the number of dependents in the household is one of the factors that hinder households from substituting firewood and charcoal with cleaner fuels. The study recommends family planning policies for fastening energy transition in developing countries. Moreover, education plays a crucial role in energy transition; a secondary education reduces the likelihood of the household's choices on firewood and kerosene but stacks with charcoal, while tertiary education ensures a complete low-carbon energy transition. As engagement in agriculture shown a great influence on firewood consumption, enhancing agroforestry might be a suitable strategy to ensure energy security and prevent households from encroaching toward the forest lands.

We also observed that households' wealth status influences their choices of cooking energy. Ascending to a wealthier group increases the likelihood of the household shifting to cleaner cooking energy. Policies for enhancing income-generating activities may be helpful for accelerating the transition to cleaner fuels.

Furthermore, the complementarity and substitutability analysis indicate that there is a strong substitutability between LPG and all traditional fuels. Regarding this, two alternative policy moves may be considered; (i) banning charcoal consumption- this can be gradually implemented by starting from urban areas where there is high consumption of charcoal and relatively high supply of alternative source of fuels. However, this move should be carefully designed and implemented to prevent households from turning back to firewood consumption. It should go hand in hand with initiatives that enhance the availability and reliability of modern energy mix such as biogas, LPG and natural gas (ii) Increasing taxation on charcoal and kerosene to further finance LPG subsidies and natural gas distribution infrastructure to accelerate the number of households connected to natural gas.

However, due to limited information, the analysis of this paper was based on non-price factors for households' transition from traditional to cleaner sources of fuel. Moreover, the study was not able to examine the complementarity and substitutability of fuels based on the changes in volumes of household energy consumption. Future studies may capitalize on the available data and take into account price factors and energy consumption levels to examine the complementarity and substitutability of cooking energy sources.

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Appendix A1: Summary Statistics of the Variables Disaggregated by Location

	Rural		Urban	
Variable	**Mean**	**Std. dev.**	**Mean**	**Std. dev**
use firewood	0.81	0.39	0.22	0.41
use charcoal	0.24	0.43	0.72	0.45
use kerosene	0.07	0.25	0.21	0.41
use LPG	0.05	0.21	0.28	0.45
use electricity	0.03	0.16	0.16	0.36
sex head	0.75	0.43	0.75	0.43
mid aged	0.51	0.50	0.52	0.50
old adult	0.19	0.39	0.16	0.37
secondary	0.12	0.32	0.30	0.46
tertiary	0.02	0.13	0.07	0.26
dependency	1.06	0.92	0.73	0.74
agriculture	0.70	0.46	0.14	0.35
poorest	0.28	0.45	0.03	0.17
poorer	0.26	0.44	0.07	0.26
middle	0.24	0.42	0.14	0.35
rich	0.14	0.34	0.33	0.47
richest	0.09	0.28	0.43	0.49
ownhouse	0.79	0.40	0.51	0.50

Appendix A 2: Determinants of the Households' Cooking Energy Decisions in Rural and Urban Areas

	Rural					Urban				
	Firewood	**Charcoal**	**Kerosene**	**Gas**	**Electricity**	**Firewood**	**Charcoal**	**Kerosene**	**Gas**	**Electricity**
sex of the household head	0.19**	-0.14**	0.11	-0.37***	-0.30**	-0.13	-0.07	0.10	-0.16**	-0.17**
	(0.07)	(0.07)	(0.09)	(0.13)	(0.13)	(0.08)	(0.07)	(0.07)	(0.08)	(0.08)
Middle aged household head	0.31***	-0.24***	0.13	0.05	0.19	0.20**	0.08	0.16**	-0.22***	-0.08
	(0.08)	(0.07)	(0.09)	(0.13)	(0.13)	(0.09)	(0.08)	(0.08)	(0.08)	(0.08)
Old adult	0.48***	-0.31***	0.38***	-0.12	-0.03	0.10	0.13	0.27**	-0.19*	0.06
	(0.11)	(0.09)	(0.11)	(0.18)	(0.20)	(0.12)	(0.11)	(0.11)	(0.11)	(0.12)
Secondary	-0.33***	0.20*	0.09	0.41***	0.37***	-0.35***	-0.11	-0.23***	0.43***	0.34***
	(0.10)	(0.11)	(0.14)	(0.15)	(0.14)	(0.11)	(0.08)	(0.09)	(0.08)	(0.09)
Tertiary	-0.58***	0.21	0.02	1.04***	0.57**	-0.62**	-0.36***	-0.34***	1.00***	0.78***
	(0.20)	(0.22)	(0.23)	(0.22)	(0.23)	(0.24)	(0.12)	(0.13)	(0.13)	(0.13)
Dependency	0.20***	-0.09**	0.01	-0.20***	-0.16**	0.19***	0.12***	0.02	-0.14***	-0.12**
	(0.04)	(0.04)	(0.04)	(0.08)	(0.07)	(0.05)	(0.04)	(0.04)	(0.05)	(0.05)
Agriculture	0.81***	-0.52***	-0.41***	-0.38***	-0.49***	0.92***	-0.65***	-0.44***	-0.30**	-0.37***
	(0.07)	(0.06)	(0.08)	(0.12)	(0.12)	(0.10)	(0.09)	(0.11)	(0.13)	(0.13)
Poorer	-0.28***	0.44***	0.10			-0.27	0.22	-0.36	-0.00	-0.24
	(0.11)	(0.10)	(0.11)			(0.23)	(0.19)	(0.22)	(0.39)	(0.48)
Middle	-0.77***	1.05***	0.36***			-0.25	0.46***	-0.14	0.22	0.19
	(0.10)	(0.09)	(0.11)			(0.21)	(0.18)	(0.20)	(0.35)	(0.44)
Rich	-1.10***	1.29***	0.41***	1.08***	1.40***	-1.02***	0.89***	-0.14	1.06***	0.88**
	(0.11)	(0.10)	(0.12)	(0.14)	(0.17)	(0.20)	(0.17)	(0.19)	(0.33)	(0.43)
Richest	-1.51***	1.36***	0.47***	1.98***	2.48***	-1.58***	0.98***	0.00	1.77***	2.09***
	(0.12)	(0.12)	(0.13)	(0.14)	(0.17)	(0.21)	(0.18)	(0.19)	(0.33)	(0.43)
Own house	0.77***	-0.47***	0.25**	-0.17	-0.53***	0.64***	-0.06	0.06	-0.14*	-0.26***

	Rural					Urban				
	Firewood	**Charcoal**	**Kerosene**	**Gas**	**Electricity**	**Firewood**	**Charcoal**	**Kerosene**	**Gas**	**Electricity**
	(0.07)	(0.07)	(0.11)	(0.12)	(0.12)	(0.08)	(0.07)	(0.07)	(0.07)	(0.07)
Constant	0.05	-0.43***	-1.92***	-1.87***	-1.96***	-0.44**	-0.10	-0.83***	-1.59***	-1.49***
	(0.12)	(0.12)	(0.15)	(0.18)	(0.19)	(0.21)	(0.18)	(0.20)	(0.34)	(0.42)
	ρCF	-0.78***		ρGC	0.01	ρCF	-0.58***		ρGC	-0.30***
		(0.02)			(0.06)		(0.04)			(0.04)
	ρKF	-0.03		ρEC	0.13**	ρKF	-0.09**		ρEC	-0.08*
		(0.05)			(0.06)		(0.04)			(0.04)
	ρGF	-0.30***		ρGK	0.06	ρGF	-0.12**		ρGK	-0.23***
		(0.06)			(0.07)		(0.05)			(0.04)
	ρEF	-0.30***		ρEK	0.05	ρEF	-0.22***		ρEK	-0.23***
		(0.07)			(0.07)		(0.05)			(0.04)
	ρKC	0.02		ρEG	0.68***	ρKC	0.15***		ρEG	0.71***
		(0.05)			(0.05)		(0.04)			(0.03)
Number of Observations		3125					2074			
Model test-Wald $\chi^2(70)$		1577.23					1424.53			
Log likelihood		-3248.7		Prob > χ^2	= 0.00		-4371.58		Prob > χ^2	= 0.00
Likelihood ratio test $\chi^2(10)$		0.00		Prob > χ^2	= 0.00		0.000		Prob > χ^2	= 0.00

Note: Standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1