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Collective model of firewood consumption, production, and labour supply: Evidence from Malawi

Raavi Aggarwal^{†¶*} and Jan Steckel^{*§}

Abstract

We develop a collective household model to analyse the non-separable link between firewood consumption, fuel collection, and individuals' labour supply in Malawi. Modelling firewood as a home produced good, we analyse the role of female bargaining power within the household, in determining optimal firewood consumption. We posit labour supply as a potential channel for firewood collection and consumption. Drawing on household and individual-level panel data for 2010-2020, we find a positive effect of fossil fuel prices on firewood consumption, with significant increases in individuals' labour supply for informal work. Greater parity in decision-making between men and women is associated with a reduced likelihood of firewood use, in a context of rising energy prices. The results highlight the the labour market effects of energy price increases, and the importance of intra-household dynamics in determining biomass consumption, thus broadening the debate on sustainable development policies in sub-Saharan Africa.

Keywords: Collective model, bargaining power, biomass use, sustainable development

JEL Codes: Q12, D13, J22

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1 Introduction

While optimal pricing of environmental externalities is an efficient instrument to reduce greenhouse gas emissions, consequent shifts in the relative prices of fossil fuels could spur substitution toward biomass use in Sub-Saharan Africa (SSA) (Olabisi et al., 2019; Alem and Demeke, 2020). The persistent use of biomass for cooking has adverse health effects via indoor air pollution, particularly in SSA (Pratiti et al., 2020; Roth et al., 2018), and results in forest degradation (Masera et al., 2015). Yet, over 80% of the urban African population depends on charcoal for energy (Zulu and Richardson, 2013), while close to 80% of the Malawian population relies on firewood for cooking (NSO, 2020).

Firewood collection in SSA is highly gendered in nature, with the burden falling disproportionately on women and children (Köhlin et al., 2011). Significant disparities exist between women and men in their time spent on cooking-related activities including fuel collection, across developing countries in SSA and Asia (Krishnapriya et al., 2021). Consumption of informal solid fuels however depends on the availability of household labour, in particular women’s time, for collection. In addition to preferences for leisure, individuals’ time allocation for market work vis-à-vis firewood collection is an outcome of the intra-household bargaining process. Availability of individuals’ time and intra-household dynamics are thus key determinants of biomass consumption in SSA, especially in Malawi where the majority of firewood used by households is obtained for free from local forests, rather than purchased on markets (NSO, 2020). These intra-household and labour market aspects of household energy use are nevertheless under-examined in the existing literature.

To theorise the role of bargaining power and the inter-linkages between energy prices and labour supply, we develop a collective household model, following the seminal works of Chiappori (1992) and Browning and Chiappori (1998). We introduce firewood as a home produced good in a non-separable framework of consumption and production, and assess the reduced-form effect of energy prices on firewood consumption among households in Malawi. We posit individuals’ labour supply as a potential channel for the household’s increased demand for firewood in a context where firewood collection has predominantly been undertaken by women and girls (Biran et al., 2004). We therefore investigate the role of female bargaining power in determining optimal firewood consumption, in a scenario of rising energy prices.

Drawing on household- and individual-level panel data from the Malawi Integrated Household Panel Surveys, 2010-20, conducted by the Malawi National Statistical Office (NSO) in collaboration with the World Bank’s Living Standards Measurement Study (LSMS), we first identify the impact of increases in fossil fuel prices on firewood consumption. We then es-

estimate the effects of energy prices on individuals' time allocation across market work and fuel collection. Lastly, we assess the effect of greater parity in decision-making between men and women in the household, on the likelihood of firewood use for cooking, drawing on cross-sectional data from the Malawi Demographic and Health Survey (DHS), 2010.

The results show a positive association between fossil fuel prices and firewood consumption in Malawi, with a 1% increase in kerosene and transport prices raising the annual demand for firewood by 0.1 - 0.2%, conditional on firewood use. Energy price hikes have significant labour market effects, with percent increases in energy prices raising the annual days spent on informal (*ganyu*) labour by 0.3 - 0.6% for women and by 0.2 - 0.6% for men, while leaving their annual hours spent on firewood collection largely unaffected. Children's time allocation mirrors patterns for adult labour, with a reallocation from firewood collection towards informal (*ganyu*) labour. Higher energy prices are further associated with a reduced likelihood of children being literate in the local Malawian language, *Chichewa*.

Women's bargaining power plays an important role in determining households' use of firewood for cooking purposes. Greater parity between men and women in the household decision-making process, which reflects women's bargaining power, is associated with a lower likelihood of firewood use in a scenario of rising kerosene prices. Similarly, increases in household wealth simultaneously to improvements in decision-making parity, are associated with a lower probability of households' use of firewood for cooking. On the contrary, increases in household wealth simultaneously to increases in kerosene prices, albeit with the household's level of decision-making parity held constant, have no statistically significant effect on the likelihood of firewood use. These findings highlight the significant role of intra-household dynamics in shaping decisions regarding energy use, while the results on labour market effects suggest important interactions with households' energy consumption decisions.

The paper is outlined as follows. Section 2 discusses the previous literature, section 3 outlines the theoretical framework and section 4 discusses comparative statics. Section 5 presents an empirical discussion and sub-sections 5.1 and 5.2 describe the data sources and summary statistics respectively. Sub-sections 5.3 and 5.4 outline the econometric strategy and present the results, while section 6 concludes. The Appendix displays further empirical results as robustness checks. We additionally present an analytical application of the theoretical model and three model extensions in the Appendix, to investigate relevant aspects of energy use in relation to gender, time use and health.

2 Related Literature

2.1 Energy use, health and labour supply

Efficient environmental policy for climate change mitigation requires an optimal mix of carbon pricing and revenue redistribution, to reduce emissions and alleviate the adverse household welfare effects of higher energy prices. In low- and middle-income countries, the persistent use of traditional biomass for cooking exacerbates the trade-off between climate policy and economic development, due to the significant health and time use burden of cooking with firewood. Recent work has explored the linkages between household energy use such as access to cleaner fuels, and women’s labour supply and health outcomes. Verma and Imelda (2022) analyse the effects of access to LPG enabled through a large-scale fuel-switching program in Indonesia, on women’s lung capacity by occupation and adult time use patterns. They document a 4% increase in women’s lung capacity due to exposure to the program, particularly for women who were primarily housekeepers. In response to health-induced productivity gains for women, the program further led to increases in both men and women’s labour supply by 13-20%. Imelda (2020) similarly finds a 25% decline in the infant mortality rate among Indonesian households provided access to LPG through the government program, over the 2007-12 period.

Access to cleaner fuels like electricity can reduce the demand for kerosene and firewood (for e.g. in Bhutan, Dendup, 2022), and facilitate women’s participation in the labour market by freeing up time from home production activities, for instance in South Africa (Dinkelman, 2011). Information provision on the adverse health effects of biomass burning can lead to an increase in the use of cleaner fuels and reduced indoor air pollution (for example in India, information provision by public health workers on the benefits of clean fuel use led to a sizeable increase in regular use of LPG and electric stoves, Afridi et al., 2021).

Women’s participation in the formal labour market further depends on social norms concerning perceptions of women’s work outside home. Dinkelman and Ngai (2021) review the recent experimental literature on men’s beliefs about women’s work, and find that men noticeably overestimate the social stigma surrounding notions of gender-appropriate work. This suggests a need for updating of men’s beliefs about societal perceptions, especially in developing countries, to galvanise women’s participation in the labour market. Along with social norms, higher female bargaining power within the home is associated with improved outcomes of child and maternal development, particularly where women “take power” in contrast to being “given power” by their husbands in the household decision-making process (Annan et al., 2021).

While these studies evaluate important interactions between energy use, gender, health

and individuals’ time allocation, the role of female bargaining power in determining households’ optimal fuel choices, is hitherto neglected in the literature. We aim to first highlight the salience of intra-household dynamics in households’ decisions pertaining to energy consumption, supported by a theoretical framework. Second, we aim to advance the empirical literature by providing evidence for the effects of fossil fuel price increases on labour market outcomes for adults and children, which have strong implications for environmental and sustainable development policy.

2.2 Agricultural Household Models

The majority of smallholder farming households in SSA make simultaneous decisions regarding consumption and production, as the household operates as both a firm, primarily for crop production, and a consumer. Agricultural household models, as developed in Singh et al., (1986) and discussed in Bardhan and Udry (1999), analyse optimal household decisions accounting for this interdependency, albeit largely in a recursive or separable framework, where consumption decisions depend on the farm’s profit maximising choices. Such recursive models have been applied to analyse the effects of food price increases on household nutrition in Ethiopia (Tesfaye, 2020), the effects of property rights allocation on labour supply in Peru (Field, 2007) and to analyse the efficiency of agricultural input use across gender segregated plots in SSA (Udry, 1996; Andrews et al., 2015).

The literature further estimates non-recursive or non-separable models, allowing for simultaneous optimisation of consumption and production choices. Lopez (1984) models the imperfect substitutability between family and hired labour on Canadian farms, while Lopez (1986) analyses the role of commuting time to off-farm work, allowing for differential household preferences for off- and on-farm work. Jacoby (1993) models the labour supply of farm households in the Peruvian Sierra, estimating the shadow wage for labour through a non-separable model of consumption and production, allowing for non-market participation.

The recent literature has rejected the assumption of recursive decision-making by farming households in the context of Indonesia, where LaFave and Thomas (2016) find that labour input decisions for on-farm work systematically depend on attributes of the utility function including the household’s demographic composition (household size and the age profile of household members), and availability of productive labour within the home. Recent evidence from Indian farms highlights the role of transaction costs in the agricultural labour market in explaining the preponderance of small farms in developing countries (Foster and Rosenzweig, 2022), which buttresses support for non-separable models.

Agricultural production is further introduced in collective household models which exam-

ine the intra-household allocation of resources (Chiappori, 1992, 1997; Apps and Rees, 1996 and Browning and Chiappori, 1998). Chiappori (1997) derives conditions for robust identification of the collective model with marketable home production. Donni and Matteazzi (2018) introduce non-participation constraints within the collective model of household labour supply and home production, while recovering the sharing rule within households. Chiappori and Ekeland (2009) comprehensively review the theory of collective models and derive conditions for identifiability where at least one private good for each member is available. They analyse models with both public and private consumption along with home production, in a collective framework. The unitary model, wherein the household members' preferences are representable by a single agent (i.e. the household itself) has been rejected in favour of the collective model, where the distribution of resources is found to be Pareto efficient (Browning and Chiappori, 1998). Dunbar et al., (2013) apply the collective approach to analyse the prevalence of poverty in Malawi and find significant differences in the poverty incidence across individuals, with children bearing a substantial burden, further lending support to the collective model approach.

3 Theoretical Framework

Consider a household with two types of members - men (M) and women (F), as the decision-makers. Households engage in firewood "production" or collection following a home production technology, with their labour as inputs in the process.

3.1 Firewood Production with Adult Labour

We model firewood as a non-marketable commodity wherein households collect and use firewood at home, primarily for food consumption, but additionally for lighting and heating purposes.¹ Households minimise the total cost of production for a given quantity of firewood that likely complements food preparation, as follows:

$$\min_{L_{WM}, L_{WF}} \quad w_M L_{WM} + w_F L_{WF} \tag{1}$$

subject to (s.t.):

$$m(L_{WM}, L_{WF}) \geq \bar{m} \tag{2}$$

¹Households could theoretically sell the collected firewood in shadow markets, at the marginal cost determined by the production technology.

The production technology exhibits constant returns to scale (CRTS) with respect to men and women's labour (L_{WM} , L_{WF}) as production inputs, which are priced at the exogenous market wage rates, w_M and w_F . The assumption of constant returns to scale implies a linear homogeneous cost function, with constant marginal cost. In this context, the Lagrange multiplier of the cost minimisation problem can be interpreted as the marginal cost of firewood production at the optimum, and thus as the price of collected firewood at the margin (Matteazzi et al., 2017; Snyder and Nicholson, 2011):

$$\mu = \frac{\frac{w_M}{\frac{\partial m(.)}{\partial L_{WM}}}}{\frac{w_F}{\frac{\partial m(.)}{\partial L_{WF}}}} = \tilde{P}_w \quad (3)$$

where $\frac{\partial m(.)}{\partial L_{Wi}}$ is the marginal product of individual i 's labour for firewood collection. The conditional labour demand functions for male and female inputs (contingent on the amount of firewood to be collected, F) can then be derived and are incorporated in individuals' labour supply decisions.²

We make the simplifying assumption that individuals' market wages best reflect the opportunity costs of their time. While the shadow wages for firewood collection would be determined in the corresponding shadow market (Jacoby, 1993), in the absence of labour market frictions, these would equal individuals' market wages. The unit cost interpretation of the cost function further ensures that the price of collected firewood only depends on exogenous parameters such as wages and the production technology. However, given the availability and use of firewood in the form of a common pool resource (Köhlin and Amacher, 2005; Köhlin and Parks, 2001), it would be more reasonable to assume diminishing returns to scale in production. Thus, in the model application (section 5), we relax the assumption of constant returns to scale, but can only analyse the model's predictions in implicit form, and with no guarantee of the existence of real solutions.³

3.2 Utility Maximisation

The household maximises the sum of women and men's individual utilities, U_F and U_M respectively, weighted by the respective Pareto weights, ϕ and $(1 - \phi)$, which are determined through a cooperative bargaining process (Chiappori, 1992). The household's objective function is the following:

²A canonical model using a Cobb-Douglas production function and quasilinear preferences for consumers is outlined in section 5.

³The literature on agricultural household models typically assumes constant returns to scale in production to ensure the existence of closed form solutions.

$$\max_{\{M, F, l_M, l_F\}} \phi U_F(M, F, l_F) + (1 - \phi) U_M(M, F, l_M) \quad (4)$$

s.t.

$$P_M M + \tilde{P}_W F + w_F l_F + w_M l_M = y + (w_F + w_M)T + \pi_w^* \quad (5)$$

$$l_i = T - (L_i + L_{Wi}) \geq 0 \quad \text{for } i = \{F, M\} \quad (6)$$

$$M \geq 0; \quad F \geq 0 \quad (7)$$

where M is a fossil-fuel based energy source such as kerosene or transport, which is traded in local markets at an exogenous price, P_M . F represents firewood collections from nearby villages, forests or own land. L_i is individual i 's market labour supply, l_i their leisure time and T the time endowment, while y is the household's total non-labour income. The shadow profits from firewood collection, π_w^* , are defined as follows:

$$\pi_w^* = \tilde{P}_W F - w_F L_{WF} - w_M L_{WM} \quad (8)$$

We allow for non-separability between household production and consumption choices, while assuming that firewood use is contingent on the household's food consumption, and is primarily for the household's domestic use. Since firewood is assumed non-marketable,⁴ shadow profits from collection are not exogenous to the household's utility maximisation problem. The budget constraint then reduces to the following, with firewood consumption being constrained by individuals' time availability and subject to their market wage rates:

$$P_M M + w_F l_F + w_M l_M = y + (w_F + w_M)T - w_F L_{WF} - w_M L_{WM} \quad (9)$$

Consumer preferences are of the egoistic type, such that individuals derive utility only from their own consumption and private leisure time. All energy items are modelled as public goods within the household, while each individual's leisure time is a private good and excludes the labour of the other member. Since the model satisfies the exclusion condition, whereby at least one commodity is private for each individual and excluded from the other individual's utility function (in this case private leisure demand), the model is identifiable (Chiappori and Ekeland, 2009). The representation of the utility maximisation problem (UMP) in equations (4) and (9) is analogous to the maximisation of individuals' utility

⁴It is important to note that while the model considers firewood as non-marketable, a minority of households in Malawi do undertake purchases of firewood in markets, at a fixed price.

functions subject to their specific resource constraints. Individuals' private resource shares are determined through the bargaining process, and add up to the household's net non-labour income, y , after deduction of household expenditures on all public goods.

The household's UMP can then be solved in two simultaneous stages (Chiappori and Ekeland, 2009). In the first stage, individuals jointly allocate household resources to the consumption of public goods, and decide on the optimal sharing rule for private resources, conditional on their Pareto weights. In the second stage, all members maximise their individual utility functions, conditional on the household's public good consumption and private resource shares allocated in the first stage, to determine optimal labour supply. We analyse the model backwards, and first derive the optimality conditions for the second stage.

3.2.1 Second-Stage

Each individual maximises their utility function, U_i , subject to the time endowment and their private resources ρ_i .

$$\max_{\{L_i, L_{Wi}\}} U_i(\bar{M}, \bar{F}, l_i) \quad (10)$$

s.t.

$$w_i l_i \leq w_i(T - L_{Wi}) + \rho_i \quad (11)$$

where $l_i = T - L_i - L_{Wi} \geq 0$.

Maximising utility with respect to market work L_i , and firewood collection time L_{Wi} , yields a unique first-order condition for leisure demand:

$$-\frac{\partial U_i}{\partial l_i} + \lambda w_i \geq 0 \quad (12)$$

where λ is the Lagrange multiplier. If the constraint holds with equality, the individual is indifferent between participating in the labour market and undertaking firewood collection.⁵

⁵Alternatively, if preferences were of the "caring" type, an individual's participation in the labour market would depend on both members' preferences and their bargaining power. The optimality condition for participation would take the form:

$$\phi \frac{\partial U_F}{\partial l_M} + (1 - \phi) \frac{\partial U_M}{\partial l_M} \geq \lambda w_M \quad (13)$$

If the inequality were strict, the individual would not participate in the labour market. In a scenario where a woman wishes to enter the labour market, even strong preferences for market work may be insufficient to induce her to work, if her bargaining power relative to her partner is too low. In some cases, labour market participation might therefore depend primarily on bargaining power.

This can be seen from an equivalent maximisation problem that equates the marginal utilities from both activities, at the optimum, as in Lopez (1984).⁶

If the shadow wage for firewood collection differed from the market wage, the individual would only undertake the activity that promised a higher wage. The UMP then yields the conditional leisure demand functions $l_F^*(\bar{M}, \bar{F}, w_F, \rho_F)$ and $l_M^*(\bar{M}, \bar{F}, w_M, \rho_M)$. The conditional leisure demands are expressed in terms of the public goods, the wage rates and private resources. The second-stage problem thus pins down individuals' time allocation between market labour and leisure, after incorporating the conditional labour demand for firewood collection from the household production process.

3.2.2 First-Stage

We derive the individuals' indirect utility functions V_i , using duality, for their optimised leisure demands.

$$V_i(M, F, w_i, \rho_i) = U_i(M, F, l_i^*(\bar{M}, \bar{F}, w_i, \rho_i)) \quad (15)$$

While an indirect utility function for private goods is typically expressed in the form of prices and income, in the case of public goods, we can express the indirect utility function in terms of the common quantity of public goods consumed, rather than the personalised Lindahl prices, with the duality results elaborated in Chiappori and Ekeland (2009). The household maximises the weighted sum of individuals' indirect utilities to solve for the optimal level of public good consumption and the sharing rule (Blundell et al., 2005), as follows:

$$\max_{\{M, F, \rho_F, \rho_M\}} \phi V_F(M, F, w_F, \rho_F) + (1 - \phi) V_M(M, F, w_M, \rho_M) \quad (16)$$

s.t.

$$\rho_F + \rho_M = y + \pi_w^* - P_M M - \tilde{P}_W F \quad (17)$$

Accounting for the non-separability between firewood production and consumption, the constraint equation simplifies as follows:

$$\rho_F + \rho_M = y - P_M M - w_F L_{WF} - w_M L_{WM} \quad (18)$$

⁶Consider a utility function of the form: $U_i(M, F, T - L_i, T - L_{Wi})$. Maximising this function subject to constraint equation (11) would yield the following optimality condition:

$$\frac{\partial U}{\partial L_i} = \frac{\partial U}{\partial L_{Wi}} \quad (14)$$

Although individuals' labour input decisions regarding firewood collection are private, the public nature of firewood consumption, the dependence of fuel collection on members' time inputs, and the link with private resources, influences members' time allocation decisions. The household's resource constraint in equation (18) implicitly assumes that members' labour market earnings are private resources and are not used to purchase the household's public goods. While this is a strong assumption, the alternative scenario would render the resource shares derived from non-labour income, net of public good expenditures, ρ_i endogenous to the second stage utility maximisation process. Based on the household's demand for firewood, both members' optimal labour supply for firewood collection is determined through the conditional input demand functions.⁷

The first-order conditions (FOCs) are as follows:

$$\phi \frac{\partial V_F}{\partial M} + (1 - \phi) \frac{\partial V_M}{\partial M} = \mu P_M \quad (19)$$

where μ is the Lagrange multiplier, interpreted as the marginal utility of household income. If individuals' preferences differ, the optimal market energy consumption choices will, in general, depend on both preferences and Pareto weights.⁸ The FOCs for the private resources are of the form:

$$\phi \frac{\partial V_F}{\partial \rho_F} = \mu \quad (20)$$

$$(1 - \phi) \frac{\partial V_M}{\partial \rho_M} = \mu \quad (21)$$

The FOC for firewood consumption takes the form:

$$\phi \frac{\partial V_F}{\partial F} + (1 - \phi) \frac{\partial V_M}{\partial F} = \mu \left(w_F \frac{\partial L_{WF}^C}{\partial F} + w_M \frac{\partial L_{WM}^C}{\partial F} \right) \quad (22)$$

The term in parentheses on the RHS is the marginal cost of firewood production, with the corresponding cost function given in equation (1), and thus the shadow price of firewood

⁷Contingent labour demand functions are of the form: $L_{Wi}^C(w, \alpha, F) = L_{Wi}^C$, where w is the vector of wage rates, α represents technology parameters and F is the level of firewood output.

⁸In the corresponding unitary model,

$$\frac{\partial V_h}{\partial M} = \phi \frac{\partial V_F}{\partial M} + (1 - \phi) \frac{\partial V_M}{\partial M},$$

the household's marginal utility from energy consumption is the weighted sum of individuals' marginal utilities. Therefore, if the collective model is correctly specified, preferences recovered from typical consumer demand analyses embody the bargaining process between the decision-makers, but are erroneously assumed identical across individuals, which leads to violation of the integrability requirement of consumer demand (Bourguignon and Chiappori, 1992).

collection, \tilde{P}_W . At the margin, households equate the weighted sum of members' utilities from firewood consumption to the household's marginal utility of income, augmented by the marginal cost of firewood collection. The latter two terms represent the increases in unit costs of firewood collection, and equal the individuals' respective wage rates, multiplied by the marginal increase in their optimal labour hours supplied for firewood collection, due to an increase in firewood demand. This term is obtained as the derivative of the contingent labour demand function with respect to firewood output. Therefore, the recursive nature of optimization between household consumption and production decisions is captured by the first-order condition, with the household's optimal firewood demand taking into account the consequent increase in hours supplied, and its impacts on household utility.

Rearranging terms, we obtain the Samuelson rule for the efficient provision of public goods, which in this case is firewood consumption within the household:

$$\frac{\frac{\partial V_F}{\partial F}}{\frac{\partial V_F}{\partial \rho_F}} + \frac{\frac{\partial V_M}{\partial F}}{\frac{\partial V_M}{\partial \rho_M}} = \tilde{P}_W \quad (23)$$

Each term on the LHS reflects an individual's marginal rate of substitution between firewood consumption and private resources, which can instead be allocated to enhance individuals' leisure time. Therefore, individuals exhibit trade-offs between additional firewood use, which requires their time input, and private leisure time, captured by their private resources. The terms further reflect their marginal willingness to pay for the public good, i.e. for firewood consumption, with their sum across individuals equal to the marginal cost of firewood production, and in the case of constant returns, the price of firewood.

4 Comparative Statics

The utility maximisation problem defined by equations (4) - (8), yields the household's optimal firewood demand $F^*(P_M, \tilde{P}_W(w, \alpha), y, \phi)$, where $w = \{w_F, w_M\}$, as a function of exogenous parameters including energy prices, wage rates, the household's non-labour income y , the Pareto weight ϕ and production technology parameters α . The demand function for firewood does not contain private resources ρ . While in the first-stage problem, the household optimally decides on private resources ρ , individuals' bargaining power plays a central role in negotiating these private resource shares. Therefore, the demand function in reduced form, depends on the Pareto weights, rather than the private resources. Further, we allow the individual weights to depend on the household's non-labour income and on individuals' market wage rates, i.e. $\rho(y, w) = \rho$.

We derive the comparative statics of the model, to answer three key policy questions. First, does an increase in the price of market energy sources, e.g. kerosene, raise firewood demand? Second, how does an increase in women's Pareto weight ϕ , simultaneously to increases in energy prices, affect the household's optimal demand for firewood? Lastly, how would an increase in the household's non-labour income, parallel to increases in energy prices and women's bargaining power, impact the household's optimal demand for firewood?

Following Browning and Chiappori (1998), we derive the Slutsky equation for the change in firewood demand in response to kerosene price increases in the collective setting, first holding the intra-household distribution of power constant. From duality, the Walrasian and Hicksian demand functions for firewood are equated at the optimum:

$$F(p, E(p, u, \phi), \phi(w, y)) = F^H(p, u, \phi(w, y)) \quad (24)$$

where $p = \{P_M, \tilde{P}_W(w, \alpha)\}$ and $E(p, u, \phi)$ is the minimal expenditure required for the household to attain a given utility level,⁹ and is thus the solution to the dual problem of the household's UMP (eqns. 4-8), given the Pareto weight ϕ (Browning and Chiappori, 1998). Differentiating both sides w.r.t. P_M , we obtain the Slutsky equation, holding members' respective weights constant:

$$\frac{\partial F}{\partial P_M} = \frac{\partial F^H}{\partial P_M} - \frac{\partial F}{\partial y} \frac{\partial E(p, u, \phi)}{\partial P_M} \quad (25)$$

The substitution effect $\frac{\partial F^H}{\partial P_M}$, could be positive or negative depending on whether kerosene and firewood are substitutes or complements in household energy use. The sign of the income effect would depend on whether firewood is a normal or inferior good. In the latter case, since $\frac{\partial F}{\partial y} < 0$, if the substitution effect were positive, there would be an overall increase in the household's demand for firewood, $\frac{\partial F}{\partial P_M} > 0$. This is because an increase in kerosene prices would reduce the household's real income, and given the inferiority of firewood, its demand would increase. We now examine how increases in female bargaining power, simultaneously to energy price increases, would impact the demand for firewood, when ϕ does not depend on energy prices, i.e. $\phi(w, y) = \phi$. Holding non-labour income and wage rates constant, the differential of firewood consumption with respect to energy prices and the Pareto weight ϕ , is expressed as:

$$dF = \frac{\partial F}{\partial P_M} dP_M + \frac{\partial F}{\partial \phi} d\phi \quad (26)$$

⁹The minimal expenditure $E(\cdot)$ equals the household's non-labour income y at the optimum, which is standard in a static model of consumption and labour supply (Card, 2014, Lecture Notes).

The first term represents the change in uncompensated (or Walrasian) demand for firewood due to higher energy prices (i.e. the LHS of equation 25), augmented by the price differential, dP_M . If the market energy source (e.g. kerosene) and firewood were substitutes, and if firewood were inferior, the first term would be positive. On the contrary, if higher female bargaining power lowers the demand for firewood (e.g. due to strong preferences for leisure, or women's labour re-allocation towards market work), the second term would be negative and could potentially outweigh the first term, resulting in a net decline in firewood demand.

Finally, we assess the impact of an increase in the household's non-labour income (or alternatively household wealth), that simultaneously raises women's bargaining power, on the demand for firewood. Increases in female bargaining power could occur through cash transfers targeted at women, which augment the household's non-labour income, thus resulting in important income effects. The net effect can be assessed by computing the differential of firewood consumption with respect to energy prices, individuals' weights and the household's non-labour income, while holding wage rates and the production technology constant.

$$dF = \frac{\partial F}{\partial P_M} dP_M + \frac{\partial F}{\partial y} dy + \frac{\partial F}{\partial \phi} \frac{\partial \phi(w, y)}{\partial y} dy \quad (27)$$

Cash transfers provided to women could raise their bargaining power, i.e. $\frac{\partial \phi(\cdot)}{\partial y} > 0$. If a higher weight for women further reduced firewood demand, i.e. $\frac{\partial F}{\partial \phi} < 0$, the potential increase in firewood demand due to higher energy prices, could be attenuated in response to shifts in the intra-household distribution of power. This result might hold in the Malawian context where firewood collection is largely undertaken by women and girls (WFP, 2017).

If women exhibit strong preferences for leisure (or equivalently for working in the labour market) or a dis-utility from firewood collection (perhaps due to the negative health effects of smoke resulting from burning firewood),¹⁰ higher bargaining power could reduce their overall demand for firewood. The positive income effects generated through cash transfers could further promote an upward shift on the energy ladder, especially if firewood were an inferior good. Transfers could thus attenuate the potential increases in firewood consumption due to the positive substitution effects of higher energy prices. Such a complementary policy would substantially enhance the effectiveness of price instruments like fossil fuel subsidy removal and emissions pricing, for sustainable development in SSA.

¹⁰The appendix outlines two alternative unitary household models, with the first incorporating the negative health effects of biomass burning in determining firewood consumption, and the second analysing the effects of increases in fuel efficiency (equivalently, the provision of improved cook-stoves), on the optimal demand for firewood.

5 Empirical Discussion

We now test the comparative statics of the model by empirically estimating the impacts of energy prices on firewood demand and labour supply, and examine the role of female bargaining power in determining optimal fuel use.

5.1 Data Sources

We utilise three rounds of household-level panel data between 2010 and 2020, drawn from the Malawi Integrated Household Panel Surveys (IHPS) conducted by the National Statistical Office, Malawi, in partnership with the World Bank’s LSMS programme.¹¹ The surveys are nationally representative of the 28 districts of Malawi, and follow a two-stage stratified sampling design. The first stage entails sampling of Census Enumeration Areas (EAs), which are defined in the Malawi Population and Housing Census for the corresponding years, consisting of around 200 households each. In the second stage, random samples of households are drawn from each of the 102 EAs in the survey.

We use household-level information on firewood consumption, total annual consumption expenditure (including spending on food, non-durable goods and durables), and geographic characteristics. We further use information on individuals’ time allocation between market work, informal labour and hours spent on firewood collection, and individual demographics such as age and level of education. We then merge the household-level consumption and time use data with energy price data from a distinct cluster (EA)-level survey for kerosene and firewood prices, based on the month and year of the survey. We additionally draw on national-level monthly time series data for the transport price index, by rural and urban areas, obtained from the annual statistical yearbooks of the National Statistical Office, Malawi. Using alternative energy price data helps circumvent potential quality concerns in kerosene prices from the household survey, and provides a robustness check for the broad effects of fossil fuel prices.

The quantity of firewood consumed is constructed as the ratio of the recorded monetary value of firewood consumption (scaled to annual levels), and the price of firewood in the corresponding district. While the theoretical framework models firewood as a non-marketable good with pure domestic consumption, the survey data do not allow us to distinguish between quantities of firewood collected from nearby forests/villages vis-à-vis firewood purchased on markets. However, data from the 2019-20 survey suggest that over half of the households that consume firewood collect it from nearby forests rather than purchasing wood in markets.

¹¹We omit the 2016-17 survey round as it does not contain community-level data on energy prices.

Time use data for men, women and children, available in the Malawi IHPS, provide information on individuals' weekly hours worked in their main job and secondary job, for which they receive regular payments. We consider these jobs to reflect formal market work. The data further record the number of days worked in a typical week on informal or daily wage, *ganyu* labour. Lastly, the survey records the hours spent by each individual on the day preceding the survey, to collect firewood and other fuel materials. We construct annual measures of all labour activities. Further details of data preparation are discussed in the Appendix.

To assess the joint effects of energy prices and parity in decision-making in the household on firewood consumption, we utilise the Malawi Demographic and Health Survey (DHS) 2010, merging household-level data with district-level information on kerosene prices for the corresponding month and year, from the community market price module of the Malawi IHPS 2010-11.¹² The measure of parity in decision-making is based on questions of who makes decisions within the household (whether the husband, wife, or both equally), regarding (i) large household purchases, (ii) households' daily consumption needs, (iii) visits to family and friends, (iv) control over women's earnings, and (v) how many children for the couple to have. A continuous variable is created with values of the number of decisions taken jointly by men and women, ranging from 0 to 5. To gauge household wealth, we use the wealth index score available in the DHS survey, taking the inverse hyperbolic sine transformation, which preserves negative values. The response is a dummy variable for whether the household uses wood as cooking fuel, relative to other energy sources like charcoal, electricity or others.

5.2 Descriptive Statistics

Summary statistics for individuals' time allocation across labour market activities for the panel sample 2010-20, are presented in Table 1. We observe that only 6.4% of women work in the formal labour market, receiving regular salaries, relative to 21.3% of men. On average, men work for 43 hours per week in formal jobs, while women work for 37 hours per week. On the contrary, participation in the informal labour market is more prevalent, with 28% of women and 35% of men engaging in *ganyu* labour. Men work for about 4.5 days per week in informal labour, relative to 4 days per week on average for women. Children are also involved in informal work, with 11% of girls and 13% of boys participating in *ganyu* labour.

There is significant disparity in individuals' participation in firewood collection activities, with women and children significantly more involved in collection, compared to men. Only

¹²Since the 2016 Malawi IHPS survey does not contain energy price data, we could not utilise the latest DHS Survey (2015-16) for the analysis. We also cannot utilise data on transport prices as we only observe household-level data for four months of the DHS survey, and lack the required variation in transport prices.

4% of men report they collected firewood on the day preceding the survey, relative to 25% of women. Among children, the burden of firewood collection falls disproportionately on girls, with 13% of young girls engaging in fuel collection, relative to 5% of boys. Adults and children both spent around 7-8 hours per week on average to collect firewood.¹³ The statistics for individuals' participation in firewood collection are however grossly underestimated, as the survey employs a 1-day recall period instead of a 7-day period. Furthermore, over 90% of Malawian households rely on woodfuel for their cooking needs, and over half of the households collect firewood from forests rather than purchasing it in markets, highlighting a significant bias in the reported survey data, due to the short recall period.

Table 1: Individuals' Time Allocation by Activity, Panel Sample 2010-20

Panel A. Adult Hours Worked in Formal Market per Week						
	Observations	% of participants	Mean	Std. Dev.	Min	Max
Women	327	6.42	36.6	18.83	2	84
Men	900	21.34	43.3	21.38	2	91
Total	1,227	13.18	41.5	20.93	2	91

Panel B. Days Worked in Informal (<i>Ganyu</i>) Labour per Week						
	Observations	% of participants	Mean	Std. Dev.	Min	Max
Women	1,442	28.31	4.15	1.61	1	7
Men	1,462	34.67	4.47	1.59	1	7
Girls	254	11.03	3.30	1.64	1	7
Boys	293	12.95	3.74	1.74	1	7
Total	3,451	24.87	4.19	1.65	1	7

Panel C. Hours Spent on Firewood Collection per Week						
	Observations	% of participants	Mean	Std. Dev.	Min	Max
Women	1,273	25.00	8.37	4.81	1	21
Men	160	3.79	7.66	4.37	4	21
Girls	296	12.85	7.70	4.50	1	21
Boys	119	5.26	6.71	4.31	4	21
Total	1,848	13.32	8.09	4.71	1	21

We additionally tabulate households' fuel consumption patterns for the panel sample to understand changes in the composition of household energy use over the 2010-20 period. Appendix Table A1 summarises the percentage share of households that consume various

¹³The weekly hours spent on fuel collection are scaled up from reports of time spent on fuel collection on the day preceding the survey.

fuels over the 2010-20 period for the panel sample. Appendix Figure A1 further displays the average expenditure share by energy source and year for the panel sample. Lastly, we present descriptive statistics for energy prices for the multiple survey years under study in Appendix Table A2. Energy prices, particularly for kerosene and firewood, exhibit significant heterogeneity across districts and over time, while the transport price index exhibits considerable monthly variation across rural-urban regions.

5.3 Estimation Strategy

We estimate reduced form models of firewood demand and individuals' labour supply in response to energy price increases, while controlling for a range of household- and individual-specific characteristics.

5.3.1 Firewood Demand

We apply the OLS Fixed Effects (FE) within-estimator for firewood demand, to the following model:

$$Y_{it} = \alpha_i + \gamma_s + \beta P_{r\tau} + \delta X_{it} + \epsilon_{it} \quad (28)$$

where Y_{it} is (i) the annual *log* monetary value of firewood consumed or (ii) the annual *log* quantity of firewood consumed by household i in survey year t . $P_{r\tau}$ is the fuel price at spatial-level r and at time τ . For kerosene, prices are at the enumeration area or district-level for month m and year t , or simply in year t for households with missing district-level data on energy prices (see section 6.1 above). For transport, prices are at the national level by rural/urban areas, in month m and year t . X_{it} is a vector of controls including the cluster or district-level price of firewood at time t , the *log* of household expenditure and a dummy variable for households' ownership of solar panels. α_i and γ_s are household and season fixed effects respectively, while ϵ_{it} is a normally distributed error term. We control for seasonal effects but do not control for year effects as the latter absorb the entire variation in the data and preclude precise identification. In further specifications, we additionally include stratum-level fixed effects, which are interactions of Malawian regions by rural/urban areas.¹⁴

¹⁴These result in six strata, i.e. for the Northern, Central and Southern regions, interacted by rural and urban areas.

5.3.2 Labour Supply

We estimate the Traditional Random-Effects Tobit model for individuals' labour supply to account for the high degree of self-selection into various labour market activities,¹⁵ with the following latent equation for labour supply at the intensive margin:

$$Y_{it} = \alpha_i + \gamma_s + \beta P_{r\tau} + \delta X_{it} + \epsilon_{it} \quad (29)$$

where Y_{it} is one of three outcomes for individual i in year t : (i) *log* hours worked per year for formal work, (ii) *log* days worked per year in informal or *ganyu* labour and (iii) *log* hours spent per year in firewood collection. Fuel prices $P_{r\tau}$ are as defined above, while the vector of controls X_{it} additionally contains individual characteristics like age, and level of education, which is categorised into primary, lower secondary, upper secondary, and college & above. We rely on the individual's level of education to capture important differences in individuals' productivity levels in a reduced-form setting, as we do not observe exogenous measures of adults' wage rates. While this is a key limitation of the analysis, we measure the reduced form effect of kerosene and transport prices on individuals' labour supply, and do not expect unobserved individual productivity to be correlated with prices at the district-level or nationally. The regressions further include seasonal controls to capture potential stock-piling of firewood in the dry season, prior to the start of the rainy season.¹⁶

5.3.3 Bargaining power effects

We estimate a Probit model to analyse the effects of kerosene prices on the likelihood of firewood use as cooking fuel, controlling for household characteristics. The latent model equation is as follows:

$$Y_{it}^* = \gamma_0 + \gamma_1 K_{d\tau} + \gamma_2 P_{it} + \gamma_3 W_{it} + \gamma_4 K_{d\tau} \times P_{it} + \gamma_5 P_{it} \times W_{it} + \gamma_6 W_{it} \times K_{d\tau} + \gamma_7 K_{d\tau} \times P_{it} \times W_{it} + \delta X_{it} + \epsilon_{it} \quad (30)$$

with $Y_{it} = 1$ if $Y_{it}^* > 0$ and 0 otherwise. Y_{it} is a dummy variable with value 1 if the household uses wood as a cook-fuel, and 0 otherwise. The covariates include the price of kerosene $K_{d\tau}$ for district d , at time τ as defined above, a continuous variable of parity in decision-making at the household-level, P_{it} , the inverse hyperbolic sine (IHS) transforma-

¹⁵Due to the small sample size of the individual-level panels, we could not apply the correlated-random effects approach of Chamberlain (1980, 1984) and Jakubson (1988).

¹⁶We thank Hannes Greve for this useful insight.

tion of the household’s wealth index, W_{it} , and a vector of control variables X_{it} , including rural/urban location, ownership of a paraffin lamp and region-level dummy variables. The model further includes pair-wise interactions between kerosene prices, decision-making parity, and household wealth, and a triple interaction between the three variables, to analyse the total effect of changes in energy prices, women’s bargaining power, and changes in wealth, on the likelihood of firewood use.

5.4 Results and Discussion

This section presents regression results for the effects of energy prices on firewood consumption, individuals’ time allocation across labour market activities, and the role of female bargaining power in determining firewood use.

5.4.1 Firewood use and time allocation

We find energy prices to be positively associated with both the expenditure value and quantity of firewood consumed, controlling for the market price of firewood, the household’s total consumption expenditure, ownership of solar panels, and including household and season fixed effects (Table 2). A 1% increase in the price of kerosene raises the quantity of firewood consumed by 0.16%. These patterns of fuel use are likely driven by shifts at the extensive margin among households at the threshold of using modern fuels like kerosene vis-à-vis firewood for cooking. The household’s consumption expenditure has a positive yet statistically insignificant effect on firewood consumption. Hence, we cannot clearly ascertain the direction of the income effect, albeit there is clear substitution from kerosene to firewood use.

While the model results in firewood demand being a function of the household’s non-labour income, in developing country contexts, measures of expenditure are typically more accurate predictors of household well-being than measures of income, with the latter potentially reflecting transitory rather than permanent sources of income (Attanasio and Pistaferri, 2016). We control for the price of firewood in these regressions, which based on the theoretical model, reflects the marginal cost of firewood collection, and captures individuals’ wage rates and unobserved production technology shocks.

Energy price increases have significant labour market effects, particularly for informal work. We find clear evidence of an increase in adults’ and children’s labour supply for informal (*ganyu*) work in response to higher energy prices (Table 3). A 1% increase in kerosene prices raises the annual days spent in informal labour by 0.6% for men and women, and by 0.9% for girls. On the other hand, adults’ labour supply for formal or regular wage work is unaffected by energy price increases.

Table 2: Effects of energy prices on firewood consumption, Panel Sample 2010-20,
OLS with Fixed-Effects

<i>Panel A</i>						
log(Firewood Value)	(1)	(2)	(3)	(4)	(5)	(6)
log(Kerosene price)	0.321*** (0.053)	0.303*** (0.054)	0.190*** (0.063)			
Transport Price Index				0.001*** (0.000)	0.001*** (0.000)	0.001** (0.000)
log(Firewood price)			0.209*** (0.073)			0.130 (0.096)
Observations	1,638	1,638	1,638	1,638	1,638	1,638
R^2	0.048	0.056	0.070	0.058	0.065	0.068
Household FE	Yes	Yes	Yes	Yes	Yes	Yes
Season FE	No	Yes	Yes	No	Yes	Yes
<i>Panel B</i>						
log(Firewood Quantity)	(1)	(2)	(3)	(4)	(5)	(6)
log(Kerosene price)	0.190*** (0.063)	0.165** (0.071)	0.163** (0.073)			
Transport Price Index				0.001** (0.000)	0.001** (0.000)	0.001* (0.000)
log(Firewood price)	-0.791*** (0.073)	-0.824*** (0.071)	-0.829*** (0.072)	-0.870*** (0.096)	-0.870*** (0.096)	-0.872*** (0.095)
log(Household Exp.)		0.094 (0.109)	0.102 (0.111)			0.086 (0.111)
Owns Solar Panel		0.269 (0.256)	0.280 (0.258)			0.170 (0.272)
Observations	1,638	1,638	1,638	1,638	1,638	1,638
R^2	0.218	0.219	0.222	0.216	0.216	0.217
Household FE	Yes	Yes	Yes	Yes	Yes	Yes
Season FE	No	Yes	Yes	Yes	Yes	Yes
Region \times Rural/Urban FE	No	No	Yes	No	No	Yes

Standard errors (clustered by enumeration area) in parentheses. Constant term suppressed.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Similarly, firewood collection time is largely unaffected by increases in kerosene prices, while girls experience a decline in collection time (Table 4). Robustness checks using the national transport price index presented in Appendix Tables A6 and A7 reveal broadly similar labour market effects.¹⁷ These results suggest that energy price increases substantially raise overall labour supply for most individuals, including children, particularly through informal market work, which underscores the salience of the adverse income effects of energy price increases. Contrary to expectation, the scarcity of time leads individuals to gain extra income through daily wage work, rather than reallocate time towards additional firewood collection.

The impacts on firewood collection time are somewhat counter-intuitive and contrary to the theoretical model, which predicts an increase in collection time contingent on increased firewood consumption through an increase in firewood collection. Given that we observe increases in firewood use at the intensive margin due to energy price increases, the absence of an effect on collection time could be explained by a probable increase in the market purchases of firewood. We test this mechanism by estimating the effects of energy prices on the likelihood of firewood purchases relative to self-collection,¹⁸ and present the results in Appendix Table A3. Results show a small positive effect of higher transport prices on the likelihood of purchasing firewood in the marketplace, while kerosene price increases have no detectable effect.

Lastly, energy price increases are associated with a reduced likelihood of children being literate in *Chichewa*, a local Malawian language (Appendix Table A4). A 1% increase in kerosene prices reduces the probability of boys' being literate in *Chichewa* by 8.3%, and by 8.6% for girls. Transport price increases are further associated with a reduced probability of girls being literate in English (Appendix Table A5). The reductions in literacy are suggestive of potentially adverse schooling effects, although we lack the requisite data on children's hours spent in school to undertake complete analysis of children's time allocation across school and work.

5.4.2 Effects of bargaining power on firewood use

At the extensive margin, higher energy prices raise the likelihood of firewood use for cooking, with a 1% increase in kerosene prices leading to a 3% increase in the probability of using

¹⁷We additionally conduct robustness checks by replicating the regressions for firewood collection time, using pooled cross-sectional data from the Malawi Integrated Household Surveys for 2010 and 2019, with a total sample of 90,432 individuals. Results are broadly similar, with kerosene prices having insignificant effects on firewood collection time.

¹⁸The survey records whether households collect firewood from forests or purchase it on the market, in part or in full. We construct a dummy variable for whether the household purchases any firewood, for these regressions.

Table 3: Average Marginal Effects of kerosene prices on individuals' labour supply,
Panel Sample 2010-20, Traditional Random Effects Tobit model

	Women		Men		Boys	Girls
	Formal	Informal	Formal	Informal	Informal	Informal
log(Kerosene price)	0.086 (0.379)	0.614*** (0.157)	-0.169 (0.236)	0.570*** (0.154)	0.454 (0.332)	0.857** (0.384)
log(Household Exp.)	0.897* (0.521)	-1.492*** (0.150)	0.122 (0.229)	-1.138*** (0.153)	-1.175*** (0.309)	-1.673*** (0.307)
log(Firewood price)	-0.078 (0.323)	1.199*** (0.107)	-0.483*** (0.174)	1.158*** (0.109)	1.733*** (0.254)	1.909*** (0.263)
Age	0.095*** (0.025)	-0.077*** (0.009)	0.113*** (0.014)	-0.072*** (0.008)	1.184*** (0.087)	1.155*** (0.100)
Primary	2.686** (1.233)	-1.663*** (0.406)	2.107*** (0.691)	-1.152*** (0.291)		
Lower Secondary	6.516*** (1.054)	-3.967*** (0.799)	4.644*** (0.575)	-1.980*** (0.412)		
Upper Secondary	11.906*** (1.088)	-4.016*** (0.818)	7.688*** (0.646)	-4.222*** (0.394)		
College & Above	14.349*** (1.654)	-6.840 (6.048)	9.396*** (1.115)	-5.214*** (1.002)		
Observations	3,994	3,994	3,735	3,735	2,239	2,268
Chi-sq.	1016.492	667.894	838.502	628.338	1123.531	574.444

Bootstrap standard errors in parentheses. Constant term suppressed. All regressions include seasonal and regional by rural/urban controls. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

firewood, at average values of all covariates (Table 5).¹⁹ Ownership of a paraffin lamp is also associated with an increased likelihood of firewood use, suggesting a complementarity between kerosene use for lighting and firewood use for cooking. Household wealth is negatively associated with the likelihood of firewood use, which suggests firewood is an inferior good for the sample of households considered.

The interaction effects of kerosene prices and parity in decision-making, and of household wealth and parity in decision-making, are negative and statistically significant at the 95% confidence level. These interaction effects can be interpreted in two alternative yet meaning-

¹⁹The average marginal effects are not displayed.

Table 4: Average Marginal Effects of Kerosene prices on individuals' hours spent on firewood collection, Panel Sample 2010-20, Traditional Random-Effects Tobit model

log(Annual Hours Firewood Collection)	Women (1)	Men (2)	Boys (3)	Girls (4)
log(Kerosene price)	-0.104 (0.180)	0.354 (0.654)	-0.661 (0.515)	-0.719** (0.317)
log(Household Exp.)	-0.474*** (0.184)	-0.907 (0.670)	-0.012 (0.483)	-0.899** (0.356)
log(Firewood price)	-0.416** (0.165)	-0.217 (0.446)	-1.058* (0.557)	0.276 (0.332)
Age	-0.040*** (0.011)	-0.007 (0.033)	0.468*** (0.142)	0.795*** (0.098)
Primary	-1.396** (0.565)	2.617* (1.388)		
Lower Secondary	-2.032*** (0.666)	-2.322 (1.801)		
Upper Secondary	-5.835*** (1.214)	-1.850 (2.832)		
College & Above	-4.779 (7.956)	0.288 (3.298)		
Observations	3,994	3,735	2,239	2,268
Chi-sq.	780.551	63.535	36.837	132.491

Bootstrap standard errors in parentheses. Constant term suppressed.

All regressions include seasonal and regional by rural/urban controls.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

ful ways. First, greater parity in decision-making between the couple in an environment of rising kerosene prices, reduces the likelihood of the household's use of firewood as a cooking fuel. Conversely, households with more parity in decision-making between men and women are less likely to resort to firewood for cooking, in response to higher kerosene prices. This holds true even when household wealth is omitted from the regression (column 3). This is important because decision-making parity might be a response variable to changes in household wealth, with the latter potentially being a mechanism for the effects of decision-making parity on the likelihood of firewood consumption.

Table 5: Effects of decision-making parity on firewood use, DHS 2010, Probit model

Firewood Use	(1)	(2)	(3)	(4)	(5)
log(Kerosene Price)	0.204* (0.111)	0.198* (0.104)	0.318*** (0.113)	0.330*** (0.118)	0.309*** (0.086)
Decision-making Parity	-0.034* (0.018)	0.025* (0.015)	0.144*** (0.022)	0.227*** (0.024)	0.239*** (0.009)
Owns Paraffin Lamp	0.084*** (0.030)	0.345*** (0.091)	0.078** (0.032)	0.343*** (0.098)	0.336*** (0.109)
Urban Household	-1.443*** (0.071)	-1.102*** (0.115)	-1.496*** (0.107)	-1.101*** (0.120)	-1.100*** (0.127)
IHS(Wealth Score)		-0.048*** (0.008)		-0.048*** (0.008)	-0.011 (0.030)
log(Firewood Price)		-0.083 (0.061)	-0.070 (0.048)	-0.080 (0.058)	-0.072 (0.063)
log(Kerosene Price) × Parity			-0.047*** (0.005)	-0.053*** (0.008)	-0.046*** (0.004)
Decision-making Parity × IHS(Wealth Score)					-0.011** (0.006)
log(Kerosene Price) × IHS(Wealth Score)					-0.006 (0.005)
log(Kerosene Price) × IHS(Wealth Score) × Parity					0.001 (0.001)
Observations	1,864	1,864	1,864	1,864	1,864
Pseudo R^2	0.252	0.331	0.259	0.337	0.346

Inclusion of regional controls. Standard errors (clustered by region) in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Similarly, wealthier households would be less likely to consume firewood if there is increased parity in intra-household decision-making. Conversely, households with greater parity between men and women would be less likely to use firewood, in the event of an increase in household wealth. We do not however find a significant effect of the triple interaction, which suggests that simultaneous changes in energy prices, women's bargaining power and

household wealth, do not necessarily further reduce the dependence on firewood use. Interestingly, increases in household wealth, simultaneously to increases in kerosene prices, do not have a significant effect on the likelihood of firewood consumption, whereas parity in decision-making between men and women within the household is an important driver to reduce the probability of firewood use.

An important implication for sustainable development policy is the provision of cash transfers which could raise household wealth and assist households to climb the energy ladder, through wealth and bargaining power effects. On the other hand, these results should be interpreted with an important caveat since we do not consider potential changes in women’s bargaining power due to household wealth, owing to data limitations. While the comparative statics analysis considers changes in women’s bargaining power due to wealth effects, in the empirical analysis, we implicitly assume that household wealth does not contemporaneously affect decision-making power in the household, and abstract from the possibility of decision-making parity being an outcome variable of household wealth. Our results for the effects of bargaining power on firewood use are therefore suggestive, rather than conclusive. This is an important aspect to be studied in future work, and potentially requires experimental data on cash transfers targeted to women, which could simultaneously affect their bargaining power within the household (for e.g. in the case of Mexico, Attanasio and Lechene, 2014).

6 Conclusion

This paper develops a collective household model to analyse the effects of energy prices on firewood consumption and individuals’ labour supply, further investigating the role of women’s bargaining power in determining optimal firewood demand. We model firewood as a home produced good in a non-separable framework with consumption and labour supply. We decompose the firewood demand response to increases in energy prices into substitution effects and income effects, further disentangling the effect of shifts in the intra-household distribution of power. Our theoretical model makes two key predictions for the case of firewood being an inferior good. First, if cooking fuel substitutes to firewood such as kerosene are available, increases in fossil fuel prices would raise the demand for firewood due to positive substitution and income effects. Second, positive wealth effects, along with improvements in women’s decision-making power, could reduce firewood consumption in response to higher energy prices.

We test the model empirically by estimating the effects of kerosene and transport prices on household firewood consumption and individuals’ labour supply, and further analyse the role of women’s bargaining power in energy use decisions. We draw on household-level panel

data from the Malawi Integrated Household Panel Survey for 2010-20, cluster-level data on energy prices, the national-level monthly transport price index for Malawi, and utilise additional data from the Malawi Demographic and Health Survey (DHS) 2010, for measures of women’s status in the household. We estimate OLS regressions with fixed-effects for firewood use, and traditional random-effects Tobit models for individuals’ labour supply, accounting for seasonal and geographical heterogeneity.

The results show an increase in firewood consumption due to energy price increases, with an overall increase in both adults’ and children’s labour supply due to the adverse income effects of price rise. Firewood collection time remains unaffected, while individuals experience increases in informal or daily wage work by up to 0.9%, in response to percent increases in kerosene prices. The lack of a significant effect on firewood collection time is partly explained by an increased likelihood of purchasing firewood in markets relative to self-collection by individuals, given the paucity of time at their disposal. Children’s literacy is also negatively associated with energy prices, with girls at a greater disadvantage than boys. We subsequently examine the role of women’s bargaining power in determining firewood use for cooking at the extensive margin. The results show that while kerosene price increases raise the likelihood of firewood use for cooking, simultaneous improvements in decision-making parity between men and women, lower the overall probability of firewood use. Further, increases in household wealth alongside greater parity in decision-making between men and women, reduce the likelihood of wood-fuel use for cooking. On the contrary, simultaneous increases in kerosene prices and household wealth, albeit with decision-making parity held constant, do not affect the likelihood of firewood use.

Our results thus highlight the relevance of women’s bargaining power in the intra-household decision-making process as a key determinant of biomass consumption, particularly given the highly gendered nature of firewood collection in Malawi and the broader SSA region. The observed increases in individual labour supply highlight the importance of mitigating the adverse income effects of price hikes, for instance, through providing cash transfers to households. The results imply that environmental policy design in developing countries will require key development strategies to raise women’s bargaining power within the household and ameliorate the adverse welfare effects of fossil fuel price increases, to effectively reduce emissions while promoting economic development.

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Appendix

A1. Data Sources and Descriptive Statistics

Data Preparation

Drawing on the Malawi Integrated Household Panel Surveys, 2010-20, we first generate mean prices by district and month from the observed cluster-level prices since market energy prices are not recorded for some enumeration areas, and in some clusters, are recorded after the households have been surveyed. If prices are not available at the district-level, we assign the corresponding households the monthly national average price per fuel. For cluster-household pairs that are unmatched by month, we assign households annual average prices for the corresponding district. We therefore infer missing price data in sequential steps to allow the maximum spatial and temporal variation possible in energy prices. Second, we correct for outliers in the energy price data by winsorising the top and bottom 5% values of the respective distributions. We additionally correct for outliers in the time use data by dropping observations for which the hours of work exceed the 99th percentile values in the corresponding hours distributions for market work and firewood collection. A limitation of the household survey is that the question on firewood collection relies on a recall period of one day rather than one week, which leads to almost 90 per cent of households reporting zero hours spent on fuel collection, despite a vast majority of Malawian households relying on wood-fuel for cooking purposes.

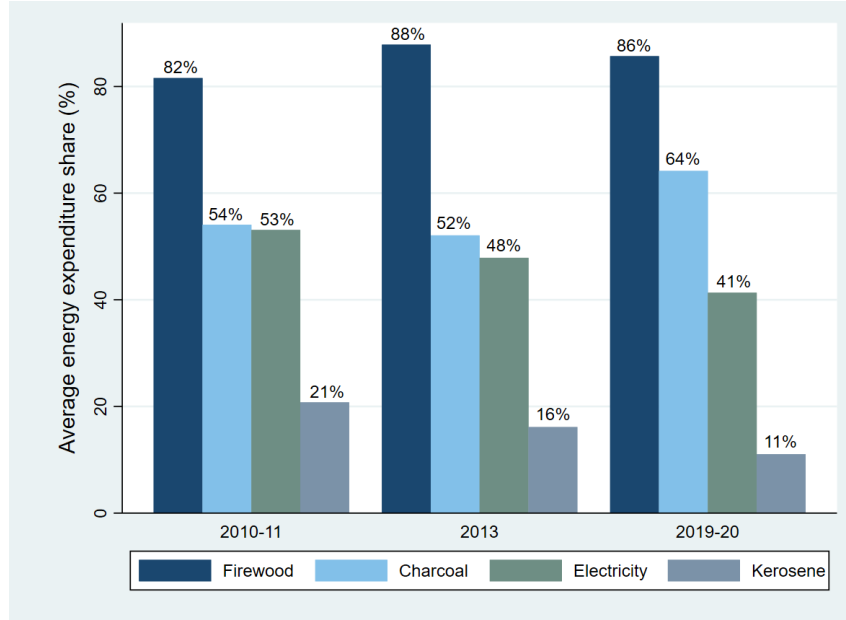
Summary Statistics

This section presents summary statistics on energy use patterns and expenditure shares by fuel and year.

Table A1. Percentage of users by fuel and year,
Panel Sample 2010-20

Energy Source	2010-11	2013	2019-20
Electricity	10.27	11.40	13.58
Kerosene	51.20	13.48	0.33
Charcoal	20.55	23.11	29.79
Firewood	83.15	87.48	80.85

Figure A1. Average Energy Expenditure shares by fuel, Panel Sample 2010-20



Note: Mean expenditure shares for each fuel are displayed for sub-samples of users. Hence, the budget shares do not sum to 100% across fuels in a particular year.

Table A2. Descriptive Statistics of Energy Prices,
Panel Sample 2010-20

Panel A. Kerosene prices					
	Observations	Mean	Std. Dev.	Min	Max
2010-11	107	129.23	83.36	10	250
2013	143	813.72	404.96	20	1,100
2019-20	166	923.47	201.29	50	1,000
Total	416	681.46	426.71	10	1,100

Panel B. Firewood prices					
	Observations	Mean	Std. Dev.	Min	Max
2010-11	107	75.70	65.70	10	200
2013	143	153.46	104.37	20	300
2019-20	166	1,307.28	1,054.90	50	2,750
Total	416	593.88	887.08	10	2,750

Panel C. Transport price index, 2010-20					
	Observations	Mean	Std. Dev.	Min	Max
Urban	21	1,147.14	672.42	412	2,024
Rural	25	812.57	377.22	448	1,363
Total	46	965.31	552.48	412	2,024

Note: All prices are in Malawian Kwacha (MK), while the transport price index is unitless.

While the share of electricity users has risen from 10% to 14% over 2010-20 (Table A1), this has been accompanied by a rise in charcoal use. However, kerosene use has declined sharply from over 50% of sample users in 2010-11 to less than 1% of users in 2019-20. Firewood consumption has remained largely stable, with around 81-87% of households using firewood over the decade. Similar to the patterns for fuel choice, the average expenditure on firewood as a share of households' total energy expenditure has remained stable for the sample of users, at 82-88%, over the sample period (Figure A1). Charcoal consumption has increased slightly, from 54% to 64% over the 2010-20 period within the panel sample, while the shares of kerosene and electricity have declined from 21% to 11%, and from 53% to 41% respectively over the decade. The decline in electricity expenditure is surprising, while the persistence of firewood use highlights the relevance of fuel stacking patterns in households' energy use.

A2. Empirical Results and Robustness Checks

This section presents additional empirical results, as well as robustness checks of the effects of transport prices on labour supply.

Table A3. Average Marginal Effects of energy prices on the likelihood of firewood purchases, Panel Sample 2010-20, Random-Effects Probit model

Firewood purchases	(1)	(2)	(3)	(4)
log(Kerosene price)	0.061 (0.055)	-0.069 (0.052)		
Transport Price Index			0.001*** (0.000)	0.001** (0.000)
log(Household Exp.)		0.439*** (0.078)		0.324*** (0.081)
log(Firewood price)		-0.038 (0.064)		-0.154** (0.074)
Observations	952	952	952	952
Chi-sq.	1.209	72.560	37.197	74.835
Seasonal Controls	No	Yes	No	Yes
Region \times Rural/Urban Controls	No	Yes	No	Yes

Standard errors (clustered by enumeration area) in parentheses.

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A4. Average Marginal Effects of Kerosene prices on children's literacy by gender,
Panel Sample 2010-20, Random-Effects Probit model

	Boys		Girls	
	Lit.(Chichewa)	Lit.(English)	Lit.(Chichewa)	Lit.(English)
log(Kerosene price)	-0.083* (0.044)	-0.085 (0.055)	-0.086* (0.045)	-0.074 (0.050)
log(Household Exp.)	0.313*** (0.052)	0.459*** (0.065)	0.298*** (0.048)	0.326*** (0.061)
log(Firewood price)	0.033 (0.075)	-0.348*** (0.090)	0.167** (0.079)	-0.251*** (0.087)
Age	0.296*** (0.021)	0.295*** (0.026)	0.300*** (0.023)	0.299*** (0.025)
Observations	1,663	1,662	1,696	1,696
Chi-sq.	220.290	158.651	195.402	160.167

Robust standard errors in parentheses. Constant term suppressed. All regressions include seasonal and regional by rural/urban controls. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A5. Average Marginal Effects of energy prices on children's literacy by gender,
Panel Sample 2010-20, Random-Effects Probit Model

	Boys		Girls	
	Lit.(Chichewa)	Lit.(English)	Lit.(Chichewa)	Lit.(English)
Transport Price Index	-0.001*** (0.000)	-0.000 (0.000)	-0.001* (0.000)	-0.001** (0.000)
log(Household Exp.)	0.342*** (0.053)	0.447*** (0.064)	0.296*** (0.048)	0.347*** (0.063)
log(Firewood price)	0.106 (0.082)	-0.369*** (0.093)	0.176** (0.083)	-0.201** (0.094)
Age	0.304*** (0.022)	0.294*** (0.025)	0.302*** (0.023)	0.303*** (0.026)
Observations	1,663	1,662	1,696	1,696
Chi-sq.	209.457	160.354	193.888	154.416

Robust standard errors in parentheses. Constant term suppressed. All regressions include seasonal and regional by rural/urban controls. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A6. Average Marginal Effects of energy prices on individuals' labour supply,
Panel Sample 2010-20, Traditional Random Effects Tobit model

	Women		Men		Boys	Girls
	Formal	Informal	Formal	Informal	Informal	Informal
Transport Price Index	0.001 (0.002)	0.003*** (0.001)	0.001 (0.001)	0.002*** (0.001)	0.005*** (0.001)	0.004*** (0.002)
log(Household Exp.)	0.839* (0.451)	-1.457*** (0.144)	0.018 (0.261)	-1.101*** (0.162)	-1.292*** (0.209)	-1.658*** (0.280)
log(Firewood price)	-0.472 (0.588)	0.712*** (0.173)	-0.711** (0.356)	0.713*** (0.190)	0.716* (0.419)	1.142*** (0.389)
Age	0.093*** (0.028)	-0.078*** (0.011)	0.112*** (0.015)	-0.072*** (0.010)	1.124*** (0.099)	1.136*** (0.092)
Primary	2.715*** (0.995)	-1.670*** (0.401)	2.126*** (0.774)	-1.184*** (0.416)		
Lower Secondary	6.520*** (1.182)	-4.083*** (0.715)	4.679*** (0.642)	-2.001*** (0.415)		
Upper Secondary	11.940*** (1.168)	-4.197*** (0.881)	7.745*** (0.522)	-4.267*** (0.465)		
College & Above	14.362*** (1.457)	-7.157 (6.302)	9.474*** (0.936)	-5.344*** (0.807)		
Observations	3,994	3,994	3,735	3,735	2,239	2,268
Chi-sq.	820.376	750.781	977.986	848.591	706.503	737.109

Bootstrap standard errors in parentheses. Constant term suppressed. All regressions include seasonal and region by rural/urban controls. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table A7. Average Marginal Effects of energy prices on individuals' hours spent on firewood collection, Panel Sample 2010-20, Traditional Random Effects Tobit model

log(Annual Hours Firewood Collection)	Women		Men		Children	
	(1)	(2)	(3)	(4)	(5)	(6)
Transport Price Index	-0.002*** (0.000)	0.000 (0.001)	-0.000 (0.001)	0.006** (0.003)	-0.003*** (0.001)	-0.003** (0.001)
Age	-0.039*** (0.013)	-0.040*** (0.014)	-0.009 (0.038)	-0.008 (0.033)	0.705*** (0.082)	0.700*** (0.067)
Primary	-1.625*** (0.393)	-1.388** (0.599)	2.272* (1.339)	2.538* (1.446)		
Lower Secondary	-2.291*** (0.539)	-2.006*** (0.592)	-2.733 (1.719)	-2.336 (1.805)		
Upper Secondary	-5.936*** (1.244)	-5.815*** (1.268)	-2.534 (2.038)	-1.732 (1.984)		
College & Above	-5.501 (4.434)	-4.771 (8.895)	-1.051 (9.354)	0.330 (10.879)		
log(Household Exp.)		-0.527** (0.208)		-1.140* (0.593)		-0.709** (0.294)
log(Firewood price)		-0.536** (0.255)		-1.652** (0.698)		0.378 (0.382)
Observations	4,002	3,994	3,739	3,735	4,515	4,507
Chi-sq.	382.585	849.199	60.438	125.176	160.855	164.008

Bootstrap standard errors in parentheses. All regressions include seasonal and regional by rural/urban controls. Constant term suppressed. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

A3. Model Extensions

This section presents an analytical application and three model extensions to analyse important aspects of energy consumption, gender, and health, that are of relevance to the environment and development community. The model application assumes individuals' preferences take the quasilinear form, with a convex production technology allowing for potentially decreasing returns to scale in firewood collection. The model is outlined in section A3.1.

In the first model extension (outlined in section A3.2), we incorporate children's labour in the firewood production process and derive the modified Samuelson rule. In the second extension (section A3.3), we examine the negative health effects of firewood use due to the smoke and pollution emitted from biomass burning, into households' optimal firewood demand, in the framework of a unitary model, abstracting from bargaining power effects. In the final model extension (section A3.4), we investigate how improvements in the fuel efficiency of firewood use, for instance, through the complementary use of improved cook-stoves (ICS), could impact households' demand for firewood vis-à-vis marketed energy sources, in a unitary model framework.

A3.1. Model Application: Quasilinear utility and convex production technology

We now present a model application, assuming the quasilinear functional form for individuals' utilities and a convex production set for firewood collection. We then derive comparative statics for the effects of energy prices and female bargaining power on the household's optimal demand for firewood.

Firewood collection and cost minimisation

We first derive the conditional labour demand for firewood collection for a generic convex production technology, subsequently allowing for decreasing returns to scale in production. Consider the following two input production function, with parameters $\beta, \gamma > 0$.

$$F = L_{wf}^{\beta} L_{wm}^{\gamma} \quad (31)$$

where L_{wf} and L_{wm} denote women and men's respective labour inputs for firewood collection. The household's cost minimisation problem yields the following first-order condition:

$$\frac{\beta}{\gamma} \frac{L_{wm}}{L_{wf}} = \frac{w_f}{w_m} \quad (32)$$

The conditional labour demand functions are obtained as follows:

$$L_{wf}^c = F^{\frac{1}{\beta+\gamma}} A_f \quad (33)$$

where $A_f = \left(\frac{\beta}{\gamma} \frac{w_m}{w_f}\right)^{\frac{\gamma}{\beta+\gamma}}$, $A_f > 0$.

$$L_{wm}^c = F^{\frac{1}{\beta+\gamma}} A_m \quad (34)$$

where $A_m = \left(\frac{\beta}{\gamma} \frac{w_m}{w_f}\right)^{\frac{-\beta}{\beta+\gamma}}$, $A_m > 0$.

Utility Maximisation

We assume the utility function is quasilinear, strictly concave and twice-differentiable. Individuals' utility is linear in purchased energy sources M and follows a Cobb-Douglas form for firewood F and private leisure l_i , for person i . The quasilinear functional form implies that firewood and leisure will not exhibit wealth effects, with all additional income spent on the market energy good, M . This may be reasonable if firewood is considered a subsistence good for basic energy needs, with households relying on market energy sources for additional energy requirements. The household's second-stage problem is modelled as follows:

$$\max_{l_i, L_{wi}} \quad U_i = M + F^{\alpha_i} l_i^{1-\alpha_i} \quad \alpha_i \in (0, 1) \quad (35)$$

s.t.

$$w_i l_i \leq w_i (T - L_{wi}) + \rho_i \quad (36)$$

$$0 \leq l_i \leq T - L_i - L_{wi} \quad (37)$$

where L_i is the individual's market labour supply. The individual's objective is to optimise their time allocation between market work and leisure, conditional on firewood production, F . The optimal time spent on firewood collection by each individual is obtained from the first-order condition of the production function, and equals the conditional labour demand functions (eqns. 30-31). The budget constraint modifies as follows:

$$w_i l_i \leq w_i (T - F^{\frac{1}{\beta+\gamma}} A_i) + \rho_i \quad (38)$$

The FOCs for the second-stage problem are as follows:

$$\frac{\partial L}{\partial l_i} = (1 - \alpha_i) F^{\alpha_i} l_i^{-\alpha_i} + \lambda w_i = 0 \quad (39)$$

$$\frac{\partial L}{\partial F} = \alpha_i F^{\alpha_i-1} l_i^{1-\alpha_i} + \lambda \frac{w_i A_i}{\beta + \gamma} F^{\frac{1}{\beta+\gamma}-1} = 0 \quad (40)$$

The conditional leisure demand function for person i is thus:

$$l_i^* = F^{\frac{1}{\beta+\gamma}} B_i \quad (41)$$

where $B_i = \frac{1-\alpha_i}{\alpha_i} \frac{A_i}{\beta+\gamma}$, $B_i > 0$. We assume $F > 0$ and hence $l_i > 0 \quad \forall i$. Thus, we will only explore interior solutions for $\{F, l_i\}$. The first-stage problem is as follows:

$$\max_{M, F, \rho_m, \rho_f} \quad \phi U_f(M, F, l_f^*) + (1 - \phi) U_m(M, F, l_m^*) \quad (42)$$

s.t.

$$\rho_m + \rho_f = y - P_m M - w_f L_{wf} - w_m L_{wm} \quad (43)$$

We substitute for the conditional leisure demand functions, and the conditional labour demand functions, with the first-stage problem modifying as follows:

$$\max_{M, F, \rho_m, \rho_f} \quad V = M + \phi F^{\alpha_f} (F^{\frac{1}{\beta+\gamma}} B_f)^{1-\alpha_f} + (1 - \phi) F^{\alpha_m} (F^{\frac{1}{\beta+\gamma}} B_m)^{1-\alpha_m} \quad (44)$$

s.t.

$$\rho_m + \rho_f = y - P_m M - w_f F^{\frac{1}{\beta+\gamma}} A_f - w_m F^{\frac{1}{\beta+\gamma}} A_m \quad (45)$$

We now relax the assumption of constant returns to scale in production, and specifically model the case of decreasing returns to scale, i.e. $\beta + \gamma < 1$. By relaxing the assumption of constant returns to scale, we allow for firewood to be a common pool resource in the natural environment and potentially be depleted due to unsustainable collections from forests. Decreasing returns to scale in production thus allow for increasing rather than constant marginal costs. This may better reflect ground realities where individuals often walk increasingly longer distances to gather wood and spend longer hours segregating high quality biomass from lower grade wood, twigs and leaves (Jagger and Shively, 2014).

The FOCs for the first-stage problem with respect to energy consumption are as follows:

$$\frac{\partial L}{\partial M} = 1 + \lambda P_m = 0 \quad (46)$$

$$\Rightarrow \lambda = \frac{-1}{P_m}.$$

$$\begin{aligned} \frac{\partial L}{\partial F} &= \phi B_f^{1-\alpha_f} \left(\alpha_f + \frac{1-\alpha_f}{\beta+\gamma} \right) F^{(1-\alpha_f)(\frac{1}{\beta+\gamma}-1)} + (1-\phi) B_m^{1-\alpha_m} \left(\alpha_m + \frac{1-\alpha_m}{\beta+\gamma} \right) F^{(1-\alpha_m)(\frac{1}{\beta+\gamma}-1)} \\ &+ \lambda F^{\frac{1}{\beta+\gamma}-1} \left(\frac{w_f A_f + w_m A_m}{\beta+\gamma} \right) = 0 \end{aligned}$$

Substituting for the value of λ , the Walrasian demand equation for firewood, in implicit form, simplifies to:

$$\phi C_1 F^{\alpha_f(1-\frac{1}{\beta+\gamma})} + (1-\phi) C_2 F^{\alpha_m(1-\frac{1}{\beta+\gamma})} = \frac{C_3}{P_m} \quad (47)$$

where $C_1 = B_f^{1-\alpha_f} \left(\alpha_f + \frac{1-\alpha_f}{\beta+\gamma} \right)$, $C_2 = B_m^{1-\alpha_m} \left(\alpha_m + \frac{1-\alpha_m}{\beta+\gamma} \right)$ and $C_3 = \left(\frac{w_f A_f + w_m A_m}{\beta+\gamma} \right)$, and $C_1, C_2, C_3 > 0$. The demand for firewood in implicit form thus depends on a number of exogenous parameters including individuals' preferences, the Cobb-Douglas share parameters in firewood production, adult wage rates and the price of market energy sources. However, it does not depend on endogenous private resources. It is further independent of the household's nonlabour income, y , due to the assumption of quasilinear preferences, wherein all additional income is allocated to consumption of market energy sources, M .

Comparative Statics

We now derive comparative statics to analyse the change in firewood demand due to an increase in the price of marketed energy items, P_M , and increases in female bargaining power, ϕ . In this model, we cannot however investigate the effects of a rise in non-labour income on firewood demand. This aspect can be examined in more complex utility functions in future work.

$$\frac{\partial F}{\partial P_m} = \frac{C_3}{P_m^2 \left[\alpha_f \left(\frac{1}{\beta+\gamma} - 1 \right) \phi C_1 F^{\alpha_f(1-\frac{1}{\beta+\gamma})-1} + \alpha_m \left(\frac{1}{\beta+\gamma} - 1 \right) (1-\phi) C_2 F^{\alpha_m(1-\frac{1}{\beta+\gamma})-1} \right]} \quad (48)$$

As there are no income effects in this model, the net effect of increases in market energy prices on firewood demand is fully captured by the substitution effect, which is positive between the two fuels, i.e. $\frac{\partial F}{\partial P_m} > 0$, since the denominator is positive (due to decreasing returns), and the C_i terms are also positive.

The effect of an increase in female bargaining power on firewood demand, $\frac{\partial F}{\partial \phi}$, is however more complex.

$$\frac{\partial F}{\partial \phi} = \frac{C_2 F^{\alpha_m(1-\frac{1}{\beta+\gamma})} - C_1 F^{\alpha_f(1-\frac{1}{\beta+\gamma})}}{\phi C_1 \alpha_f (1 - \frac{1}{\beta+\gamma}) F^{\alpha_f(1-\frac{1}{\beta+\gamma})-1} + (1-\phi) C_2 \alpha_m (1 - \frac{1}{\beta+\gamma}) F^{\alpha_m(1-\frac{1}{\beta+\gamma})-1}} \quad (49)$$

Due to decreasing returns to scale in firewood production, the denominator is negative. The overall change in firewood demand due to an increase in female bargaining power will be negative if and only if $\frac{C_2}{F^{\alpha_m(\frac{1}{\beta+\gamma}-1)}} > \frac{C_1}{F^{\alpha_f(\frac{1}{\beta+\gamma}-1)}}$. The model therefore does not lead to unambiguous predictions about the direction of change in firewood consumption due to increases in women's bargaining power within the household. This effect depends in a complex manner on both adults' preferences for firewood consumption vis-à-vis leisure, their market wage rates, their productivity of firewood collection and the overall returns to scale of the production technology.

A3.2. The role of children's labour

We first extend the framework to model children's labour input in firewood collection.

Firewood production

The firewood production function now has three inputs, and potential substitution effects between adult and child labour will depend critically on the elasticity of substitution between pairs of inputs. Consider the Constant Elasticity of Substitution (CES) functional form for firewood production:

$$F = (L_{WM}^\delta + L_{WF}^\delta + L_{WC}^\delta)^{\frac{1}{\delta}} \quad (50)$$

with $\delta > 0$ as the substitution parameter. The cost function modifies as follows:

$$C = w_M L_{WM} + w_F L_{WF} + w_C L_{WC} \quad (51)$$

with w_C representing the market wage rate for children's labour. Minimising the cost function over all labour inputs yields the contingent demand for children's labour as a function of the wage rates and technology parameter:

$$L_{WC}^C = \frac{F}{\left[1 + \left(\frac{w_M}{w_C}\right)^{1-\sigma} + \left(\frac{w_F}{w_C}\right)^{1-\sigma}\right]^{\frac{\sigma}{\sigma-1}}} \quad (52)$$

with the elasticity of substitution, $\sigma = \frac{1}{1-\delta}$. For $\sigma < 1$, $\frac{\partial L_{WC}^C}{\partial F} > 0$, and an exogenous increase in the household's demand for firewood will raise children's time spent on firewood collection at the optimum, if children already participate in collection activities.²⁰ Whether a higher value for σ , which reflects greater substitution possibilities between adults' and children's labour for firewood collection, would raise children's time inputs, will depend on the relative wage rates, and the elasticity of substitution.

Utility maximisation

We modify individuals' utility functions to reflect their preferences for children's time spent on firewood collection, modelling children's labour as public goods between the adult decision makers, rather than allowing children to be independent decision-makers in the model. The household now maximises the following weighted sum of utilities:

$$U_H = \phi U_F(M, F, l_F, L_{WC}) + (1 - \phi) U_M(M, F, l_M, L_{WC}) \quad (53)$$

s.t.

$$P_M M + w_F l_F + w_M l_M = y + (w_F + w_M)T - w_M L_{WM} - w_F L_{WF} - w_C L_{WC} \quad (54)$$

$$0 \leq l_i \leq T - L_i - L_{Wi} \quad \text{for } i = \{F, M\} \quad (55)$$

$$M \geq 0; F \geq 0 \quad (56)$$

The second stage of the two-stage problem remains unchanged, and yields the first-order condition in equation (12). However, the first-stage problem modifies, with the household maximising the weighted sum of individuals' indirect utilities:

$$\max_{\{M, F, \rho_F, \rho_M\}} \phi V_F(M, F, w_F, \rho_F, L_{WC}^C) + (1 - \phi) V_M(M, F, w_M, \rho_M, L_{WC}^C) \quad (57)$$

s.t.

$$\rho_F + \rho_M = y - P_M M - w_M L_{WM} - w_F L_{WF} - w_C L_{WC} \quad (58)$$

If the household members suffer weak dis-utility from children's undertaking firewood collection, i.e. $\frac{\partial U_j}{\partial L_{WC}} \leq 0 \quad \forall j$, with at least one decision-maker exhibiting strict dis-utility, i.e. $\frac{\partial U_i}{\partial L_{WC}} < 0$, the optimal demand for firewood will account for members' preferences over

²⁰However, in the case of adult and child labour being perfect substitutes in firewood collection, the optimal demand for child labour could occur at a boundary point, resulting in children's switching in and out of firewood collection, due to increases in firewood output or exogenous changes in parameter values.

children's labour activities.

While the FOCs for market energy sources and the resource shares remain unchanged, the FOC for firewood modifies as follows:

$$\begin{aligned} & \phi \left(\frac{\partial V_F}{\partial F} + \frac{\partial V_F}{\partial L_{WC}} \frac{\partial L_{WC}^C}{\partial F} \right) + (1 - \phi) \left(\frac{\partial V_M}{\partial F} + \frac{\partial V_M}{\partial L_{WC}} \frac{\partial L_{WC}^C}{\partial F} \right) \\ &= \mu \left(w_M \frac{\partial L_{WM}^C}{\partial F} + w_F \frac{\partial L_{WF}^C}{\partial F} + w_C \frac{\partial L_{WC}^C}{\partial F} \right) \end{aligned} \quad (59)$$

At the optimum, the household equates the weighted sum of individuals' marginal utilities from firewood collection to the marginal cost of firewood production, augmented by the Lagrange multiplier, i.e. the marginal utility of household resources available for private goods. Members now take into account their preferences for children's engagement in firewood collection $\frac{\partial V_i}{\partial L_{WC}}$, augmented by the marginal increase in children's optimal hours supplied in response to an increase in firewood output $\frac{\partial L_{WC}^C}{\partial F}$. While the derivative of the conditional labour demand for children with respect to firewood production is determined by the production process, the potential negative effect of children's collection time on adults' utility, could lower their net utility from firewood consumption. A combination of preferences and bargaining power between members would thus determine optimal firewood consumption, accounting for children's labour. Further, the Samuelson rule would modify as follows:

$$\frac{\frac{\partial V_F}{\partial F} + \frac{\partial V_F}{\partial L_{WC}} \frac{\partial L_{WC}^C}{\partial F}}{\frac{\partial V_F}{\partial \rho_F}} + \frac{\frac{\partial V_M}{\partial F} + \frac{\partial V_M}{\partial L_{WC}} \frac{\partial L_{WC}^C}{\partial F}}{\frac{\partial V_M}{\partial \rho_M}} = \tilde{P}_w \quad (60)$$

Each term on the LHS reflects the member's marginal rate of substitution between firewood and private resources, and therefore their marginal willingness to pay (MWP) for firewood consumption. The MWP takes into account individuals' possible dis-utility from children's labour input into firewood collection, which might overall lower their MWP for firewood provision within the household. However, whether the marginal utility from additional private resources stays constant or rises, and the overall effects of children's labour on the marginal cost of firewood production and its price, would depend on the elasticity of substitution between inputs, relative wages, and the optimal consumption bundles at which the indirect utility functions are evaluated.

Children's labour in firewood collection is nevertheless an important channel for the household's demand for firewood. Given the production technology and optimality conditions

for individuals' labour inputs in firewood collection, a lower household demand for children's time spent in collection activities, could translate into reduced firewood consumption for the household. Alternatively, the production technology might change, with children no longer participating in firewood collection.

A3.3. Unitary household model with health effects of firewood use

We now consider the case of a unitary household model, thus abstracting from the influence of intra-household bargaining power, and incorporate the negative health effects of firewood use, due to smoke produced upon burning of biomass. We retain the initial specification for firewood production, but consider only the case of constant returns to scale to simplify calculations, i.e. $\beta + \gamma = 1$.

Consider the following modified household utility function, $U_h = U(M, F - s(F), l_m, l_f)$, where $s(F)$ is a function of the amount of pollution or smoke produced from the burning of firewood. For simplicity, we assume the smoke function is linear in the amount of firewood burnt, $s(F) = aF$, where a is the marginal pollution generated. We further assume household utility is of the Cobb-Douglas form, with the following maximisation problem:

$$U = M^{\rho_1} F^{\rho_2} h^{\rho_3} l_m^{\rho_4} l_f^{\rho_5} \quad (61)$$

where $\rho_5 = 1 - \rho_1 - \rho_2 - \rho_3 - \rho_4$, and the budget constraint is as follows:

$$P_m M + w_m l_m + w_f l_f = y + (w_m + w_f)T - w_m L_{wm} - w_f L_{wf} + h \quad (62)$$

where $h = \bar{h} - aF^\alpha$ is the household's level of health and a numeraire good in the model. Health is declining in firewood consumption, with \bar{h} being the initial endowment of health. The budget constraint modifies as follows:

$$P_m M + w_m l_m + w_f l_f + aF^\alpha = y + (w_m + w_f)T - w_m L_{wm} - w_f L_{wf} + \bar{h} \quad (63)$$

Constrained maximisation yields the following optimality conditions:

$$\frac{\rho_1 F}{M(\rho_2 - \rho_3 a \alpha \frac{F^\alpha}{h})} = \frac{P_m}{w_m A_m + w_f A_f + a \alpha F^{\alpha-1}} \quad (64)$$

This is the marginal rate of substitution of M for F , which accounts for the health damages of firewood use. The marginal rate of substitution between firewood and market energy sources accounts for health damages due to smoke emitted from wood burning. The household equates the ratio of net marginal utilities from firewood vs. market energy consumption,

to the relative price of market energy sources (P_m) to firewood.

$$\frac{\rho_5}{\rho_1} \frac{M}{l_f} = \frac{w_f}{P_m} \quad (65)$$

$$\frac{\rho_4}{\rho_1} \frac{M}{l_m} = \frac{w_m}{P_m} \quad (66)$$

The fourth optimality condition is the budget constraint, which is obtained from differentiation of the value function with respect to the Lagrange multiplier.

We now assume a simple functional form for health such that health declines linearly in firewood consumption, i.e. $\alpha = 1$. We then obtain the firewood demand function in implicit form, as follows:

$$F^2 a D_2 \rho_3 - F h (D_2 - D_2 \rho_3) - a D_1 \rho_3 F + D_1 \rho_2 h = 0 \quad (67)$$

where $D_1 = y + (w_m + w_f)T + \bar{h}$ and $D_2 = a + w_m A_m + w_f A_f$. We next compute the change in firewood demand due to an exogenous increase in the amount of smoke produced per unit of wood burnt, translating into an increase in the marginal health damage for individuals, $\frac{\partial F}{\partial a}$. This comparative static can be used to analyse the effects of the quality of biomass (in terms of smoke emitted) on households' optimal consumption decisions.

$$\frac{\partial F}{\partial a} = \frac{-[F^2 \rho_3 (a + D_2) - F D_1 (\rho_2 + \rho_3) - F h (1 - \rho_3) + F (1 - \rho_3)]}{2a D_2 \rho_3 F - h D_2 (1 - \rho_3) - a D_1 (\rho_2 + \rho_3) + a (1 - \rho_3)} \quad (68)$$

The overall change in firewood demand due to an exogenous increase in the pollution content of biomass and the related health damages a , depends in a rather complex way on the household's preferences for firewood consumption vis-à-vis health, individuals' wage rates and the marginal cost of firewood production. The scope of the problem is magnified due to interactions with labour supply decisions, through the self-collection of wood, as opposed to market purchases of woodfuels. Hence, there are no unambiguous predictions about households' reactions to firewood consumption when incorporating the negative health effects of wood burning, in a context of firewood collections.

A3.4. Unitary household model with efficient use of biomass

We continue with the case of a unitary household model, but abstract from health effects, while incorporating the effects of potentially exogenous increases in the efficiency of woodfuels. These improvements in fuel efficiency are equivalent to a household's complementary

use of efficient cook-stoves, while relying on the original source of biomass. Improved cook-stoves (ICS) thus offer a pathway to reduce the amount of biomass required to cook a certain amount of food and could ease forest pressures from biomass collection (Jeuland et al., 2020).

Household utility is now of the Constant Elasticity of Substitution (CES) form, with the following maximisation problem, where a represents an exogenous fuel-efficiency parameter:

$$\max_{M,F,l_m,l_f} U = (M^\rho + (1+a)^\rho F^\rho + l_m^\rho + l_f^\rho)^{\frac{1}{\rho}} \quad (69)$$

subject to:

$$P_m M + w_m l_m + w_f l_f = y + (w_m + w_f)T - w_m L_{wm} - w_f L_{wf} \quad (70)$$

The optimality conditions are as follows:

$$\frac{1}{(1+a)^\rho} \left(\frac{M}{F} \right)^{\rho-1} = \frac{P_m}{w_m \frac{\partial L_{wm}^c}{\partial F} + w_f \frac{\partial L_{wf}^c}{\partial F}} \quad (71)$$

$$\left(\frac{l_m}{l_f} \right)^{\rho-1} = \frac{w_m}{w_f} \quad (72)$$

$$\left(\frac{l_f}{M} \right)^{\rho-1} = \frac{w_f}{P_m} \quad (73)$$

where $\frac{\partial L_{wi}^c}{\partial F}$ is the partial derivative of the conditional labour demand function for individual i (eqns. 30-31) with respect to firewood. Substituting for the partial derivatives, the above first-order condition modifies to:

$$\frac{1}{(1+a)^\rho} \left(\frac{M}{F} \right)^{\rho-1} = \frac{P_m}{w_m A_m + w_f A_f} \quad (74)$$

The last FOC corresponds to the budget constraint:

$$M[P_m + P_m^{\frac{1}{1-\rho}}(w_m^{\frac{\rho}{\rho-1}} + w_f^{\frac{\rho}{\rho-1}})] = y + (w_m + w_f)T - F(w_m A_m + w_f A_f) \quad (75)$$

Solving eqns. (71)-(74) yields the household's optimal demand for firewood:

$$F^* = \frac{y + (w_m + w_f)T}{(w_m A_m + w_f A_f)[1 + (1+a)^{\frac{\rho}{\rho-1}}(w_m A_m + w_f A_f)^{\frac{\rho}{1-\rho}}(P_m^{\frac{\rho}{\rho-1}} + w_m^{\frac{\rho}{\rho-1}} + w_f^{\frac{\rho}{\rho-1}})]} \quad (76)$$

To examine comparative statics, we compute the following partial derivatives: $\frac{\partial F^*}{\partial P_m}$, $\frac{\partial F^*}{\partial a}$

and $\frac{\partial M^*}{\partial a}$. We observe that $\frac{\partial F^*}{\partial y} > 0$ since firewood is modelled as a normal good in the CES utility function. The partial derivatives are:

$$\frac{\partial F^*}{\partial a} = -\frac{\frac{\rho}{\rho-1}(1+a)^{\frac{1}{\rho-1}} E_1 E_3 E_2^{\frac{1}{1-\rho}}}{[E_2\{1 + (1+a)^{\frac{\rho}{\rho-1}} E_2^{\frac{\rho}{1-\rho}} E_3\}]^2} \quad (77)$$

where $E_1 = y + (w_m + w_f)T$, $E_2 = w_m A_m + w_f A_f$ and $E_3 = P_m^{\frac{\rho}{\rho-1}} + w_m^{\frac{\rho}{\rho-1}} + w_f^{\frac{\rho}{\rho-1}}$.

$$\frac{\partial M^*}{\partial a} = -\frac{\partial F^*}{\partial a} \frac{(w_m A_m + w_f A_f)}{[P_m + P_m^{\frac{1}{1-\rho}} (w_m^{\frac{\rho}{\rho-1}} + w_f^{\frac{\rho}{\rho-1}})]} \quad (78)$$

$$\frac{\partial F^*}{\partial P_m} = -\frac{\frac{\rho}{\rho-1}(1+a)^{\frac{\rho}{\rho-1}} E_1 E_2^{\frac{1}{1-\rho}} P_m^{\frac{1}{\rho-1}}}{[E_2\{1 + (1+a)^{\frac{\rho}{\rho-1}} E_2^{\frac{\rho}{1-\rho}} E_3\}]^2} \quad (79)$$

The effect of an exogenous increase in the efficiency of firewood a , on its optimal demand is evidently negative. The demand response for marketed fuels, M , due to increases in the fuel efficiency of firewood a , is clearly positive. This reflects substitution among fuels within the household, given income, prices, wage rates and household preferences. Moreover, the net effect of higher market energy prices P_m , on firewood demand is negative. This may appear contradictory to intuition, albeit only holds true in the case of firewood being a normal good, rather than an inferior good. Since firewood is modelled as a normal good in the CES utility function, we find the change in Walrasian demand to be negative, with the negative income effect outweighing the positive substitution effect.

However, in many applied contexts, firewood would be considered an inferior good rather than a normal good, in which case its demand would strictly increase in response to increases in fossil fuel prices. Whether firewood is a normal or an inferior good depends on the study context, and will likely vary across different SSA countries. Country-specific analysis would shed light on the potential effects of fossil fuel subsidy reform and emissions pricing on households' overall demand for biomass consumption.

References

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