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Household Fuel Use in Developing Countries: Review of Theory and Evidence

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Abstract

Because of recent concerns about the negative externalities of traditional fuel use on the environment and health, the issue of the household fuel transition in developing countries, from dirty fuels towards clean fuels, has received growing research attention. This paper provides an up-to-date survey of the economic literature on household fuel use in these countries. First, we present the conceptual and theoretical frameworks. Then, we discuss the empirical results that show how a wide range of factors drive the household fuel transition. Finally, we suggest priorities for policy initiatives and highlight areas of future research.

Keywords: Household decisions, Fuel transition, Energy consumption
JEL Classification: Q41; Q42; R22

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1. Introduction

Currently, around 2.7 billion people still primarily rely on traditional biomass for cooking and heating in developing countries (Yao et al. 2012). This is a cause for severe environmental and health problems. For example, the incomplete burning of these fuels is responsible for indoor air pollution, mostly associated with carbon monoxide, particulate matter, sulphur dioxide and nitrogen dioxide. These pollutants play a major role in generating respiratory diseases and cardiovascular mortality. The consumption of these fuels also spurs climate change by releasing carbon dioxide into the atmosphere. In turn, climate change damages agricultural production and subsequently threatens the nutritional health of human beings.

Because of these concerns, the issue of household fuel transition in developing countries, from dirty and traditional fuels to clean and modern fuels, has received growing research attention. Over the past three decades, a number of studies have investigated the factors driving the transition. Even though, some studies are merely based on simple descriptive statistics, one can see an emergence of the use of econometric methods to quantify the patterns and factors of household fuel use.

Despite intensive research, the knowledge about the determinants of household fuel use remains limited. For example, the actual impact of fuel prices on fuel substitution is still debated in the literature. Often, different conclusions have been reached concerning the effects of social-economic factors that drive fuel substitution. These divergences among authors translate into uncertainties when designing adequate energy policies.

In this context, we review a wide body of literature on the subject. The purposes of this survey are, thus, to identify knowledge gaps regarding the complex factors that drive the fuel transition, and, second, to facilitate policy design for promoting the use of cleaner fuels. Our survey complements and extends the contributions of Barnes and Floor (1996), Kowsari and Zerriffi (2011), Lewis and Pattanayak (2012), van der Kroon et al. (2013) and Malla and Timilsina (2014) in several respects. First, it presents a more comprehensive and updated review of the existing empirical findings on household fuel transition in developing countries, detailing for the first time the related econometric issues and theoretical issues. Second, it reviews the current state of knowledge and issues related to the theory of household fuel use, a relatively little treated question

The remainder of the paper is organized as follows. Section 2 provides a review of the theoretical research. Section 3 discusses the empirical determinants of household fuel use. Section 4 examines the policy implications derived from the research. Finally, Section 5 offers concluding remarks and suggestions for future research.

2. Theoretical literature

This section discusses the conceptual and theoretical frameworks that guide the analyses of household fuel use in developing countries.

2.1 The "Energy ladder" theory

The 'energy ladder' has been a commonly used concept in explaining household fuel use in developing countries. The energy ladder depicts a process by which households, as their income rises, move away from traditional fuels (e.g., biomass), first to adopt intermediate fuels (kerosene, coal), and then to use modern fuels (gas, electricity).[1] In that sense, the energy ladder concept serves as a stylized extension of the typical income effect of consumer economic theory that explains how consumers substitute necessary goods and luxury goods for inferior goods, as their income rises. A subjacent assumption is that households are faced with an array of fuel choices that can be arranged according to increasing technological sophistication, and that this is reflected in household preferences.[2] As a consequence, as their income increases, households shift to more sophisticated energy carriers and simultaneously give up less

[1] Heltberg (2005), Chambwera and Folmer (2007), Lay et al. (2013).

[2] Hosier and Dowd (1987) Chambwera and Folmer (2007), Link et al. (2012).

sophisticated alternatives.[3] In this theory, the characteristics of the final technologies are implicitly associated with some features of consumer preferences that divide the fuels into necessary goods and luxury goods. Although such hypothesis has still to be fully validated empirically, one achievement of this theory is its ability to fit well common observations of the strong income dependency of household fuel use.

2.2 The 'Fuel stacking' theory

However, Masera et al. (2000) criticized the energy ladder theory on the grounds that it cannot adequately describe the dynamics of households' fuel use. Instead, they note that fuel stacking is common in both urban and rural areas of developing countries. Fuel stacking corresponds to multiple fuel use patterns—where households choose a combination of fuels from both lower and upper levels of the ladder. Indeed, modern fuels may serve only as partial, rather than perfect substitutes for traditional fuels (van der Kroon et al. 2013, 2014). Multiple fuel use arises from several reasons, such as, occasional shortages of modern fuels (Hosier and Kipondya 1993; Kowsari and Zerriffi 2011), high cost of appliances associated with using exclusively modern fuels (Davis 1998), fluctuations of commercial fuel prices (Leach 1992) and preferences inducing households not to fully adopt modern fuels (Masera et al. 2000). The complexity of the fuel switching process thus suggests that there is a multiplicity of factors, besides income, that may affect fuel use. This led some authors to delve into more sophisticated modeling approaches.

2.3 Urban household models

Edwards and Langpap (2005) and Gupta and Köhlin (2006) set up household consumer models to describe the simultaneous consumption of non-commercial and commercial fuels in urban areas. They model households' fuel consumption by

[3] Kowsari and Zerriffi (2011), Rahut et al. (2014).

following standard consumers' utility maximization principles subject to a budget constraint, which bring about the driving role of prices. Even, in such narrow setting, the set of considered consumption goods vary with the studied contexts and the authors. For example, Edwards and Langpap (2005) suppose that households maximize utility through the consumption of fuels, market good and stove (see Table 1). Instead Gupta and Köhlin (2006) assume utility defined over consumption of fuels, food, health and other goods. These different specifications correspond to implicit assumptions of separability in preferences so as to allow for two-stage budgeting focusing on some goods of interest only. In all cases, fuel consumption is seen as fully determined by income, market prices and household preferences. However, this approach makes it hard to understand how non-market fuels, such as firewood and straw, may be included in household decisions, and what is the interaction with agricultural activities involving these products.

2.4 Agricultural household models

As a response to these limitations, a few authors proposed a more complex theoretical framework, particularly well fitted to rural households. It is well recognized that rural households in developing countries often face absent or incomplete markets, not only for fuels (e.g., firewood, electricity), but also for agricultural products, labor and credit. In the absence of market failure, a rural household may be seen as behaving firstly as a profit maximizing producer, and then as a utility maximizing consumer given the profit realized in the first stage. Instead, under market failure, the allocation decisions for production and consumption are made jointly in a non-separable fashion.

Different types of market failures may lead to non-separabilities that matter for the analysis of fuel use. For example, Heltberg et al. (2000) consider the market failures for crop residues, animal dung and labor. They study the substitution of private non-marketed fuels (animal dung and crop residues) for firewood, in response to increasing firewood scarcity. In that case, the diverse rural household's decisions relating to energy supply, energy demand, farm and off-farm labor supply are made simultaneously. In this framework, rural households are modeled as maximizing utility, subject to: leisure and budget constraints, an agricultural production function, a residue and dung production function, and finally a fuelwood collection function. Even under separability, the household total income is endogenous since it depends on production decisions that generate farm profits. A further complication brought by the non-separability is that the production constraints, or other non-budget constraints, have to be explicitly considered in the determination of consumption decisions, instead of merely summarizing their effects through an extended income variable in the budget. In a non-separable model, the fuel use decision may thus be seen as guided by the household-specific shadow price of fuel, which depends on household and community characteristics associated with both preferences and all constraints.

Chen et al. (2006) extend the approach of Heltberg et al. (2000) by introducing the missing market for firewood, and emphasize the substitution between firewood and coal. Manning and Taylor (2014) consider rural labor market failure and substitution between firewood and gas. Finally, Muller and Yan (2014) propose a fully-fledged non-separable decision model that simultaneously links fuel use decisions with agricultural production, domestic technology, fuel collection technology and rationing of fuels.

2.5 Assessment

The conceptual and theoretical frameworks discussed above rely on the microeconomic theory of the consumer and they serve as the prominent explanations of the household fuel transition in developing countries. These approaches have progressively addressed how fuel decisions occur as part of the multiple activities in which households of developing countries engage. However, the challenge is still significant to obtain both sophisticated and tractable explanations of fuel uses in less developed countries. Detailed descriptions of market failures, domestic technologies, interactions between agricultural outputs and fuel types, and fuel rationing should play a larger role in realistic model specification. We now turn to empirical determinants of household fuel use that reflect the above theoretical reflections.

3. Empirical literature

Consistently with our theoretical discussion, the determinants of fuel use that are considered in the empirical literature can be categorized into: incomes, prices, household preferences, production characteristics and energy supply factors. Table 2 lists the effects estimated in the empirical literature, along with the data sources and the estimation methods. Early research into the determinants of the quantity of fuels consumed often applies OLS regression technique, sometimes with selectivity correction..[4] To allow for zero quantity of fuels consumed, some studies use Tobit models.[5] Other authors investigate fuel choices from cross-section data with multinomial, probit or logit models. Finally, Muller and Yan (2014) estimate panel data random effect logit and multinomial models to investigate fuel choices in China. There is therefore a tendency towards increasingly flexible specifications, allowing for the discreteness in fuel type choices.

Note that the literature makes typically the implicit assumption that the estimated correlation effects well reflect causal effects of interest, sometimes with instrumentation of some total expenditure variables. It shares this feature with most consumption studies. Furthermore, we discuss all empirical results under the hypothesis that most specification errors in the models can be neglected, a strong while inevitable assumption in the state of this literature.

4 e.g., Chen et al. (2006), Gupta and Köhlin (2006), Lee (2013).
5 Edwards and Langpap (2005), Chen et al. (2006), Abebaw (2007), Zhang and Koji (2012), Lee (2013).

3.1 Income

The effects of income on fuel use have been investigated in almost all empirical econometric studies. Most authors specify income as a measure of household earnings.[6] Several authors also use household expenditure as a proxy for income.[7] That is because expenditure data are often more reliable and more reflective of long-term income. Household wealth is sometimes used as an alternative measure approximated from information on household durable assets (Chen et al. 2006; Démurger and Fournier 2011).

Numerous studies point to income as the major driver behind the uptake of modern fuels.[8] Hosier and Dowd (1987) find that Zimbabwean urban households tend to move away from wood, towards kerosene and electricity, as their income rises. Ouedraogo (2006) observes in Burkina Faso that a higher income induces urban households to choose natural gas over kerosene. Baiyegunhi and Hassan (2014) show in rural Nigeria that the transition from fuelwood to kerosene, natural gas and electricity occurs along to rising income. A similar trend is observed when household expenditure is used as a proxy for income. Gupta and Köhlin (2006) find in urban India some evidence for an energy transition from fuelwood and kerosene to LPG (Light Petroleum Gas), which is largely driven by expenditure levels. Lay et al. (2013) show in Kenya that rising expenditure induces households to choose electricity and solar energy over wood and kerosene. In addition, Démurger and Fournier (2011) provide evidence indicating that Chinese rural households respond to rising wealth by substituting coal for firewood. All these studies seem to corroborate the energy ladder concept, which emphases income in explaining the transition from 'inferior' traditional fuels to 'normal' modern fuels.

However, such a simple pattern of income dependence is increasingly questioned by emerging empirical evidence showing that the effect of income on fuelwood demand in

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[6] For example, Hosier and Dowd (1987), Abebaw (2007), Arthur et al. (2010), Zhang and Koji (2012), Baiyegunhi and Hassan (2014) and Nlom and Karimov (2014).

[7] An et al. (2002), Edwards and Langpap (2005), Rao and Reddy (2007), Akpalu et al. (2011) and Lee (2013).

[8] e.g., Brew-Hammond (2010), Peng et al. (2010) and Kowsari and Zerriffi (2011).

rural and urban households may sometimes be insignificant regardless of how income is measured.[9] Mekonnen (1999), Israel (2002), Lee (2013) and Guta (2014) report that in some contexts fuelwood is not an inferior good as often thought. Edwards and Langpap (2005) show that wood is a normal good for low income households, but an inferior good for high income households in Guatemala (i.e., an inverse U relationship between income and wood consumption). Heltberg (2004, 2005) observe in different countries that, with increasing income, households tend to add modern fuels into their mix as partial rather than perfect substitutes for traditional ones. All these studies bring evidence against the energy ladder concept.

Table 3 reports the estimated income elasticities of fuel consumption, and of fuel choices for different fuel types, in the empirical literature.[10] The results show a wide range of estimates. For example, the income elasticity estimates for firewood consumption range from -1.7 to 1.85. Besides, the income elasticities of the choice probability for firewood fall into the -0.23 to 0.04 range. In turn, the income elasticity of charcoal consumption can drop as low as -0.28 (Hughes-Cromwick 1985) or rise as high as 2.95 (Pitt 1985). In contrast, the estimates of the income elasticity of kerosene consumption are almost always positive and relatively inelastic, from 0.07 (Lee 2013) to 0.59 (Pitt 1985). This implies that kerosene can be safely assumed to be a normal good for most households. In contrast, the estimates of gas and electricity income elasticities vary a lot across studies. The estimates reported by Macauley et al. (1989), Akpalu et al. (2011) and Lee (2013) suggest that LPG and electricity are necessary goods, while the results found by Hughes-Cromwick (1985) and Gupta and Köhlin (2006) instead indicate that they are rather luxury goods in their studied context. Muller and Yan (2014) find an income elasticity of -0.15 for the choice probability of coal in rural China. In addition, the choice probabilities for gas and electricity appear to be

[9] Kaul and Liu (1992), Chen et al. (2006), Akpalu et al. (2011), Zhang and Koji (2012) and Manning and Taylor (2014).

[10] As they are usually not provided by the authors, we computed, when possible, the elasticities from the published estimated coefficients and descriptive statistics, sometimes using lognormal approximations. However, the calculated elasticities in Farsi et al. (2007) turn out not to be reasonable and we drop them. In Gupta and Kohlin (2006) and in Lay et al. (2013) only mean or median incomes are provided without dispersion information, and the calculus is not possible in that case. Finally, the elasticities in Muller and Yan (2014) are calculated from the multinomial logit estimates.

rather inelastic. On the whole, it seems fair to say that while some fuels are more likely to be necessities in most cases (firewood, biomass) and others normal goods (kerosene), ultimately their classification into inferior goods, necessities and luxuries depends on the studied context and must therefore be carefully established empirically.

3.2 Prices

The role of fuel prices in household fuel use is emphasized in an extensive literature. Table 2 shows the diversity of the price information used. However, most studies consider market prices among these for firewood, coal, charcoal, kerosene, LPG and electricity[11]. Instead, Mekonnen (1999) and Démurger and Fournier (2011) use collection time as a proxy for the shadow price of firewood.

There is much evidence showing significant negative own-price effects both for the quantity of fuel consumed and the probability of choosing this fuel. For instance, Farsi et al. (2007) in India and Zhang and Koji (2012) in Biejing, China find that an increase in LPG price significantly reduces the probability of choosing LPG and the LPG consumption, respectively. Many authors[12] come up with a negative relationship between firewood consumption and firewood price. However, the magnitude of the effects varies across products, years and countries. For kerosene, Gupta and Köhlin (2006) and Akpalu et al. (2011) observe that the demand is elastic (elasticity greater than unity in absolute value) with respect to own price in India and Ghana (see Table 4), while Pitt (1985) finds in Indonesia an own-price elasticity closer to unity in absolute value and Lee (2013) an elasticity of -0.32 in Uganda. Farsi et al. (2007) and Lay et al. (2013) observe that the price of kerosene is associated with the expected negative effect on kerosene choice in India and Kenya. Moreover, there is also evidence of cases for which the own price has no significant impact on fuel use. Thus, Gupta and Köhlin (2006) find in India an insignificant (negative) own-price elasticity for coal. Although

[11] e.g., An et al. (2002), Gupta and Köhlin (2006), Akpalu et al. (2011), Zhang and Koji (2012).
[12] Pitt (1985), Mekonnen (1999), Gupta and Köhlin (2006), Akpalu et al. (2011), Démurger and Fournier (2011), Lee (2013) and Nlom and Karimov (2014).

own-price elasticities for coal separate into the ones for charcoal (mostly for the poorest countries) and proper coal, they are still generally significantly negative, ranging from -0.96 (Guta, 2014, for coal consumption) to -0.29 (Muller and Yan, 2004, for coal choice). Surprisingly, few estimates are available for electricity, for which we could only calculate the elasticities for three studies. Though, on the whole, negative own-price effects are rather well established empirically.

The cross-price effect estimates found in the literature are more controversial. Some scholars suggest that cross-price effects can be an important driver of fuel substitution. Peng et al. (2010) show that high coal prices increase the probability of choosing biomass in China, suggesting that coal and biomass may be substitutes. Heltberg (2005) reports a significant substitution effect between light petroleum gas and wood in Guatemala. Pitt (1985) finds a significant substitution effect between kerosene and firewood in Indonesia. However, these findings are challenged by the evidence provided by other authors. Kaul and Liu (1992) and Zhang and Koji (2012) find that an insignificant estimated coefficient of coal price for explaining fuelwood consumption in China. Gupta and Köhlin (2006) conclude that coal and fuelwood have negative cross-price elasticities in India. Akpalu et al. (2011) also claim to observe complementarities between LPG and firewood in Ghana. Lay et al. (2013) report a statistically significant negative effect of kerosene price on choosing wood in Kenya.

As a matter of fact, most statements of complementarities and substitutabilities of fuels by diverse authors are strictly speaking inaccurate since they are deduced from estimated direct price effects instead of compensated effects. In theory, such complementary/substitution relationships should be derived from a Slutsky equation, for example using a simple consumer model. In that case, cross-price effects can be decomposed into substitution and income effects. But it may occur that the income effect offsets the substitution effect, which would invalidate some of the stated interpretations in the literature. For example, the cross-price elasticity of -0.699 reported by Akpalu et al. (2011) would suggest at first sight that LPG and firewood are complements. However, since LPG has a relatively high income elasticity of 0.701 in this study, a decrease in real income due to an increase in firewood price may result in a decreased demand for LPG, even though the two considered fuels were (Slutsky-)substitutes.

Therefore, face to this impressive amount of analyses on the substitutability/complementarity of consumed fuels, it is useful to recall a few fundamentals of economic theory in order to relativise their interpretations. First, in a basic consumer model setting, one should estimate and control for the income effects before to deduce any substitutability/complementarity relationship. However, there is still more trouble ahead. Indeed, the relatively simple analysis of price effects in the consumer model does not extend so easily to more complex household models. Often, the prices of other consumed and produced goods may also affect fuel use. Finally, when consumption and production are not separable, which is the case for rural households under missing markets, the observed prices do not fully summarize the shadow prices that determine household decisions. In that case, e.g., in Muller and Yan (2014), it is still possible to exhibit how variations in food prices may affect fuel choices. Muller and Yan (2014) find that an increase in the price of purchased food make Chinese rural households to choose cheaper dirty fuels, while an increase in the price of self-produced food stimulates the switch to clean fuels. These considerations imply that price effect estimates in simple econometric specifications may be, at best, considered only as approximate estimates rather than definite ones, especially for rural areas. Therefore, caution must be applied when interpreting the estimated direct and especially cross price effects in the literature.

3.3 Household preferences

Previous research tends to focus on household characteristics that reflect blatant disparities in households' energy preferences. A wide range of factors describing age, gender, education, occupation, religion, lifestyle, household size, device characteristics and environment awareness have received attention.

1) Age

The empirical findings on the role of age in explaining household fuel use remain contradictory. Some studies find that age is positively associated with preference for traditional fuels. Baiyegunhi and Hassan (2014) observe that an increase in the age of household head induces Nigerian rural households to shift away from natural gas towards fuelwood. Edwards and Langpap (2005) show a positive and significant association of household head's age with wood consumption in Guatemalan households. Démurger and Fournier (2011) find that household average age has a positive and significant impact on firewood consumption in rural households of northern China. Gebreegziabher et al. (2012) report that older household heads are more likely to consume charcoal, while less likely to consume kerosene and electricity in Ethiopia. Rahut et al. (2014) show that households with older heads prefer fuelwood to electricity in Bhutan. Such preferences for traditional fuels support the notion that older people tend to perpetuate traditional habits, related to fuels, more than young people.

However, other authors find that age is instead positively associated with preference for modern fuels. Farsi et al. (2007) and Gupta and Köhlin (2006) provide evidence showing that older household heads are more likely to prefer LNG (Light Natural Gas) to wood in Indian households. Rao and Reddy (2007) use instead the average age of household members and find similar results. Guta (2012) finds that older household heads are more likely to prefer modern fuels to traditional fuels in Ethiopian rural households. Özcan et al. (2013) observe that older household heads are more likely to shift away from wood towards natural gas, liquid fuel and electricity in Turkey. These results may suggest a life cycle effect where young people facing liquidity constraints would resort to cheaper fuels, while old people would be able to afford cleaner fuels more easily. In addition, An et al. (2002), Israel (2002) and Abebaw (2007) claim that age is not affecting fuel use.

2) *Gender*

Gender is another debated factor. There is evidence indicating that female-headed households prefer modern fuels to traditional fuels (Farsi et al. 2007; Rao and Reddy

2007; Rahut et al. 2014). This may be attributed to the fact that women are often responsible for household cooking and thus they are directly affected by the air pollution emitted from the burning of the dirty fuels. However, this evidence is challenged by An et al. (2002), Ouedraogo (2006) and Abebaw (2007) who observe that the coefficient of gender of the household's head is insignificant in some contexts. Link et al. (2012) show that a high proportion of female members induce households to use fuelwood in Nepal. This is attributed to the fact that women are the main gatherers of fuelwood. In contrast, Heltberg (2005) observes that a large proportion of female does not affect the use of fuelwood in Guatemala. Moreover, Israel (2002) finds an association of a high female share of the family earned income with a low probability of using firewood in urban Bolivia. Women who work for monetary compensation may have higher opportunity costs of time and thus prefer time-saving fuel. Nonetheless, Gupta and Köhlin (2006) find that the number of women not working does not affect fuel use in India. The general impression produced by all these results is that the role of gender in explaining fuel use stems from a combination of preferences characteristics, time opportunity cost considerations and within-household bargaining position of women.

3) *Education*

The importance of education in the decision making process of fuel use is emphasized in various studies. For example, education level is found to have a negative relationship with firewood consumption by Abebaw (2007) and Démurger and Fournier (2011). The opportunity costs of fuel collection time, seen as increasing in education, may explain the observed results. Likewise, more education generally implies higher income. It may thus be that the estimated education effect is just an ill observed income effect, which is consistent with typical rankings of fuels according to necessities and luxuries. Gupta and Köhlin (2006) and Baiyegunhi and Hassan (2014) observe in India and Nigeria that a higher education level induces households to move away from firewood dependence towards the use of kerosene and LPG. Gebreegziabher et al. (2012) find in Ethiopia that, the higher the education level, the less likely the households will choose wood, while the more likely the households will choose electricity. Lay et al. (2013) show in Kenya that a higher education level is associated with a higher probability of using electricity and solar energy, and with a lower probability of using wood and kerosene. Beyond its effect on tastes and time opportunity costs, education as a powerful determinant of fuel switching could also be explained by better education translating into higher awareness of the negative health impacts of dirty fuels, and enhanced knowledge about efficiency and convenience of modern fuels (Farsi et al. 2007). Identifying how these distinct channels of education influence combine or separate is one of the challenges of future research.

4) *Household size*

Household size also plays an important role in energy choices. Israel (2002), Abebaw (2007) and Zhang and Koji (2012) all find evidence of negative association of household size with per capita energy consumption. These results may reveal the presence of economies of scale in energy use. Alternatively, they may merely stand in for a subjacent income effect if equivalent incomes are measured by dividing income by a scale increasing in household size, as usual. Note that the effect of household size on fuel switching still remains ambiguous empirically. The results in the studies of Reddy (1995), Ouedraogo (2006), Rao and Reddy (2007), Pandey and Chaubal (2011) and Özcan et al. (2013) indicate that larger households prefer dirty fuels over clean fuels. One possible reason is that household size is often larger in poorer households that cannot afford modern fuels. Instead, Hosier and Dowd (1987), Gupta and Köhlin (2006) and Baiyegunhi and Hassan (2014) find the opposite trend: households with larger members are more likely to choose clean fuels. Besides, Chen et al. (2006) and Guta (2012) show insignificant impact of household size on household fuel transition. Another contrasting finding is that of Heltberg (2004), who reports that larger households are more likely to consume both dirty and clean fuels (i.e., they are more involved in fuel stacking). Clearly, the nature and the shape of the effects of household composition on fuel use still need more investigations to identify what the mechanisms at work are.

5) *Lifestyle*

Lifestyle factors such as cooking habits, food tastes and cultural beliefs are found to be closely linked to the observed fuel use behavior. Baiyegunhi and Hassan (2014) find in Nigeria that longer cooking time hampers the transition from fuelwood to natural gas and electricity. Pundo and Fraser (2006) obtain a similar result with Kenyan households preferring firewood over charcoal and kerosene when food requires lengthy cooking. A possible reason may be that fuelwood alternatives have higher relative costs per unit of time (Baiyegunhi and Hassan 2014). It may also be that lengthy cooking is found inconvenient by some household members, and using some fuel type may help reduce cooking time. The taste of the cooked meals may also be a reason for fuel choice. For example, Ouedraogo (2006) finds that a more common occurrence of cooking tô increases the likelihood of using firewood in Ouagadougou.[13]

3.4. Domestic constraints

Practical domestic constraints play a role for how cooking tasks can be performed. They can be gathered into too categories respectively linked to dwelling and device characteristics.

1) *Dwelling characteristics*

A few dwelling characteristics are sometimes listed among the determinants of fuel choices. Diverse measures of dwelling characteristics have been used: dwelling ownership, material used for floor, roof and wall, modern or traditional dwelling unit, number of room, drinking water source and whether house is electrified or not. The dwelling characteristics are often considered as proxies of a household's wealth and living conditions. They can also be seen as constraints to choices. For example, inflammable house material may deter the use of firewood; or installing some cooking

[13] Tô is a staple food made of millet, sorghum or maize flower, a traditional meal in Burkina Faso, which tastes better when cooked with firewood.

device may favour some fuels. Using electricity is facilitated by the existence of electric connections already in place, and this may be more likely in modern-type housing.

Arthur et al. (2010), Lay et al. (2013) and Baiyegunhi and Hassan (2014) find that house owners are more likely to shift towards cleaner fuels as compared to tenants, which is contrary to the results reported by Ouedraogo (2006) and Pundo and Fraser (2006). Baiyegunhi and Hassan (2014) observe in Nigeria that households living in traditional houses are less likely to choose natural gas and electricity over fuelwood. Heltberg (2005) shows in Guatemala the association of number of rooms with a switch away from wood towards LPG exclusively. Arthur et al. (2010) find in Mozambique that house size measured by the number of rooms is associated with adoption of electricity. Similarly, they found that the access to piped water induces an increase in the likelihood of using electricity. Heltberg (2004) also exhibits a link between access to tap water and LPG usage in eight different countries. Moreover, Heltberg (2004) and Ouedraogo (2006) point to the higher propensity of electrified households to move towards modern fuels. All these results, consistent with the energy ladder model, suggest that subjacent income effects may be present, if one chooses to interpret the coefficient of these dwelling characteristics as related to some ill observed income effect. However, other explanations are also possible as for example the proximity of wood material that could be used simultaneously to construct dwellings and as fuel, or other unobserved domestic constraints.

2) *Device characteristics*

Other determining factors may include cooking and heating device and appliance characteristics, since they imply different domestic technologies of fuel use. Obviously, not all sources of energy are compatible with using traditional furnaces, for example. In that sense, the choice of fuel may be simultaneous with device acquisition or may be constrained by the devices already available at home.

However, the empirical evidence in this regard is scant. Chen et al. (2006) find in Chinese villages that the possession of improved stoves does not affect fuelwood consumption but results in lower coal consumption. Hughes-Cromwick (1985) and

Manning and Taylor (2014) suggest that ownership of modern cooking and heating appliances is a necessary condition for adopting higher-grade energy sources. Similarly, Edwards and Langpap (2005) claim that in Guatemala the high upfront cost of appliances is a significant impediment to the adoption of LPG as an alternative to wood . These results point to joint choices of energy sources and of appliances, while they need confirmation.

3.5 Production characteristics

Several authors provide evidence that the pattern of fuel use of rural households may depend on agricultural production characteristics. This is consistent with non-separable agricultural household models in which consumption and production decisions are made jointly. In this sense, the fuel consumption decisions may be seen as guided by the household-specific shadow prices of fuel, which potentially depend on all household and community characteristics associated with consumption and production. To reflect agricultural production characteristics, the authors have relied on the following variables: farmland size, livestock number, household size and ratios of labor force by activities, which are directly included in fuel use regressions.

The evidence on the effects of household production assets, as measured by farmland size or livestock, on fuel use is ambiguous. However, it is often in favour of a direct link between fuel choice and the biomass byproducts of the farm activities. Chen et al. (2006) find that, in a remote Chinese village, farmland size does not affect firewood consumption. On the contrary, still for China, Démurger and Fournier (2011) report that farmland size is associated with a significant increase in firewood consumption in Labagoumen township. Likewise, Kaul and Liu (1992) and Pandey and Chaubal (2011) find a close link between farmland size and the use of biomass in China and India. Démurger and Fournier (2011) also observe that households with more livestock have lower firewood consumption, which is contrary to the findings of Kaul and Liu (1992), and Mekonnen (1999) in the distinct Ethiopian context, who finds the opposite effect.

Guta (2012) finds, in Ethiopia, that households with a larger livestock prefer traditional fuels and mix of fuels over modern fuels only. These contradictory results found in different contexts may reflect different local habits in fuel collection. In any case, it is interesting to note that the correlation of household assets with fuel choice cannot be readily interpreted as a mere income effect since it does not systematically follow the 'ladder' of energy sources.

The empirical findings for the effect of household time endowment, measured by household size, or proportion of active members, are mixed. As mentioned before, the positive association of household size with biomass consumption is often observed.[14] Beyond the already mentioned interpretation of income effects, another, not exclusive interpretation is that of larger households having more available labor both for firewood collection and agricultural production. This labour endowment translates into lower opportunity costs of collecting firewood and preparing crop residues for combustion. Chen et al. (2006) find in China a positive association between proportion of active members and fuelwood consumption, albeit Zhang and Koji (2012) find an opposite trend. Still for rural China, Muller and Yan (2014) find an association of agricultural specialization with higher probability of using biomass as fuel. In all cases, at least in rural areas, production characteristics, including agricultural specialization or labor force endowment, appear to be connected to fuel choices, although this is rarely taken into account in the modeling approaches in the literature.

3.6 Access

Obviously, availability and accessibility of fuels should contribute to explaining household fuel use. In the literature, the availability of traditional fuels has been measured by: distance to fuelwood (Kaul and Liu 1992; An et al. 2002; Heltberg 2005), households' perceptions of availability of fuelwood (Hosier and Dowd 1987) and geographic location (Peng et al. 2010). On the other hand, the accessibility of modern

[14] In Démurger and Fournier (2011), Pandey and Chaubal (2011) and Rahut et al. (2014), while not in Chen et al. (2006).

fuels has been measured by: households' perceptions of availability of LPG (Gupta and Köhlin 2006), community access to electricity (Heltberg 2004; Lay et al. 2013), prevalence of solar home systems (Lay et al. 2013) and renewable energy technologies (Zhang and Koji 2012).

It is also recognized that the scarcity of traditional fuels may affect fuel use. Several authors find that households living far from fuelwood sources tend to shift towards fuelwood alternatives.[15] This can be explained by higher opportunity costs of collection time. Hosier and Dowd (1987) find that households who do not perceive any difficulty in collecting wood tend to use more wood in Zimbabwe.

Some scholars go as far as to attribute the fuel transition to improved access to modern energy, mostly electricity. Heltberg (2004) reports a strong link between electrification at community level, on the one hand, and incidence of LPG use in India and Brazil, on the other. Lay et al. (2013) observe that improved access to electric power induces Kenyan households to move away from wood and kerosene towards electricity. An et al. (2002) argue that low voltage levels and high outage frequencies hinder the adoption of electricity by Chinese. Zhang and Koji (2012) and Lay et al. (2013) provide evidence that access to renewable energy technology fosters a greater acceptance of modern fuels by households. In the next section, we discuss a few policy implications of all these empirical findings.

4. Policy Implications for the Fuel Transition

In this section, we examine a few policy implications about how to foster the fuel transition. First, some economic changes may not stem from policies, while they could still enhance incomes, and thereby spur the transition to modern fuels because of income effects, as long as dirty fuels are inferior goods and clean fuels are necessary or luxury goods. This is the case of the improvement of living standards that arises

[15] Kaul and Liu (1992), An et al. (2002) and Chen et al. (2006).

naturally from the growth of the economy. However, the question of why the use of firewood is persistent as income rises remains not well answered. This may be first related to the uncertain characterization of firewood as either a normal or an inferior good. It may also be that other factors, such as preferences for food cooked firewood, limited access to modern fuels, or opportunity costs from time-consuming activities, dominate income effects.

Second, price policies can be implemented in the form of price taxes to deter the consumption of dirty fuels, and/or price subsidies to foster the use of clean fuels. In some countries, a certain degree of local decentralization of price policies is possible (e.g., in China, Su, 2011). Nonetheless, the commonly observed negative effect of own-price suggests that central governments ought to tax carbon-intensive fuels on the one hand, and subsidize modern clean fuel types on the other hand. However, the lack of agreement on the levels of elasticities across countries implies that actual price responses should be carefully investigated in each context before designing tax policies. Some words of caution are of order here. Although price subsidies for modern fuels have been historically used for promoting fuel transition, they are often undesirable, beyond the well known issue of the price distortions caused by price subsidies. One reason is that subsidies may be financially unsustainable for the State. Another reason is that subsidy programs are often ill targeted. Indeed, they typically benefit high-income households disproportionately more than the poor. Finally, the poor face barriers of high connection costs for electricity. Then, they may little benefit from subsidies, and therefore little change their fuel use pattern. Under these circumstances, policy makers need to look beyond pricing measures for broader policy options.

Third, more policy emphasis should be laid on the factors fostering household preferences that favor modern clean fuels. In particular, specific education curricula should be promoted so as to better inform households of the benefits of adopting clean fuels. Practical training on how to use the fuels and the corresponding devices would be useful and easy to implement. For example, one could disseminate the lessons from the numerous development projects promoting the use of improved furnaces in less developed countries. In addition, policy initiatives should encourage the transformation of the traditional lifestyle, since sustained use of modern fuels requires compatibility with local lifestyles. For example, diet changes may make firewood cooking less attractive.

Fourth, the costs of the practical use of different fuels could be converted into policy instruments. For example, the government may increase the opportunity cost of time for gathering biomass. Policy could also directly address stove acquisition and start-up cost problems, because of the connected choices of fuel types and of appliances. The initial investment cost of modern fuel devices has been mentioned in the empirical literature as a barrier to upward fuel switching. Providing subsidies or credit for purchasing these devices seems to be a promising policy direction.

Fifth, the findings exhibiting the dependence of rural household fuel use on agricultural production characteristics suggest that policies should account for the non-separability of consumption and production decisions in the contexts of imperfect rural markets. Therefore, effective policies for promoting the fuel transition in rural areas could depend on socioeconomic or technological characteristics pertaining to consumption and production activities, and shaping household's responses to market failures. For example, in China, financial incentives are proposed by the government to pork producers to incentivized them to raise their output level. Such policy measures are likely to generate a higher use of biomass by-products as fuels by these households or their neighbours. Some coordination of agricultural and energy policies would be desirable in that case.

Finally, policies should lay more emphasis on supply-driven factors. On the one hand, and given the evidence showing a strong link between the household fuel transition and access to modern energy, either governments or markets should ensure a sufficient and reliable supply of modern fuels. On the other hand, policy makers could devote more efforts to restrict the availability of traditional fuels. Given the strong effect of wood scarcity on this fuel use, forbidding wood collection, or at least raising the opportunity costs of wood collection by barriers may yield results. To reduce biomass use as fuel, the government may support the commercialization of biomass by subsidizing investment in biomass-based clean energy (e.g., biomass-based power generation) or other industrial uses. Surely, more policy recommendations could be suggested from what has been learned in the literature. However, many interesting findings still remain rather isolated and would require confirmation.

5. Conclusion

Our survey has detailed the theoretical and empirical underpinnings of household fuel use in developing countries. Household fuel use was initially explained by the "energy ladder" concept that much boils down to traditional income effects in the economic consumer model. Subsequently, more sophisticated urban and agricultural household models were proposed to explain fuel use patterns. Our review of the empirical literature reveals a few noticeable findings. Firstly, beyond income, an intricate web of closely interrelated social-economic factors drive the household fuel transition, and the extent of influence from these factors varies widely within or across countries. Secondly, the pace of the upward transition brought about by shifting energy prices also varies widely across countries. Thirdly, the sustained use of modern clean fuels requires the compatibility of stove technologies with local lifestyles. Fourthly, in contexts of imperfect markets, the fuel transition in rural households depends upon the interaction of non-separable consumption and production household decisions. Finally, easy access to modern energy sources is a necessary condition for the transition.

Although there has been considerable progress in both the theoretical and empirical research on household fuel use in the past three decades, there remain areas where more research is needed. First, future studies should provide additional evidence on the determinants of fuel stacking. The hypothesis of fuel stacking behavior, especially in rural households, has been gaining increasing support in the literature. Nonetheless, econometric estimations of fuel stacking models are almost completely lacking. As a consequence, the causes of fuel stacking are still not well understood.

Second, future studies should further examine the impacts of awareness of the health hazards of indoor air pollution resulting from dirty fuel use. There is a growing recognition that such awareness may motivate households to shift toward clean fuels. However, to date only Gupta and Köhlin (2006) have provided empirical evidence on these effects.

Third, additional evidence on evaluating the effectiveness of renewable energy technologies is needed for designing future policies aimed at promoting the deployment of these technologies. The diversification brought by renewable energies technologies is expected to improve the energy consumption structure in developing countries. However, understanding of the role that renewable energy technologies play in the household fuel transition is still lacking.

Fourth, future research should further explore the impacts of off-farm employment on the rural households' fuel transition. Off-farm employment participation, especially through migration, is one of the quintessential features of economic development in developing countries. Off-farm employment complicatedly affects household fuel transition through providing new income sources, increasing fuel consumption, diminishing household available labor and also changing household habits (Shi et al. 2009). However, current research has not adequately addressed these issues.

Finally, future research should not neglect the impacts of food prices, especially on rural households. As a matter of fact, rising food prices could either foster or impede the fuel transition, both through consumer-side and producer-side effects. On the consumer side, an increase in the price of purchased food may induce rural households to choose cheap dirty fuels so as to be able to meet their necessary food needs. On the producer side, an increase in the price of self-produced food may shift the budget constraint by an extra income. This additional income effect may stimulate the fuel transition to clean fuels if fuel is a normal good. Moreover, non-separable effects of food prices may occur. For example, a hike in pork price in China may stimulate both pig production and the production biomass by-products that are used as convenient energy sources by producer households. What is also missing is a theoretical standard comparative statics framework that would clarify the meaning of the estimated price effects, and help eliciting substitutability and complementarity with fuels. In these conditions, it is still early days for a deep understanding of food price effects on household fuel use.

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Table 1 Theoretical models of fuel use

Author	Utility function	Firewood collection/private fuel production function	Agricultural production function	Income constraint	Time constraint
Chen et al. (2006)[a]	$U(c_H(e_f, e_c, S), c_M, l; z)$	$q_f(l_f; z_v)$	$q_a(l_a; z_h)$	$p_M c_M + p_c e_c = p_a q_a + w l_{out} + E$	$l_f + l_a + l_{out} + l = T$
Edwards and Langpap (2005)[b]	$U(c_m, c_h(f(e_f) + g(e,S)); z)$			$p_m c_m + p_{e_f} e_f + p_e e + p_s S \leq y$	
Gupta and Köhlin (2006)[c]	$U(c(G, F_i), H(I, K_i), X; z)$			$p_i F_i + p_g G + p_h I + p_x X = y$	
Heltberg et al. (2000)[d]	$U(c_H(e_f, e_p, S), c_M, l^m, l^w; z)$	$q_f(l_f^w; z_v)$ $q_p = \alpha q_a - inp$	$q_a(l_a^m, l_a^w, inp; z_h)$	$p_M c_M = p_f(q_f - e_f) + p_a q_a + w l_{out}^m$	
Manning and Taylor (2014)[e]	$U(\frac{c_m}{\delta}, \frac{c_F(e_f, e_g, l_c, S)}{\delta}, l)$	$q_f(l_f, k_f)$	$q_a(l_a)$	$p_M c_M + p_s S = D((1-\delta)T; a) + p_a q_a$	$l_f + l_a + l_c + l = \delta T$
Muller and Yan (2014)[f]	$U(C(C^h, C^p; \Omega),$ $F(F^d(F^{dw}, F^{ds}, F^{dc}),$	$q^{dw}(L_{dw})$ $q^{ds} = \alpha Q_c + \beta M$	$Q_{AG}(Q_c(L_c, A_c),$ $Q_l(M^p, M^h(L_l)); \phi)$	$C^h p^h + C^p p^p + F^{dc} p^{dc} + F^{cl} p^{cl} + F^{ce} p^{ce}$ $= (Q_{AG} p^h - A_c p^{ac} - M^p p^{mp}) + w L_{off} + Y_0$	$L_{dw} + L_c + L_l + L_{off} + l = T$

$F^c(F^{cl}, F^{ce}); V), l; Z)$

a) c_m describes the consumption vector of market goods, c_h is the consumption vector of household goods, e_f and e are the amounts of firewood and energy used, S indicates whether the household owns a stove or not, z represents the vector of household characteristics, p_m, p_{e_f}, p_e and p_s are the prices of market good, firewood, energy and stove, respectively, y is income.

b) C is food consumption, G groceries, F_i is the vector of fuels as input in the domestic food consumption technology (cooking), H is an health indicator, I is health-related investment and consumption, K_i denotes the polluting characteristics of fuel, X describes other goods and services.

c) c_H is the vector of consumption goods that require energy inputs, e_c is coal consumption, c_M denotes the vector of other consumption goods, l is leisure, q_f is collected firewood, l_f is the labor time spent in collecting firewood, z_v is a vector of exogenous variables reflecting forest access, q_a is the vector of agricultural outputs, l_a is household labor time spent in agriculture, z_h is a vector of household endowments pertaining to farming, p_M, p_c and p_a are the respective prices of other goods, coal and agricultural goods, w is the exogenous wage rate, l_{out} is labor time spent off-farm, E is the exogenous household income, T is the total available household time.

d) e_p is the consumption vector of private non-marketed fuels (e.g., crop residues, animal dung), l^m and l^w are the leisure times, respectively for adult men, women and children, l_f^w is female and child labor time spent collecting firewood, l_a^m and l_a^w are male farm labor time, and female/child labor time, respectively, inp measures the use of residues and dung as farm inputs, q_p is the vector of the private non-marketed fuel productions, l_{out}^m is male labor time in off-farm work.

e) c_F is the vector of home-produced food, e_g measures the use of gas, l_c is the household labor time spent in cooking, δ is the proportion of households living at home and represents the proportion of the labor endowment in the household, T is time endowment in household, $(1-\delta)T$ describes migrations to the US, a is the migration cost, D denotes the remittances.

f) C^h and C^p describe the vectors of the household produced and consumed food, on the one hand, and of the market-purchased food, on the other. Ω stands for predetermined variables related to the domestic technology and constraints yielding the final food consumption. Z is a vector of household characteristics pertaining to preferences, notably with respect to fuel use. F^d and F^c are, respectively, indices for dirty and clean fuel consumptions . F^d consists of used quantities of firewood (F^{dw}), straw (F^{ds}) and coal (F^{dc}), while F^c is made of quantities of liquefied natural gas (F^{cl}) and electricity (F^{ce}). Vector V denotes predetermined variables associated with the cooking technology and access constraints. q^{dw} is the quantity of collected firewood, L_{dw} is the household labor time spent collecting firewood. Q_c and Q_l are crop and livestock production levels, respectively. L_c is the household labor time spent in crop production. A_c represents the other fixed agricultural inputs. M^p and M^h are the purchased and homemade cattle feeding quantities. L_l denotes the labor time allocated in cattle feeding activities. ϕ is a vector of household endowments pertaining to land and livestock. α and β denote the corresponding proportions. q^{ds} is the straw output produced by the household. p^h and p^p respectively refer to the prices of household produced and market purchased food; p^{dc}, p^{cl} and p^{ce} are the prices of coal, liquefied natural gas and electricity, respectively; p^{ac} represents the prices of the other fixed inputs in crop production; p^{mp} is the price of purchased feeding; L_{off} denotes the household labor time allocated in off-farm; w is the wage rate and Y_0 denotes the other exogenous incomes.

Table 2 Empirical literature on fuel use in developing countries

Author	Fuel type	Data source	Econometric method	Income	Fuel price	Household characteristics	Community characteristics
Abebaw (2007)	Fuel consumption (firewood, charcoal)	Jimma town of Ethiopia, household survey, urban, 2000	Tobit model	Per capita monthly household income Square of per capita monthly household income		Household head's age Household size Household head's gender Household head's education Cattle ownership Refrigerator ownership Home ownership	Perceived fuelwood supply in future Distance from nearest fuelwood entry rout to the town
Ahmad and Puppim de Oliveira (2015)	Fuel choice (traditional, mixed and modern fuels)	Indian Human Development Survey, urban, 2004	Multinomial logit model	Household income	Firewood price LPG price Kerosene price	Household size Highest education Number of meals per day Piped water supply Electricity supply	
Akpalu et al. (2011)	Fuel consumption (firewood, charcoal, kerosene, LPG)	Ghana Living Standards Survey, 1998	Regression analysis	Household expenditure	Kerosene price Firewood price Charcoal price		Geographic location

An et al. (2002)	Fuel choice (fuelwood, electricity)	Wolong in China, household survey, rural, 1999	Logit model	Household expenditure	Electricity price	-Age Gender Education	Outage Voltage frequency Distance to Fuelwood Geographic location
Arthur et al. (2010)	Fuel choice (charcoal, kerosene, electricity)	Mozambique, household survey, rural and urban, 2002	Logit model	Household daily income		Household head's education Household size Dwelling ownership Dwelling type Drinking Water Primary energy consumption share Share of cash on total earnings	
Baiyegunhi and Hassan (2014)	Fuel choice (fuelwood, kerosene, natural gas, electricity)	Nigeria, household survey, rural, 2010	Multinomial logit model	Monthly household income	Fuelwood price	Household head's age Household head's education Household head's occupation Household size Dwelling ownership Dwelling type Duration of food cooked	Distance to fuel source

Chen et al. (2006)	Fuel consumption (firewood, coal)	China. household survey, rural, 2000	OLS Tobit model	-Household wealth Household income		Ownership of improved stove Household size Ratio of labor force Number of educated members Cultivated area	Distance to forest
Cheng and Urpelainen (2014)	Fuel choice (modern fuel, fuel stacking)	India, National Sample Survey, 1987 and 2010	Two-stage probit model	Household monthly expenditure	Firewood price Kerosene price Electricity price LPG Price	Household head's education Household head’s gender Household size Land	
Démurger and Fournier (2011)	Fuel consumption (firewood) Fuel choice (coal)	Labagoumen township in China, household survey, rural, 2001	Probit model	Household wealth Household wealth square	Collection time	Average age Average education of adult members Household size Household size square Non-agricultural labor force Farmland size Having children or siblings outside Number of livestock Dwelling size per capita	
Edwards and Langpap	Fuel consumption	Guatemala,	Tobit model	Household	Wood price	Household head’s age	Ethnicity

(2005)	(wood)	household survey, rural/ urban, 2000		expenditure Household expenditure square	Coal price LPG price Electricity price	Household size Stove ownership	
Farsi et al. (2007)	Fuel choice (firewood, kerosene, liquid petroleum gas)	India, National Sample Survey, urban, 1999	Ordered probit model	Per capita monthly household expenditure	LPG price Kerosene price Firewood price	Household head's age Household head's gender Household head's education Household size	Number of LPG distributor Geographic location
Gebreegziabher et al. (2012)	Fuel choice (dung, wood, charcoal, kerosene, electricity)	Tigrai in Ethiopia, household survey, urban, 2003	Probit model	Household expenditure	Wood price Charcoal price Kerosene price Electricity price	Household head's age Household head's education Household head's occupation Household size	
Gregory and Stern (2014)	Fuel consumption (Dung, Wood, Kerosene)	India, household survey, rural, 2009-2010	Regression analysis	Per capita monthly household income		Household size Female share Children share Kerosene stove Other stove Electricity supply	
Gupta and Köhlin (2006)	Fuel choice and consumption (fuelwood, coal, kerosene and	Kolkata in India, household survey, urban, 2000	OLS Probit model	Per capita household annually expenditure	Wood price Coal price Kerosene price	Household head's age Household head's education Number of women not	Households' perceptions of availability of fuelwood and

	LPG)					working Household size Household size square Households' perceptions of air pollution caused by fuelwood and coal	LPG Geographic location
Guta (2012)	Fuel choice (Traditional fuels, mix of traditional and modern fuels, modern fuels)	Ethiopia, household survey, rural, 2000 and 2004	Multinomial logit model	Household monthly expenditure		Household head's age Household head's age square Household head's gender Household head's education Household size Household size square Time spent on fuel collection Total number of livestock Land holding size	
Guta (2014)	Fuel consumption (biomass, fuelwood, Charcoal)	Ethiopia, Ethiopian Rural Household Survey, 2004	Tobit model	Non-labour income Electricity expenditures	Charcoal price Kerosene price	Number of livestock Land Fuelwood time Family size Household head's age Household head's sex	Population density

						Household head's education Female adults labour force share Household member's highest education level Improved efficiency biomass stove	
Heltberg (2004)	Fuel choice (LPG, fuel Switching)	Brazil Pesquisa Sobre Padro˜es de Vida, rural and urban, 1996 Ghana Living Standards Survey, rural and urban, 1998, Guatemala National Survey of Living Conditions, rural and urban, 2000 India National Sample Survey, rural and urban, 1999 Nepal Living	Multinomial logit model Logit model	Household Per capita expenditure		Household head's education Spouse's education Household size Drinking water Household electrified Average number meals per day	Community access to electricity

		Standards Survey, rural and urban, 1995 Nicaragua Living Standard Measurement Survey, rural and urban, 1998 South Africa Integrated Household Survey, rural and urban, 1993 Vietnam Household Living Standards Survey, rural and urban, 1997					
Heltberg (2005)	Fuel choice (wood, LPG, LPG-charcoal mix)	Guatemala, Living Standard Measurement Surveys, urban and rural, 2000	Multinomial logit model	Household expenditure per capita	LPG price Kerosene price Firewood price	Household size Education Dwelling type Proportion of female	Access to Electricity Ethnic group Distance to Fuelwood Geographic location
Hosier and Dowd (1987)	Fuel choice (wood, kerosene,	Zimbabwe, National Household Survey,	Multinomial logit model	Household monthly	Relative price of kerosene to	Household size	Households' perceptions of

	electricity, mixedfuel)	urban, 1984		income	electricity		availability of fuelwood Geographic location
Hughes-Cromwick (1985)	Fuel consumption (charcoal, paraffin, gas, electricity)	Nairobi in Kenya, household Survey, urban, 1981	Regression analysis	Household annually income	Gas price Electricity price	Household size Number of electric and charcoal appliances	
Israel (2002)	Fuel choice (firewood) Fuel consumption (firewood)	Bolivian Integrated Household Survey, urban, 1989	Probit model Heckman selection	Household per capita expenditure Household per capita expenditure squared		Household head's age Household head's education Household head's indigenous language Household size Proportion of female earned income Cooking for sale	Geographic location
Jiang and O'Neill (2004)	Fuel choice (biomass)	China, nationally representative survey, rural, 1999	Logit model	Household income Household expenditure		Household head's age Household head's sex Household head's education Household head's Occupation Household size Household structure	Geographic location
Kaul and Liu (1992)	Fuel consumption (wood, stalks and	China, household survey,	Regression analysis	Household income	Coal price	Household size Cultivated' land	Distance to fuelwood and

	coal)	rural, 1988				Livestock owned	coal Forestland per capita Geographic location
Lay et al. (2013)	Fuel choice (wood, kerosene, electricity, solar, dry cell)	Kenya Integrated Household Budget Survey, rural and urban, 2005	Multinomial logit model	Household annually expenditure	Kerosene price	Household head's education Dwelling type Dwelling ownership	Community access to electricity Prevalence of solar home systems Geographic location
Lee (2013)	Fuel consumption (electricity, kerosene, firewood, charcoal), Fuel choice (non-solid fuels, solid fuels,mixed) Fuel choice (electrification)	Ugandan National Household Energy Survey, rural and urban, 2009	Tobit model Multinomial logit model Logistic model OLS	Household per capita expenditure Household per capita expenditure square	Kerosene price Firewood price	Education Household size	Private water connection Public water source
Lee et al. (2015)	Fuel choice (Fuelwood, gas)	Indonesia, household survey, rural	Logistic model	Household monthly income		House condition Gas stove Value of livestock	Large/small fuelwood markets

						Forest cultivation area Garden area Education Household size Travel time to forest	
Link et al. (2012)	Fuel choice (wood)	Nepal, household survey, rural, 1996 and 2001	Multilevel logistic model	Household income		Number of adults Proportion of female House plot ownership	Community access to electricity Wood collection time Ethnic group Other community context
Macauley et al. (1989)	Fuel consumption (wood, LPG)	Raipur in India, household survey, urban, 1985	Regression analysis	Household monthly income			
Mekonnen (1999)	Fuel consumption (biomass, dung)	Ethiopia, household survey, rural, 1996	Heckman's two-step	Household income	Cost of time spent to collect a unit of fuel	Household size Number of trees Number of cattle	Marginal product of labour computed from fuel collection functions Geographic location
Manning and Taylor (2014)	Fuel consumption (gas, wood)	Mexico National Rural Household Survey, rural, 2007	IV model Heckman Selection	Household income		Households with migrant Rate of stove use	Median village wage

		and 2010	Heckman selection with IV Tobit model			Household head’s indigenous language Education	
Muller and Yan (2014)	Fuel choice (wood/straw, coal, LNG and electricity)	China Health and Nutrition Survey, rural, 2000, 2004 and 2006	Random effects panel logit model Multinomial logit model	Household income	Coal price LNG price Electricity price	Household head’s age Household head’s sex Household head’s education Household head’s occupation Household head’s marital status Household size Dwelling attributes Lifestyle types Household’s agricultural specialization	Share of households with agricultural activities Off-farm employment participation Geographic location Access to telephone and bus services Food prices
Nlom and Karimov (2014)	Fuel choice (firewood, kerosene, LPG)	Cameroon, national survey, rural and urban, 2004	Ordered probit model	Household monthly income	Electricity price Kerosene price Firewood price	Household head’s age Household head’s education Dwelling type	
Onyebuchi (1989)	Fuel consumption (traditional energy)	Nigeria, household survey, rural and urban, 1982	Regression analysis	Household income		Household size	
Ouedraogo (2006)	Fuel choice (LPG, charcoal,	Ouagadougou, household	Multinomial logit model	Household income		Household head’s age Household head’s sex	

	firewood, kerosene, other solid fuels)	expenditure survey, 1996				Household head’s education Household head’s religion Household size Cooking frequency Dwelling type Dwelling ownership Household lighting source
Özcan et al. (2013)	Fuel choice (dung, wood, coal, natural gas, electricity, liquid fuel)	Turkey, Household Budget Surveys, rural and urban, 2002–2006,	Multinomial logit model	Household monthly income		Household head’s age Household head’s education Household head’s occupation Household size Dwelling type Heating system
Pandey and Chaubal (2011)	Fuel choice (clean fuels)	India, National Sample Survey, rural, 2004	Logit model	Household monthly per capita expenditure		Average household education Household size Number of higher educated females Agricultural household type Farm size

						Regular income Caste	
Peng et al. (2010)	Fuel choice (biomass) Fuel consumption (biomass)	Hubei in China, household survey, rural, 2004	Logit model Tobit model	Household income	Coal price	Household head's education Household size	Electricity access Geographic location
Pitt (1985)	Fuel consumption (kerosene, firewood, charcoal)	Indonesia, SUSENAS, rural and urban, 1978	Regression analysis	Household expenditure	Kerosene price Wood price	Household size Household member age > 10 years	Geographic location
Pundo and Fraser (2006)	Fuel choice (firewood, charcoal, kerosene)	Kenya, Kisumu Household Survey, rural, 2001	Multinomial logit model Logit model			Household head's age Household head's occupation Household head's education Spouse's age Spouse's education Household size Dwelling ownership Dwelling type Cooking time	
Rahut et al. (2014)	Fuel choice (fuelwood, kerosene, gas, electricity)	Bhutan Living Standard Survey, rural and urban, 2007	Multinomial logit model	Household per capita expenditure		Household head's age Household head's age square Household head's gender	Distance from market Access to electricity

						Household head's education Children Old people Household size Wetland owned Dry land owned	
Rao and Reddy (2007)	Fuel choice (firewood, kerosene, LPG, other fuels)	India, National Sample Survey, rural and urban, 1999	Multinomial logit model	Monthly household expenditure Square of household expenditure		Average age of household members Household head's gender Mean education of household member Highest educational level Household size Square of household size	Religion Social group Geographic location
Reddy (1995)	Fuel choice (firewood, charcoal, kerosene, LPG, electricity)	Bangalore in India, household survey,	Multinomial logit model	Per capita household income	Relative price of carder	Household head's occupation Household size	
Sehjpal et al. (2014)	Fuel choice (biomass, LPG)	Madhya Pradesh in India, household survey, 2000	Logit model	Monthly per capita expenditure	Firewood price Kerosene price LPG price	Primary livelihood activity of male members	

						Social Status Education level of male/ female members Household Size Land Size Electricity Access Average time spent by women for cooking per day
Zhang et al. (2014)	Fuel consumption (Biomass), Fuel choice (use versus non-use of biomass)	Shanxi, Guizhou and Zhejiang in China, household survey, 2010 or 2011	OLS Logit model Tobit model	Household annually income	Coal price	Days spent on collecting biomass Farmland size Dwelling size Household size
Zhang and Hassen (2014)	Fuel choice (firewood, coal, LNG)	Nine provinces in China, China Health and Nutrition Survey, 1989, 1991, 1993, 1997, 2000, 2004, 2006, and 2009	Ordered probit model Generalized ordered probit model Random effect ordered probit model Multinomial model Random Multinomial	Household income	Coal price LNG price	Household head's age Household head's gender Household head's education Household head's married status Household head's Occupation Household size

			model				
Zhang and Koji (2012)	Fuel consumption (coal, electricity, LPG)	Beijing in China, household survey, rural, 2009	Tobit model	-Household per capita income Household per capita income square	Coal price LPG price	Household size Ratio of labor force Ratio of mid-educated household numbers	Renewable energy technologies Geographic location

Table 3 Income elasticity for fuel consumption and fuel choice: comparison of selected studies

Authors	**Fuel types**						
	Biomass	Firewood	Charcoal	Coal	Kerosene	Gas	Electricity
Fuel consumption							
Abebaw (2007)		0.007	0.004				
Akpalu et al. (2011)			0.54		0.38	0.7	
Chen et al. (2006)		-0.35 to -1.7		-0.04 to 0.05			
Démurger and Fournier (2011)		-0.53					
Gregory and Stern (2014)		-0.07 to 0.16			0.1to 0.15		
Gupta and Köhlin (2006)		-0.29			-0.6	1.64	
Guta (2014)	0.02	0.01	0.05				
Hughes-Cromwick (1985)			-0.23 to -0.28				1.58 to 1.6
Lee (2013)		0.01	0.45		0.07		0.2
Macauley et al. (1989)		-0.43				0.17	
Manning and Taylor (2014)						0.05 to 0.1	
Mekonnen (1999)	0.06						
Pitt (1985)		-0.68 to 1.85	0.06 to 2.95		0.23 to 0.59		
Zhang et al. (2014)	-0.12 to -0.18						
Fuel choice							
Lee (2013)							0.71
Lee et al. (2015)		0.04				0.31	
Muller and Yan (2014)		-0.23		-0.15		0.35	
Ouedraogo (2006)					-0.24	0.28	
Özcan et al. (2013)				-0.04 to 0.02		0.45 to 0.96	0.46
Zhang et al. (2014)	-0.05 to -0.15						

Table 4 Own-price elasticity for fuel consumption and fuel choice: comparison of selected studies

Authors	Fuel types					
	Firewood	Charcoal	Coal	Kerosene	Gas	Electricity
Fuel consumption						
Akpalu et al. (2011)	-0.87	-0.94		-1.3	-8.91	
Gupta and Köhlin (2006)	-0.83			-3.88		
Guta (2014)	-0.38	-0.96				
Hughes-Cromwick (1985)					-3.09	-0.34 to -0.35
Kaul and Liu (1992)			-0.79			
Lee (2013)	-0.32			-0.32		
Pitt (1985)	-1.1 to -1.14	-0.64 to -0.72		-0.93 to -1.1		
Fuel choice						
An et al. (2002)						-1.3 to -2.22
Muller and Yan (2014)			-0.29			-0.53