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Does fuel price subsidy work? Household energy transition under imperfect labor market in rural China

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ABSTRACT

Dependence on traditional biomass energy, such as crop residues and firewood, has a number of negative impacts on sustainable rural livelihoods in many developing countries. Subsidizing modern fuels has been adopted by many governments and development agencies to increase the adoption of modern clean fuels, however, its effectiveness on rural energy transition away from traditional biomass energy is rarely investigated. This paper seeks to understand the effectiveness of fuel price subsidies based on a non-separable agricultural household model. We developed a theoretical framework explaining household behavioral responses to price incentives in the presence of labor market imperfections and tested this framework with rural household data in China. We found that the policy interventions focusing on fuel pricing are largely ineffective in promoting household energy transition partly due to imperfect rural labor markets. This finding has important policy implications for accelerating energy transitions. Based on our findings, we recommend that more attention needs to be paid to non-price mechanisms, such as providing technical support (e.g. increasing R&D investment in exploring new energy technologies and providing demonstration projects), constructing accompanying modern energy infrastructures, providing off-farm employment opportunities, and establishing a sound and effective social safety.

1. Introduction

Over a third of world's population still burns solid fuels (mostly biomass, but also coal) in inefficient stoves or open fires for cooking, heating, and other residential purposes (Baumgartner et al., 2019). Dependence on traditional biomass, such as crop residues, firewood, charcoal and dung, for residential energy use is pervasive in low- and middle-income countries, particularly in rural areas (Burke and Dundas, 2015; Adusah-Poku and Takeuchi, 2019). The use of traditional biomass energy affects rural livelihoods in many ways, such as through higher risks of suffering respiratory diseases and other health problems, and the time spent collecting and processing fuels rather than on income generating activities (e.g. agricultural production and off-farm employment) (WHO, 2014; Burke and Dundas, 2015). Moreover, due to the fact that firewood occupies the largest share in traditional biomass energy consumption, excessively using traditional biomass has resulted in significant depletion of forest resources in many developing countries and regions, with serious negative consequences on the environment such as loss of biodiversity, ecosystem degradation and global warming (Guta, 2014). Thus, improving access to and use of cleaner and more efficient household energy has huge potential to deliver substantial health, environmental, and development gains (Baumgartner et al., 2019).

Many governments and development agencies have adopted various measures to reduce the heavy reliance on traditional biomass use as well as to accelerate the process of household energy transition towards modern energy sources. One commonly used measure is building infrastructure and providing access to clean energy technologies and services to encourage households to adopt advanced fuels such as electricity and gas (e.g. liquefied petroleum gas (LPG), natural gas, and biogas). Sub-Saharan African countries, for example Uganda, Ethiopia, Tanzania, and Ghana, have made significant efforts to extend centralized national power grids to rural areas and to construct decentralized renewable energy systems including mini-grids and small standalone

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solar photovoltaic (PV) systems adapted to small-scale farming (Guta, 2014; Abdul-Salam and Phimister, 2019; Choumert-Nkolo et al., 2019; Adusah-Poku and Takeuchi, 2019). Meanwhile, a number of Asian developing countries, such as China, India, Cambodia, Nepal, Indonesia and Vietnam have vigorously promoted rural electrification and household-based biogas programs to facilitate rural residential energy transition (Chen and Liu, 2017; Putra et al., 2017; Hyman and Bailis, 2018; Nguyen et al., 2019; Chhay and Yamazaki, 2021; Maji et al., 2021). Although the use of traditional biomass energy has been declining, it still takes up considerable share in rural energy consumption in most developing countries (Choumert-Nkolo et al., 2019). Even when households have already had access to modern energy sources, they often practice 'fuel stacking' or 'fuel mixing', wherein they continue to use solid biomass after adopting LPG, natural gas, or/and biogas along with electricity (Masera et al., 2000; Chen et al., 2016; Mekonnen et al., 2017; Chen, 2021; Maji et al., 2021). This implies that making a clean break with traditional solid biomass use is unlikely to occur in many developing regions anytime soon (Choumert-Nkolo et al., 2019). Another important measure to reduce traditional solid biomass energy use is introducing bans on open-air burning of crop residues and initiatives towards sustainable waste management practices such as crop residue retention and biofuel production (e.g. straw gasification and power generation). However, they have been found to be ineffective in changing rural households' behaviors in many countries, including China, India and Russia (Theesfield and Jelink, 2017; Bhuvaneshwari et al., 2019; Hou et al., 2019). Many prior studies on examining the effects of the aforementioned measures in influencing household energy use have provided evidence that high costs of modern fuels and lower purchasing power are major barriers for rural poor to adoption of modern fuels (Pandey and Chaubal, 2011; Abdul-Salam and Phimister, 2019; Muller and Yan, 2018; Adusah-Poku and Takeuchi, 2019; Hou et al., 2019). Therefore, considerable efforts are still needed to enable poor households to afford those fuels in the developing world.

Fuel price subsidies[1] are among the most common policy instruments in current use (Coady et al., 2017; Ferraresi et al., 2018; Lin and Kuang, 2020). The original intention of fuel price subsidies in low- and middle-income developing countries is attempt to shift energy consumption patterns away from biomass to modern fuels among low-income households by using price controls and tax exemptions (Gangopadhyay et al., 2005; Soile and Mu, 2015; Peltovuori, 2017). However, a growing body of studies have found that most of the fuel price subsidies failed to improve the welfare of the poor and to affect biomass use in developing countries (Granado et al., 2012; Coady et al., 2015; Ferraresi et al., 2018; Lin and Kuang, 2020). For example, in India, Indonesia, China, Kiribati, Nigeria and Mexico, fuel price subsidies typically concentrated in high-income households rather than evenly distributing across all households (Gangopadhyay et al., 2005; Dartanto, 2013; Soile and Mu, 2015; Peltovuori, 2017; Lin and Kuang, 2020; Díaz and Medlock, 2021). Massive fuel price subsidies also increased fiscal pressures on governments, resulting in increasing poverty (Peltovuori, 2017). These issues have given rise to heated debates about whether fuel price subsidies should be phased out and how to reform the existing subsidies to benefit the poor in developing countries (Dartanto, 2013; Soile and Mu, 2015; Coady et al., 2017). Numerous studies have pointed out that understanding the mechanisms underlying the impacts of the price shocks caused by the removal or the adjustment of fuel price subsidies on the poor households is crucial in designing future reform schemes (Frondel, 2004; Arthur et al., 2012; Ngui et al., 2011; Soile and Mu, 2015; Ferraresi et al., 2018). Despite this, there is a lack of research on the roles of fuel price subsidies in household traditional biomass energy use in rural areas. The setting of optimal energy prices and subsidy levels for accelerating rural household energy transition away from solid biomass continues to be problematic for the governments of most developing countries (Irfan et al., 2018; Wang et al., 2020). Thus, in order to examine the impact of fuel price fluctuations on rural energy transition, investigating households' behavioral of traditional biomass energy use to the changes in fuel prices are imperative. By contrast, studies on examining the effectiveness of other price incentives on household energy use are rare. Although there are a few studies indicating that raising the wage rate of rural labor could lead to a transition from traditional biomass to modern fuels (Qiu et al., 2018), the impacts of changing the prices of agricultural products and other purchased goods were neglected.

Most recently, a large number of studies on rural household energy using behaviors in developing countries have shown that apart from income (or wealth), exposure to market imperfections frequently prevents poor households from employing modern fuels (Heltberg et al., 2000; Bensch et al., 2015; Levine et al., 2016; Abdul-Salam and Phimister, 2019). For example, capital market imperfections, such as liquidity and credit constraints, reduce household adoption of the capital-intensive modern energy system with non-negligible upfront costs (Bensch et al., 2015; Levine et al., 2016; Abdul-Salam and Phimister, 2019). Limited access to or absent of energy market decreases the likelihood of using modern clean fuels (Heltberg et al., 2000; Chen et al., 2016; Chen, 2021). Empirical studies tend to emphasize the impacts of credit market imperfections on the ability or/and willingness of poor farm households to purchase modern fuels (Hill, 2010; Abdul-Salam and Phimister, 2019). Their results revealed that credit-constrained households have substantially lower adoption rates of advanced energy sources than those with access to credit (Adusah-Poku and Takeuchi, 2019). However, there is relatively little evidence on the impact of labor market imperfections on household energy use behaviors.

Rural households in most developing countries usually face labor market imperfections (Benjamin, 1992; Burke and Dundas, 2015; Soundararajan, 2019). There may be an exogenously imposed binding constraint on off-farm employment[2] in rural areas. Frequent drivers behind this are the relatively low educational level of rural households for getting non-farm jobs, the high transaction cost of the inconvenient transportation systems in remote areas, and the fear of losing the land use rights of the household members working off-farm (Bowlus and Sicular, 2003; Jia, 2012). On account of these labor market failures, numerous studies analyzed household biomass energy-using behaviors in developing countries based on agricultural household models (AHM). Most of them investigated the impacts of the prices of fuels, labor opportunities and household characteristics on household energy use in the consideration of household's joint decisions on consumption and production (Amacher et al., 1996; Gupta and Köhlin, 2006; Chen et al., 2006). Their findings indicated that households' behavioral responses to the changes in fuel prices and the opportunity cost of time spent on biomass collection are significant (Guta, 2014; Démurger and Fournier, 2011; Mekonnen et al., 2017) and that labor market performance is an important factor in shaping household biomass energy use behaviors (Heltberg et al., 2000). However, these studies have not analyzed in-depth how a binding constraint on off-farm employment affects the effectiveness of the price incentives on household energy transition.

To address these research gaps, this paper develops an analytical framework based on agricultural household modeling and provides insights into the mechanisms by which market failures, particularly in the labor market, influence household behavioral responses for biomass

[1] Broadly speaking, fuel price subsidies refer to policies and interventions that make consumer prices below the market prices, including direct or indirect price support aiming at reducing the cost of energy (Steenblik, 1995; Lin and Kuang, 2020).

[2] Considering a ration represented by a maximum amount of hours that a household may work off its own farm, the ration binds when desired labor supply exceeds available off-farm opportunities plus on-farm labor demand at the market wage (Benjamin, 1992)

energy use and price incentives for energy transition. We apply this analytical framework to the case of rural households in Sichuan Province in China. Our primary finding is that fuel price subsidy does not work in securing a transition away from traditional biomass energy. This is partly because that the constrained labor market reduces the flexibility in household's behavior through rising the shadow wage. Besides, offering other price incentives, for example giving agricultural price support, lowering the prices of non-energy commodities or increasing the wage rate, also appears ineffective in promoting household energy transition, as the estimated elasticities indicate that household demand for traditional biomass energy is price inelastic. Thus, non-pricing policy instruments should be given priority and measures to mitigate the labor market failures should be taken to improve the effectiveness and impact of existing price policies.

The rest of this paper is organized as follows. Section 2 elaborates the theoretical framework of this study based on a non-separable AHM. The empirical specifications and estimation strategies of the AHM are described in Section 3. Section 4 presents the sample selection procedure, the data used in analysis, and the residential energy use status of the surveyed households. Section 5 reports the estimation results of the AHM. Section 6 summarizes and discusses the main findings of this study and gives policy implications for future rural energy development strategies.

2. Theoretical framework

2.1. Household biomass energy using behaviors in a non-separable AHM

We start from a non-separable agricultural household model (AHM)[3] with biomass energy use. The model is adapted on the basis of the classical model provided by Benjamin (1992). It integrates biomass collection and biomass energy consumption into the intra-household economic activities for investigating how a household makes decision on biomass energy use. We assume that all household members have common preferences regarding consumption and resource allocation. Hence, a twice-differentiable quasi-concave household utility function can be defined as follows:

$$\mathrm{U}(C_e, C_b, C_a, C_m, l; s, u) \tag{1}$$

where the vector u is a set of household characteristics, which can influence preferences; l is leisure. Following Heltberg et al. (2000), we divide household total consumption into four categories: consumption of goods and services, including cooking, heating and lighting, that requires commercial energy[4] inputs C_e and biomass energy inputs C_b, self-consumed agricultural products C_a, and other marketed goods and services C_m. s is a set of factors that influence the energy using efficiency (i.e. possession of improved stove, and cooking or heating habit etc.).

The agricultural production of the household is assumed to be continuous and monotonic in L_a, twice-differentiable and strongly concave. It is represented by the function:

$$q_a = F_a(L_a; Z) \text{ with } F_a^{'} > 0, F_a^{''} < 0 \tag{2}$$

where Z is a set of all inputs except labor (i.e. land, water, and all the other inputs) which is assumed to be exogenous.

Similarly, we assume that the labor supplied to biomass collection is L_b, and define the biomass collection function as:

$$q_b = F_b(L_b; B) \text{ with } F_b^{'} > 0, F_b^{''} < 0 \tag{3}$$

where B is an exogenous vector of household characteristics pertaining to the accessibility and availability of biomass resources such as the distance from the forest or the field to the house, the transportation cost, and the stock of biomass resources.

We also assume that a household has fixed time endowment T which can be allocated to four non-overlapping livelihood activities: working on farm for production profits (L_a), working for biomass collection (L_b),[5] working off-farm for wage (L_o), and leisure (l) for welfare maximization. Hence, we have:

$$T = L_a + L_b + L_o + l \tag{4}$$

Now, we additionally assume that the market for commercial energy is perfect. Meanwhile, the biomass collected by households is assumed to be non-tradable,[6] that is, the amount of biomass consumed as energy is lower than the total collected amount. Then, we have the constraint for household biomass energy consumption:

$$C_b \le q_b \tag{5a}$$

Particularly, a binding constraint on off-farm labor is introduced in the agricultural household model as:

$$L_o \le H < T \tag{5b}$$

Here, we also assume that the markets for all the other goods and services are perfect. The full income constraint for the household:

$$p_a(q_a - C_a) + wL_o + E \ge p_m C_m + p_e C_e \tag{5c}$$

where p_a is the producer price of self-consumed agricultural products; p_e is the consumer price of commercial energy; p_m is the consumer price of market commodities (except commercial energy); w is the market wage rate for labor and E is the exogenous income of the household which includes remittances, transfers, and all the other real non-labor income.

Then we solve the optimization problem of the household by establishing a Lagrangian function subject to the constraints (5a to 5c):

$$U^L = U(C_m, C_a, C_b, C_e, T - L_a - L_b - L_o; s, u) + \lambda[p_a(q_a - C_a) + wL_o + E - p_m C_m - p_e C_e] - \mu(L_o - H) - \eta(C_b - q_b) \; w.r.t. C_a, C_b, C_m, C_e, L, L_a, L_b, L_o \tag{6}$$

[3] According to Benjamin (1992), the separation property of the agricultural household model (AHM) holds if the labor market is perfect. When there is no market failure in the labor market, household's labor allocation decision to maximize its production profit is independent of that for utility maximization (See Appendix A1). Otherwise, with imperfect labor market, the household's on and off-farm labor decisions will not be separable.

[4] In this paper, commercial energy is defined as the modern fuels that can be purchased from the existing market, including coal, LPG, natural gas, and electricity. The fuel price subsidy is assumed to be introduced on the consumer price of commercial energy.

[5] Thus, the total labor input for intra-household production activities is L ($L = L_a + L_b$).

[6] According to the results of our household survey, in our study region in rural China, the biomass (either crop straws or firewood) is traded by few households, only accounting for a rather small share of the sampled households. Thus, we assume that the market for biomass energy is missing in our study region.

Reorganizing the Kuhn-Tucker conditions,[7] the equilibrium of household labor allocation can be obtained:

$$\frac{\partial U^L}{\partial l} = \frac{\partial U}{\partial C_b}\frac{\partial q_b}{\partial L_b} = \lambda\frac{\partial p_a q_a}{\partial L_a} = \lambda\frac{\partial p_a q_a}{\partial L} + \eta\frac{\partial q_b}{\partial L} = \lambda w - \mu \tag{7}$$

Condition (7) reveals that household collects biomass until the point where the marginal utility of leisure equals to the marginal utility of biomass energy in household consumption times the marginal product of biomass collection labor, which in turn, is equalized to the marginal productivity of labor in agricultural production.[8] In other words, the marginal value product of labor in intra-household production activities is equal to the opportunity cost of the household labor (the utility of leisure). This result is in line with the findings of Heltberg et al., (2000) that biomass collection is determined by the opportunity cost of the time (i.e. the shadow wage (w^*)). It also states that the time is allocated among biomass collection, farm work, off-farm employment and leisure relying on wage rate.

Thus, the reduced-form equations for household labor allocation can be derived:

$$\left.\begin{matrix} L_a^* \\ L_b^* \\ L^* \end{matrix}\right\} = L'(w, p_a, p_e, p_m, w^*, T, E; B, Z, s, u); L^* = L_a^* + L_b^* \tag{8}$$

And then yields the shadow full income of the household after calculating the maximum generalized profits π^*:

$$Y^* = \pi^* + w^*(T-H) + wH + E \tag{9}$$

As a consumer, the household decides the level of consumption to maximize its utility under the shadow full income constraint. This leads to a consumption system for the household as follow:

$$\left.\begin{matrix} C_a^* \\ C_b^* \\ C_e^* \\ C_m^* \\ l^* \end{matrix}\right\} = C'(w, p_a, p_e, p_m, w^*, Y^*, T, E; B, Z, s, u) \tag{10}$$

The expressions (8) and (10) form the basis of the empirical work. As it is shown in them, the production and consumption decisions made when labor market fails are interlinked by labor allocated to working activities (i.e. on-farm and off-farm work) and its counterpart in the consumption system (i.e. leisure).

2.2. Impact of imperfect labor market on household biomass energy use behaviors

In an imperfect labor market, a household allocates labor to agricultural production and biomass collection up to the point where the marginal value product of these activities equals to the marginal utility of leisure consumption and to the opportunity cost of the time, that is, the shadow wage of the household labor. Thus, the shadow wage indicates the internal perception of the severity of the constraint on the household (De Janvry et al., 1991). The change of household biomass energy-using behaviors is measured by its production and consumption responses on the existing markets. Before going further, we derive the household model to shed light on the mechanism of how household behavioral responses of biomass energy use to price changes in this subsection.

2.2.1. Fuel price changes and shadow wage

Suppose now that there is only one constrained market for labor and that one market price p_x (i.e.w, p_a, p_e, p_m) changes. Let L^* and l^* respectively denote the optimal labor allocated to intra-household production activities and leisure, the household time endowment can be expressed as $-L^* + (T-H) = l^*$ at equilibrium. Following De Janvry et al., 1991, total differentiation of this identity and substitution of the quantity of labor allocated to intra-household activities (L^*) and leisure consumption (l^*) derived from the Eqs. (8) to (10) gives:

$$-\frac{\partial L^*}{\partial w^*}dw^* - \frac{\partial L^*}{\partial p_x}dp_x = \frac{\partial l^*}{\partial w^*}dw^* + \frac{\partial l^*}{\partial p_x}dp_x + \frac{\partial l^*}{\partial Y^*}\left[\frac{\partial \pi^*}{\partial w^*} + (T-H)\right]dw^* + \frac{\partial l^*}{\partial Y^*}\left(\frac{\partial \pi^*}{\partial p_x}\right)dp_x$$

$$\Longrightarrow -\left[\frac{\partial L^*}{\partial p_x} + \frac{\partial l^*}{\partial p_x} + \frac{\partial l^*}{\partial Y^*}\left(\frac{\partial \pi^*}{\partial p_x}\right)\right]dp_x = \left[\frac{\partial L^*}{\partial w^*} + \frac{\partial l^*}{\partial w^*} + \frac{\partial l^*}{\partial Y^*}\left[\frac{\partial \pi^*}{\partial w^*} + (T-H)\right]\right]dw^*$$

$$\Longrightarrow -\left[\frac{\partial L^*}{\partial p_x}\frac{p_x}{L^*}L^* + \frac{\partial l^*}{\partial p_x}\frac{p_x}{l^*}l^* + \frac{\partial l^*}{\partial Y^*}\frac{Y^*}{l^*}\frac{l^*}{Y^*}p_x\left(\frac{\partial \pi^*}{\partial p_x}\right)\right]\frac{dp_x}{p_x} = \left[\frac{\partial L^*}{\partial w^*}\frac{w^*}{L^*}L^* + \frac{\partial l^*}{\partial w^*}\frac{w^*}{l^*}l^* + \frac{\partial l^*}{\partial Y^*}\frac{Y^*}{l^*}\frac{l^*}{Y^*}w^*\left[\frac{\partial \pi^*}{\partial w^*} + (T-H)\right]\right]\frac{dw^*}{w^*}$$

In elasticity form, the above expression can be written as:

$$-\left[E_{L^*,p_x}L^* + E_{l^*,p_x}l^* + E_{l^*,Y^*}\frac{p_x}{Y^*}\left(\frac{\partial \pi^*}{\partial p_x}\right)l^*\right]\frac{dp_x}{p_x} = \left[E_{L^*,w^*}L^* + E_{l^*,w^*}l^* + E_{l^*,Y^*}\frac{w^*l^*}{Y^*}\left[-L^* + (T-H)\right]\right]\frac{dw^*}{w^*}$$

$$\Longrightarrow -\left[E_{L^*,p_x}L^*/l^* + E_{l^*,p_x} + E_{l^*,Y^*}\frac{p_x}{Y^*}\left(\frac{\partial \pi^*}{\partial p_x}\right)\right]l^*\frac{dp_x}{p_x} = \left[E_{L^*,w^*}L^*/l^* + E_{l^*,w^*} + E_{l^*,Y^*}\frac{w^*l^*}{Y^*}\right]l^*\frac{dw^*}{w^*}$$

$$\Longrightarrow E_{w^*,p_x} = \frac{dw^*}{w^*}\Big/\frac{dp_x}{p_x} = -\frac{E_{L^*,p_x} + \gamma\left[E_{l^*,p_x} + E_{l^*,Y^*}\frac{p_x}{Y^*}\left(\frac{\partial \pi^*}{\partial p_x}\right)\right]}{E_{L^*,w^*} + \gamma\left(E_{l^*,w^*} + E_{l^*,Y^*}\frac{w^*l^*}{Y^*}\right)}$$

Then, we can figure out the elasticity of the endogenous shadow

[7] The Kuhn-Tucker conditions are provided in Appendix A2.

[8] In condition (7), $\lambda w^* = \lambda w - \mu \Rightarrow w^* = w - \frac{\mu}{\lambda}$. As the Lagrangian multipliers μ and λ are positive, the shadow wage rate (w^*) is less than the market wage rate (w).

wage w^* with respect to the market price p_x[9]:

$$E_{w^*,p_x} = -\frac{E_{L^*,p_x} + \gamma\left(E_{l^*,p_x} + E_{l^*,Y^*}S_x\right)}{E_{L^*,w^*} + \gamma\left(E_{l^*,w^*} + E_{l^*,Y^*}S_l\right)} \tag{11}$$

where.

$E_{L^*,\ w^*}$ and $E_{L^*,\ p_x}$ are the direct and cross-price elasticity of labor demand for home production.

$E_{l^*,\ w^*}$ and $E_{l^*,\ p_x}$ are the direct and cross-price elasticity of leisure consumption.

$E_{l^*,\ Y^*}$ is the full income elasticity of leisure consumption.

γ is the ratio $l^*/_L$, $\gamma > 0$.

$S_l = \frac{w^* l^*}{Y^*}$ and $S_x = \frac{q_x p_x}{Y^*}$ (or $\frac{wH}{Y^*}$ in the case of a change in market wage rate) are share parameters in shadow income.

In this elasticity, the numerator demonstrates the disequilibrium created by a change in the market price p_x on the imperfect labor market. The first term $E_{L^*,\ p_x}$ is for the change in labor time allocated to production activities while the second term shows the change in leisure consumption coming from the cross-price effect $E_{l^*,\ p_x}$ and the income effect $E_{l^*,\ Y^*}$. Analogously, the expression in the denominator reflects the disequilibrium caused by the change in the endogenous shadow wage. The first term $E_{L^*,\ w^*}$ represents the effect of a change in the shadow wage on labor demand for intra-household production activities while the second term reveals the response of leisure consumption to a change in the shadow wage of household labor. The overall expression shows that the endogenous shadow wage (w^*) will change in response to a change of p_x in order for these two disequilibria to compensate each other and for labor market to be in equilibrium.

Specifically, we can expect that labor demand for intra-household production responds negatively to shadow wage; and that leisure consumption has a negative direct price elasticity ($E_{l^*,\ w^*} + E_{l^*,\ Y^*}S_l$). Hence, the sign of the denominator in elasticity (11) is unambiguously negative.

In the numerator, providing a fuel price subsidy reduces the consumer price of commercial fuels (p_e). When there is a perfect labor market, according to the separation property of an AHM, a decrease in the consumer price of commercial energy does not affect the farmer's on and off-farm labor allocation decision (Benjamin, 1992). This implies that in the numerator in Eq. (12), the effect only comes from a substitution between leisure and the fuels in consumption. As the demand for leisure declines as the price of commercial energy decreases, the numerator is unambiguously negative in this case with the result that $E_{w^*,\ px}$is negative: under imperfect labor market, a fuel price subsidy lowers the consumer price of fuels and hence the shadow wage.

The case of decreasing the consumer price of other purchased goods (p_m) is very similar. A decline in the price of the marketed goods induces a decrease in the shadow wage.

By contrast, if raising the producer price of self-consumed agricultural products (p_a), the effects of the numerator are more complex. On the production side, as output supply responses positively to its own price, an increase in the market price of self-consumed agricultural products increases the demand of labor for home production. On the consumption side, there are two effects: a substitution of leisure for self-consumed agricultural products that become more expensive, and an income effect. Cumulation of these two effects raises leisure consumption. Production and consumption effects are thus cumulative and the numerator is positive. In addition, if the price that increases is that of labor (w), the numerator represents a substitution effect between labor supply to working activities and leisure consumption. Its sign depends on the work-leisure decision of household. Normally in rural areas, due to the relatively low wage rate, the substitution effect of a rising wage is larger than its income effect. The labor supply for work thus rises and the numerator is positive. For these two cases, $E_{w^*,\ p_x}$ is positive: with a constrained labor market, an increase in the price of self-consumed agricultural products or labor raises the shadow wage and destabilizes household internally through perceived labor scarcity.

[9] For more details on changes in different market prices, see Appendix A3.

2.2.2. The effects of price changes on household biomass energy use

On the production side, the elasticities of biomass collection with constrained labor market are derived by differentiation of (3) (with L_b substituted by (8)):

$$\left(\frac{\partial q_b}{\partial p_x}\right)^G = \frac{\partial q_b}{\partial p_x} + \frac{\partial q_b}{\partial w^*}\frac{\partial w^*}{\partial p_x}$$

$$\Longrightarrow \left(\frac{\partial q_b}{\partial p_x}\right)^G = \frac{\partial q_b}{\partial p_x}\frac{p_x}{q_b}\frac{q_b}{p_x} + \frac{\partial q_b}{\partial w^*}\frac{\partial w^*}{\partial p_x}\frac{w^*}{q_b}\frac{p_x}{w^*}\frac{w^*}{p_x}\frac{q_b}{w^*}$$

$$\Longrightarrow \left(\frac{\partial q_b}{\partial p_x}\right)^G = E_{q_b,p_x}\frac{q_b}{p_x} + E_{q_b,w^*}E_{w^*,p_x}\frac{q_b}{p_x}$$

$$\Longrightarrow \left(\frac{\partial q_b}{\partial p_x}\right)^G \frac{p_x}{q_b} = E_{q_b,p_x} + E_{q_b,w^*}E_{w^*,p_x}$$

$$\Longrightarrow \left(E_{q_b,p_x}\right)^G = E_{q_b,p_x} + E_{q_b,w^*}E_{w^*,p_x} \tag{12a}$$

The global elasticities of biomass energy consumption are directly obtained by differentiation of (10):

$$\left(\frac{\partial C_b}{\partial p_x}\right)^G = \frac{\partial C_b}{\partial p_x} + \frac{\partial C_b}{\partial w^*}\frac{\partial w^*}{\partial p_x} + \frac{\partial C_b}{\partial Y^*}\left(\frac{\partial Y^*}{\partial w^*}\frac{\partial w^*}{\partial p_x} + \frac{\partial Y^*}{\partial p_x}\right)$$

$$\Longrightarrow \left(\frac{\partial C_b}{\partial p_x}\right)^G = \frac{\partial C_b}{\partial p_x}\frac{p_x}{C_b}\frac{C_b}{p_x} + \frac{\partial C_b}{\partial w^*}\frac{\partial w^*}{\partial p_x}\frac{w^*}{C_b}\frac{p_x}{w^*}\frac{w^*}{p_x}\frac{C_b}{w^*} + \frac{\partial C_b}{\partial Y^*}\frac{Y^*}{C_b}\left(\frac{\partial Y^*}{\partial w^*}\frac{\partial w^*}{\partial p_x} + \frac{\partial Y^*}{\partial p_x}\right)\frac{C_b}{Y^*}$$

$$\Longrightarrow \left(\frac{\partial C_b}{\partial p_x}\right)^G = E_{C_b,p_x}\frac{C_b}{p_x} + E_{C_b,w^*}E_{w^*,p_x}\frac{C_b}{p_x} + E_{C_b,Y^*}\left(l^*\frac{\partial w^*}{\partial p_x} + \frac{\partial Y^*}{\partial p_x}\right)\frac{C_b}{Y^*}$$

$$\Rightarrow \left(E_{C_b,p_x}\right)^G = E_{C_b,p_x} + E_{C_b,w^*}E_{w^*,p_x} + E_{C_b,Y^*}\left(l^*\frac{\partial w^*}{\partial p_x} + \frac{\partial Y^*}{\partial p_x}\right)\frac{p_x}{Y^*}$$

$$\Longrightarrow \left(E_{C_b,p_x}\right)^G = \left(E_{C_b,p_x}\right)^H + E_{w^*,p_x}\left(E_{C_b,w^*}\right)^H \tag{12b}$$

Where $(E_{C_b,\ p_x})^H = E_{C_b,\ p_x} + E_{C_b,\ Y^*}S_x$ is the direct response of biomass energy consumption to a change in the market prices in a separable AHM, consisting of the standard cross-price elasticity of biomass energy consumption ($E_{C_b,\ p_x}$) and the income effect on biomass energy consumption ($E_{C_b,\ Y^*}S_x$).

In Eq. (12a) and (12b), $E_{qb,\ px}$ gives the behavioral response for biomass collection, while $E_{Cb,\ px}$ shows that for biomass energy consumption. If the indirect effect of the external price via the change in the shadow wage (the second term on the right-hand side of both equations) has a sign which is opposite to that of the direct effect (the first term on the right-hand side of both equations), the global elasticities of $(E_{qb,\ px})^G$ and $(E_{Cb,\ px})^G$with labor market failure are thus unambiguously inferior to the elasticities when the labor market is perfect. Similarly, if both the direct and indirect effects have the same sign, the global elasticities are unambiguously larger than the direct effect.

3. Empirical strategy

The theoretical framework with the derived elasticities presented in Section 2 have provided insights into the economic mechanisms through which the binding constraint on off-farm employment affects household biomass energy. The reduced form equations specified in expressions (8) and (10) define both household labor allocated to biomass collection and household bimass energy consumption jointly as a function of the market price of self-consumed agricultural products, commercial energy, other marketed goods and labor, the shadow wage rate, and other exogenous factors. Based on these, we assume that the households in our sample are self-sufficient in both labor and biomass energy and set off from estimating the household model using a two-step estimating strategy. The shadow wages of household labor are firstly estimated through production modeling and then are included into a demand system and a translog cost system. The parameter estimates of both systems are used to calculate the elasticities of the shadow wage with respect to the market prices (E_{w^*, p_x}) (elasticity (11)) as well as the global consumption and labor demand elasticities ($(E_{q_b, p_x})^G$ and $(E_{C_b, p_x})^G$) (elasticity (12a) and (12b)) in Section 2.

3.1. Shadow wage estimation

Firstly, the agriculture-energy production relationship is specified as a system of Cobb-Douglas production functions[10]:

$$lnY_i = \gamma_i + \alpha_i lnL_i + \delta_i Z_i + \varepsilon_i \forall i \in \{a, b\} \quad (13)$$

Where ε_i is the error term. The agricultural output Y_a is measured by the total value of agricultural products produced by the farm household. Y_b is the total amount of collected biomass. Z_i is a vector of other inputs or influencing factors of the production activities (i.e. the areas of cultivated arable land and the quantity of intermediate inputs in agricultural production function and the distance to biomass collecting spots in biomass collection function) and household location dummies.

Once the equations in (13) have been estimated[11], the shadow wage of household labor can be calculated according to the equilibrium condition outlined in (8):

$$w^* = MPL = \frac{\widehat{\alpha}_a \widehat{Y}_a}{L_a} \quad (14)$$

Where $\widehat{Y}_a$ is the predicted value of agricultural output[12]; $\widehat{\alpha}_a$ is the estimated coefficients associated with the agricultural labor input.

3.2. Household consumption decision

On the consumption side, a linear approximate almost ideal demand system model (LA/AIDS, see Deaton and Muellbauer, 1980) is adopted to estimate the impacts of price changes on household biomass energy consumption behaviors. Let ES_i denote the expenditure share of the ith good, the demand for consumption goods i is represented by a system of equations as follows (Buse, 1994):

$$ES_i = \alpha_i + \sum_j \gamma_{ij} ln(p_j) + \beta_i ln(Y/P^*) + \rho_i X + \varepsilon_i \quad (15)$$

Subject to

$$\sum_i \alpha_i = 1; \sum_i \beta_i = 0; \sum_i \gamma_{ij} = 0; \gamma_{ij} = \gamma_{ji}$$

Where $lnP^* = \sum_i ES_i lnp_i$ is the linear Stone's price index suggested by Deaton and Muellbauer (1980)[13]. Y indicates total budget (e.g. shadow full income); p_j denotes the price of good j; α_i is the good-specific constant; β_i is the parameter of the budget effect of demand; γ_{ij} are the parameters of the effects of relative price changes and ρ_i is the coefficient of household characteristics affecting consumption X (such as demographic characteristics and household location).

We group household consumption into five categories of goods: self-consumed agricultural products (including rice, maize, wheat, rapeseed, vegetables, and livestock products); biomass energy (composed of firewood and crop residues); commercial energy (consist of electricity, coal, natural gas, and LPG); other purchased goods; and leisure time. Since the variations in the prices for the households who are living in the same region are quite small, we set up household-specific prices by using subgroups consumption structure under the assumption that the expenditure shares of the commodities in the same group are constant (Beznoska, 2014). The prices are then calculated by the sum of weighted prices of each term in that category (Castellón et al., 2012)[14].

The LA/AIDS model is estimated by using constrained iterative seemingly unrelated regression (Constrained ITSUR) method (Zellner, 1962). This method allows the estimation of contemporaneous correlation in error terms across system equations, which then to be used to derive more efficient estimates. In the ITSUR procedure, the demand equation of other marketed goods (ES_o) is excluded from the system. The parameters of this excluded equation can be figured out in terms of the parameters of other equations using the add-up restriction $\sum_i \alpha_i = 1$, since the sum of the shares of expenditure is equal to 1.

Considering the endogeneity problems related to the estimation of the LA/AID model, the zero-expenditure problem occurs in the consumption group of biomass energy due to household's non-participation decision regarding biomass collection. Therefore, estimating the system only with the households who participate in collecting biomass may induce biased results. In order to correct the potential sample selection bias, we adopt the method proposed by Heckman (1979) and Heien and Wessells (1990) to include the inverse Mills ratio (R_b) as an instrument in the expenditure share equation of biomass energy in the LA/AID model.

Another endogeneity problem is caused by including the shadow wage of household labor and the shadow price of biomass energy in the model. Moreover, as the allocation of budget (full shadow income) depends on the work-leisure decision, which is determined within household, the term ln(Y/P^*) is also endogenous (Beznoska, 2014). As suggested by Henning and Henningsen (2007), these variables are affected by household characteristics (X) proxied by demographic factors, household location as well as by the price of other commodities.

Based on the estimated parameters ($\widehat{\beta}_i$ and $\widehat{\gamma}_{ij}$) of this LA/AIDS model, Marshallian (uncompensated) and Hicksian (compensated) price elasticities can be calculated by using the formulas given by Chalfant (1987) and Green and Alston (1990) in Eqs. (17a-17c).

Expenditure (full income) elasticities:

$$E_{C_i, Y^*} = \frac{\widehat{\beta}_i}{\overline{ES}_i} + 1 \quad (16a)$$

Marshallian (uncompensated) price elasticities:

[10] As firewood makes up the majority of the collected biomass and crop straws are usually collected after harvest, biomass collection is assumed to be independent of agricultural production. This is to say, the total amount of collected biomass (Y_b) is not defined as a function of agricultural output (Y_a). However, considering the correlation between these two production activities in terms of labor allocation decision, we jointly estimate the two production functions as a production system.

[11] The estimation method of the production system is given in Appendix (See Appendix A4)

[12] $\widehat{Y_a} = \widehat{\alpha_a} lnL_a + \widehat{\delta_a} Z_a$ is the linear prediction of agricultural production based on the estimated coefficients of the production function (13).

[13] However, this index is an endogenous variable, because it depends on household expenditure shares. Therefore, we replace the individual expenditure shares with the sample mean ($\overline{ES_i}$) to avoid potential endogeneity problem.

[14] For the group of other marketed goods, we adopt the method suggested by West and Parry (2009) using the price data to calculate a price index for the composite market goods. The price data were collected from the official website of Sichuan government: http://www.sc.gov.cn/10462/10464/10594/10601/2013/10/8/10279526.shtml and our field survey. For biomass energy, its shadow wage is calculated as $Shadow\ price\ of\ biomass\ energy \approx \frac{w_i^*(CNY\ per\ hour) \times Collecting\ time(Hours)}{Total\ amount\ of\ collected\ biomass\ (kg)}$.

$$E_{C_i,p_j} = -\delta_{ij} + \frac{\hat{\gamma}_{ij}}{\overline{ES}_i} - \hat{\beta}_i\left(\overline{ES}_j/\overline{ES}_i\right) \quad (16b)$$

Where if $i = j$, $\delta_{ij} = 1$, otherwise, $\delta_{ij} = 0$.

The Hicksian (compensated) price elasticities:

$$E^*_{C_i,p_j} = E_{C_i,p_j} + \overline{ES}_j E_{C_i,Y^*} \quad (16c)$$

3.3. Household production and labor demand

In order to investigate household labor demand for different income-generating activities, a translog cost function with multiple inputs is employed (Hamermesh, 1993). Following Fisher et al. (2005), we assume all income (including shadow income) generation activities as a process of production. Then for a production function with three inputs (i.e. labor working off-farm, labor allocated to home production, and intermediate inputs for agricultural production including fertilizers, pesticides and plastic films), the translog cost function is given as (Dogan and Akay, 2016):

$$\ln TC = \alpha_0 + \alpha_i lnp_i + \frac{1}{2}\sum_i\sum_j \gamma_{ij} lnp_i lnp_j + \alpha_y lnY_P + \mu_i \quad (17)$$

Constrained to

$$\sum_i \alpha_i = 1; \sum_j \gamma_{ij} = 0; \gamma_{ij} = \gamma_{ji}$$

Adopting Shephard's lemma to take the differentiation of this translog cost function with respect to input prices, the labor cost share equations needed to be estimated are obtained (Mas-colell et al., 1995):

$$LS_i = \alpha_i + \gamma_{ij} ln\left(\frac{p_j}{p_z}\right) + \gamma_{ii} ln\left(\frac{p_i}{p_z}\right) + \tau_i \quad (18)$$

Where α_0 is the constant term; μ and τ are the error terms; TC represents total cost; Y_P is the total value of output; p_i is the prices of household labor (i.e. the market wage rate (w) and shadow wage rate (w^*)); LS_i denotes the cost share of labor inputs (i.e. labor in home production (LS_w*) and off-farm employed labor (LS_w)); p_z is the weighted price of intermediate inputs. The other factors such as area of arable land, the ratio of the dependence to labor and location dummies are also included in the model. Finally, the inverse Mills ratio (R_0') is added in the off-farm labor cost share equation as an instrument to correct the potential sample selection bias (Heckman, 1979).

The translog cost function (17) and the system of labor cost share Eq. (18) form a system of multiple equations with the three cross-equation parameter restrictions. This system is estimated also using the constrained iterative seemingly unrelated regression (Constrained ITSUR) method. Then, the formula given by Chalfant (1987) can be applied to calculate the price elasticities of labor supply[15]:

$$E_{L^*,w^*} = 1 + \frac{\hat{\gamma}_{ii}}{(\overline{LS}_i)^2} - \frac{1}{\overline{LS}_i} \quad (19a)$$

$$E_{L^*,w} = \frac{\hat{\gamma}_{ij}}{\overline{LS}_i} + \overline{LS}_j \quad (19b)$$

Particularly, as the unobservable shadow wage and shadow income are endogenously determined within household, we use the natural logarithm of non-labor income (lnE) and household head characteristics (the age, gender and educational level) as instruments[16].

[15] $\overline{LS}_i$ denotes the sample mean of the labor shares.

[16] The potential endogeneity problem comes from the dependence of the values of production output and labor input on the intra-household labor allocation decision (Heltberg et al., 2000; Beznoska, 2014; Guta, 2014). As the selected variables are exogenous and they can be assumed to be less correlated with household labor allocation decision, they are appropriate instruments.

4. Data description

In this paper, we focus on rural households in Sichuan Province of China. There are three reasons. First, the total amount of rural residential energy consumption was about 38 Million tsce[17] in 2014, taking the first place in China (Cong et al., 2017). Second, traditional solid biomass energy (i.e. crop straw and firewood) remains the principal type of residential energy in rural areas. Available official statistics show that the total amount of crop straw and firewood consumed by rural households was about 13.4 Million tsce, accounting for about 34.6% of the total energy consumption in 2018 (SCREO, 2019). Third, the rural areas, especially those in remote mountainous areas with large minority population, are the poorest areas in China (Montalvo and Ravallion, 2010). The rural per capita income was 14,670 CNY[18] in 2019, lower than the national average level of 16,020 CNY (National Bureau of Statistics, 2020). Moreover, the shares of agriculture in GDP and rural labor employment were 11.5% and 63.5%, respectively, by the end of 2017 (National Bureau of Statistics, China (NBS), 2018), suggesting that rural labor productivity in agriculture was much lower than it was in non-agricultural sectors of the economy. In other words, the marginal productivity of agricultural worker was lower than the market wage rate. Hence, labor market was imperfect and failed to allocate rural labor efficiently.

The data used in this paper were collected from a field survey of 576 rural households in six counties of Sichuan Province from August 2013 to February 2014. We applied a stratified sampling approach: 176 counties of Sichuan Province were categorized into three zones- high, middle, and low- in terms of the rural per capita income level. Two counties were randomly chosen from each zone. Three towns, each with two villages, were randomly selected from each county. Eventually, 15–16 respondents were randomly surveyed in each village. After eliminating invalid questionnaires and outliers, the total number of agricultural households for our analysis is 524[19]. More specifically, in low-income zone, 175 households from Jiuzhaigou and Mao County (inhabited by Tibetan and Qiang people) in Aba Prefecture were selected. 179 households were drawn from middle-income zone located in Jiang'an and Changning of Yibin City. Finally, 170 households living in Mianzhushi and Shifangshi from Deyang City were chosen as representatives for high-income zone.

Fig. 1 shows the energy sources adopted by the surveyed households for residential use. Nearly 99.6% of the households employed more than one type of energy. According to Fig. 1, all households used electricity. Households from plain and hilly areas had access to the national grid, whereas those from mountainous areas were connected to nearby small hydropower generation stations. Firewood took the largest share (approximately 65.8%) in the surveyed households, while crop straw was used by about 35.5% of them. This means that the traditional solid biomass occupied a relatively large proportion in rural household residential energy choices.

Fig. 1 also indicates that in addition to electricity, household energy

[17] In this paper, kgsce = kilogram(s) standard coal equivalent; tsce = ton(s) standard coal equivalent.

[18] CNY is abbreviation of Chinese currency. 1 CNY ≈ 0.1450 US Dollars in 2019 (NBSC, 2020).

[19] The representativeness of our sample was tested by comparing the characteristics of the sampled households with the official statistics of the Sixth National Population Census of China (2010). The average household size of the sampled households are 4.1 persons in 2013, with 51.4% male, 11.17% children (≤14), and 11.92% elderly people (≥65). The values of these demographic variables are close to the official data (In 2010, the average household size in Sichuan Province is 3.1 persons; 50.9% of family members are male, and the shares of children (≤14) and elderly people (≥65) in family members are 19.01% and 12.26%, respectively). Thus, considering the population growth in China, the data collected from our household survey can be regarded as being consistent with the official data.

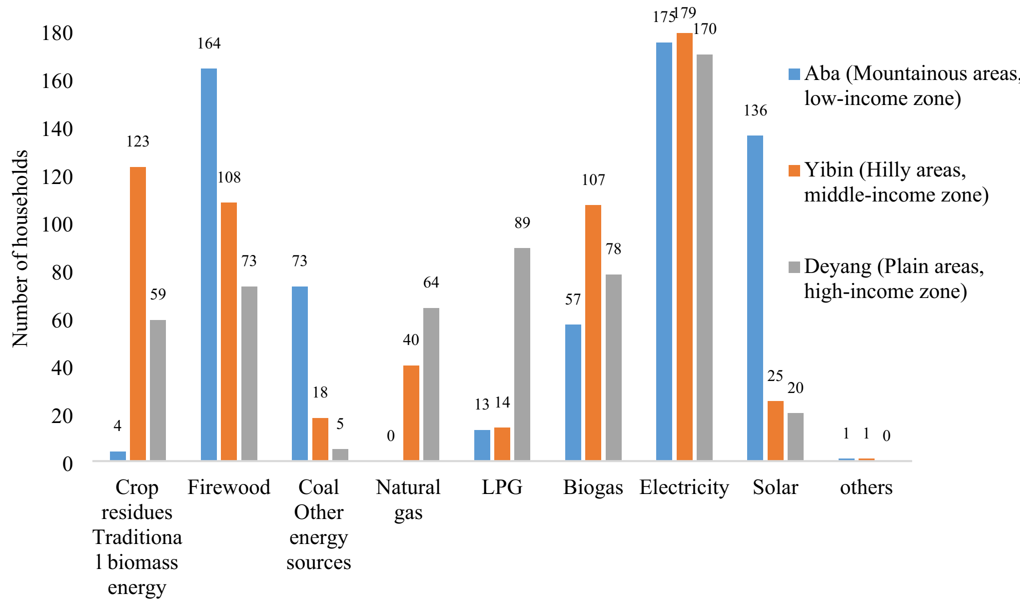

Fig. 1. Residential energy use patterns of the surveyed households in 2013.
Source: Author's own field survey.

Table 1
Household residential energy consumption in 2013 (per household per year).

	Aba	Yibin	Deyang	Sample mean
Biomass energy				
Crop residues (Kg)	4	442	217	223
Firewood (Kg)	3015	2144	339	1849
Biogas (m^3)	55	166	82	102
Commercial energy				
Coal (Kg)	165	29	9	68
LPG (Tank)	0.2	0.6	4.9	1.9
Natural gas (m^3)	0	44	57	34
Electricity (kWh)	1712	1663	2018	1795
Total residential energy consumption (Kgsce)	2350	1873	909	1720
Share of traditional biomass energy in total (%)	73.5	65.4	27.9	62.5

Source: Author's own field survey.

use differs among different regions. About 93.7% of the low-income households from the mountainous areas preferred firewood in cooking and space heating. Solar (77.7%) was the major type of non-biomass energy used to heat water for showers, as the high-altitude zones usually have adequate sunshine. Among the middle-income households located in hilly areas, biomass energy took the dominant position in residential energy use. The percentages of households using crop residues, firewood and biogas were around 68.7%, 60.3% and 59.8%, respectively. For the high-income households who are living in plain areas, LPG had the largest user share (about 52.4%). Compared to the other two household groups, the proportion of traditional biomass energy (crop residues and firewood) consumers was smaller, while that of gas (LPG, biogas and natural gas) users was larger in this richer group. Households from high-income zones were more likely to use cleaner fuels with higher efficiency and quality such as electricity and gas, but without abandoning traditional solid biomass energy.

Table 2
Household time allocation to different working activities in 2013.

	Aba	Yibin	Deyang	Sample mean
Time allocation on farm work (hours per household)	841	771	667	761
Time allocation on off-farm work (hours per household)	3727	4551	3716	4005
Time allocation on biomass collection (hours per household)	382	261	75	312

Source: Author's own field survey.

Table 1 shows the energy consumption status of the sampled households in 2013. On average, the total amount of energy consumed by each surveyed household was about 1720 kgsce. Traditional biomass energy was accountable for about 62.5% of the total energy consumption. More specifically, the mean consumption of crop residues, firewood and biogas among sampled households were 223 kg, 1849 kg and 102 m^3 respectively. Besides, households also used commercial energy including coal (65 kg), LPG (1.9 tank), natural gas (34m^3) and electricity (1795 kWh) to meet their energy demand for living.

Households from Aba had the largest residential energy consumption amount (2350 kgsce), while those from Deyang had the smallest (909 kgsce). Traditional biomass energy took the dominant position (73.5%) in total residential energy consumption in Aba, while taking the smallest share (63%) in that of Deyang. It can be seen from Table 1 that averagely, the households from Aba consumed the largest amount of firewood (3015 kg), while those from Deyang used the least amount (339 kg). Due to the geographic and weather conditions, crops such as rice and wheat cannot be cultivated in mountainous areas. Thus, there were no enough available straws for the households located in Aba to use as energy. Whereas, households living in Yibin, the crop production zone of Sichuan Province, had abundant crop residues. Therefore, they consumed the largest amount of crop straws (442 kg per year). On the other hand, households located in plain areas consumed more of other types of commercial energy (e.g. LPG, natural gas and electricity) apart from coal than those from mountainous and hilly areas, because they are relatively wealthier and can afford the more expensive energy and costly energy using devices.

Table 2 shows the household time allocation to different activities in the same year. Generally, the sampled households distributed their working time among farm work, off-farm work and biomass collection. Off-farm work took the longest time (4005 h per household), while biomass collection took the shortest time (312 h per household). In detail, households from mountainous areas (Aba) spend the longest time (841 h) on agricultural production, while the households in plain areas

Table 3
Estimation results of the production system using IT3SLS.

Variables	Total value of agricultural production ($\ln Y_a$)	Total amount of collected biomass ($\ln Y_b$)
Hours working on agricultural production ($\ln L_a$)	0.6274***	
	(0.0935)	
Hours working on biomass collection ($\ln L_b$)		0.3540***
		(0.0447)
Areas of arable land (ln)	0.2665***	
	(0.0758)	
Total value of intermediate inputs (ln)	0.0222	
	(0.0145)	
Age of household head	−0.0048	−0.0069
	(0.0046)	(0.0049)
Gender of household head	0.0681	0.1355
	(0.1720)	(0.1757)
Educational year of household head	0.0536***	0.0200
	(0.0145)	(0.0149)
Distance to biomass collecting spot		0.0033
		(0.0113)
d_1 (=1 if the household located in mountainous areas)	0.3013***	−0.1463
	(0.1106)	(0.1264)
d_2 (=1 if the household located in plain areas)	0.4796***	−0.3718**
	(0.1319)	(0.1681)
_cons	4.2388***	6.5835***
	(0.6141)	(0.4342)
Sample selection correction (R_b)		−0.5955**
		(0.2632)
Endogenous variables [a]	$\ln Y_a$, $\ln Y_b$	
No. of Obs.	394	

Note: The missing dummy for regions is 'Hilly area'. The significance levels are *10%, **5% and ***1%. Values in parentheses are standard errors of estimated parameters. The significant coefficient of the IMR (R_b) indicates that sample selection bias would happen if the system of production functions were estimated without taking household participation decisions on biomass collection into consideration.

(Deyang) spend the shortest time (667 h) on farm work. Correspondingly, households in mountainous areas allocated more time (382 h per year) on biomass collection than those from the other two areas, whereas households who are living in the plain areas spend less time (75 h per year) collecting biomass. For off-farm employment, households from Yibin allocated the longest time (4551 h per year) to off-farm work on average, while households from Deyang spend the shortest time (3716 h per year). Table A3 Table A3 in the Appendix lists all variables used in this study along with their respective definitions and descriptive statistics.

5. Results

5.1. Model estimation results

The estimates of the Cobb-Douglas production system are reported in Table 3. Labor inputs have significantly positive effects on both agricultural production and biomass collection. The household head's schooling has a positive impact on both outputs, supporting the widely accepted role of human capital in improving production. For agricultural production, other inputs (i.e. arable land and intermediate inputs) have positive impacts. Furthermore, household location is an important factor for household production. Compared with the households from hilly areas, households located in mountainous areas have more outputs from agricultural production, while those located in plain areas collect less biomass. The household shadow wage is estimated using the coefficients of the production system and then, included in our econometric analysis in next steps.

a. All other variables in this system are treated as exogenous to the system and uncorrelated with the disturbances. The exogenous variables are taken to be instruments for the endogenous variables.

The estimated coefficients of the LA/AIDS model are listed in Table 4. The coefficients of the variables indicate that shadow price (including that of biomass energy and leisure) determined by the shadow wage of household labor the most important influencing factor for household biomass consumption. In addition, demographic characteristics and household location can also significantly impact the consumption.

The estimation results of the system of the translog cost function and labor cost share equations with the instrumental variables are presented in Table 5. The estimated parameters reflect that arable land areas, the ratio of dependence to labor, and household location are determinants for household labor allocation to working activities.

5.2. Elasticities

On the consumption side, the estimated coefficients of the LA/AIDS model (reported in Table 4) are adopted to compute the full income elasticities and Marshallian and Hicksian price elasticities.

As it is shown in Table 6, all full income elasticities are positive. This indicates that all the five types of commodities are normal goods. Therefore, based on the Chinese real situation that rural income keeps on increasing, household consumption on all commodity categories will continue to grow accordingly. In particular, the magnitude of the full income elasticity of commercial energy consumption is less than one (0.7450), suggesting that the expenditure on commercial energy is irresponsive to the changes in the level of household income. In other words, commercial energy is a kind of necessities for the surveyed rural households.

Moreover, the compensated elasticities (Hicksian price elasticities) are derived from solving the dual problem of expenditure minimization at a certain utility level, assuming constant purchasing power, while the uncompensated elasticities (Marshallian price elasticities) is obtained from maximizing utility subject to the budget constraint. Both of them reflect household's reaction to the changes in the prices of different commodities. Table 6 demonstrates that the signs of all own-price elasticities are negative. This result is consistent with the theoretical proposition that the expenditure on commodities will decrease when the prices of them increase. In terms of their magnitudes, self-consumed agricultural products and biomass energy are price inelastic (self-consumed agricultural products: −0.8383 for Marshallian price elasticity and − 0.9431 for Hicksian price elasticity; biomass energy: −0.4524 for Marshallian price elasticity and − 0.8383 for Hicksian price elasticity), as households' consumption of these two types of goods derives from their own production. On the contrary, households' demand for purchased goods (i.e. commercial energy and the other marketed goods) is price-sensitive, as the absolute values of its own-price elasticities are larger than one (commercial energy: −1.3982 for Marshallian price elasticity and − 1.3937 for Hicksian price elasticity; other marketed goods: −1.3865 for Marshallian price elasticity and − 1.1606 for Hicksian price elasticity). As regards the demand for leisure, the magnitude of its own-price elasticity (−0.8335 for Marshallian price elasticity and − 0.1455 for Hicksian price elasticity) is larger than its income elasticity (0.8327), probably indicating that as income increases, households proportionately allocates more time to working activities and reduce their time allocation to leisure.

Turning to the cross-price elasticities of demand for biomass energy, we will focus on the Marshallian (uncompensated) elasticities, which consider both substitution effect and income effect. According to the Marshallian cross-price elasticities, biomass energy consumption increases when the price of commercial energy (0.0008) or other marketed goods rises (0.0170), while decreasing when the price of self-consumed agricultural products increases (−0.0054). Besides, households appear to be unresponsive to price incentives as judged by the low cross-price elasticities of biomass energy consumption with respect to the exogenous prices (e.g. the price of self-consumed agricultural products,

Table 4
Parameter estimation of LA/AIDS model using censored SURE.

Variables	Expenditure share of				
	Self-consumed agricultural products	Biomass energy	Commercial energy	Leisure	Other purchased goods
Price of self-consumed agricultural products (ln)	0.0065***				
	(0.0020)				
Shadow price of biomass energy (ln)	−0.0005	0.0060***			
	(0.0008)	(0.0006)			
Price of commercial energy (ln)	0.0005**	0.0001	−0.0024***		
	(0.0002)	(0.0002)	(0.0005)		
Shadow price of leisure (ln)	−0.0169***	−0.0037**	0.0006	0.02334**	
	(0.0030)	(0.0014)	(0.0005)	(0.0110)	
Price of other marketed goods (ln)	0.0104***	−0.0019	0.0012***	−0.0034	−0.0804
	(0.0025)	(0.0012)	(0.0004)	(0.0088)	
ln(Y/P^*)	0.0259***	0.0007	−0.0015	−0.1382***	0.1033
	(0.0092)	(0.0044)	(0.0012)	(0.0313)	
Family size	−0.0103***	−0.0032**	−0.0004	0.0570***	
	(0.0025)	(0.0012)	(0.0003)	(0.0086)	
Fraction of female adults	0.0285*	0.0175**	−0.0005	−0.1591**	
	(0.0167)	(0.0079)	(0.0021)	(0.0565)	
Fraction of male adults	0.0492***	0.0091	0.0042**	−0.0886*	
	(0.0159)	(0.0074)	(0.0020)	(0.0537)	
Fraction of children (≤14 years old)	0.0231	0.0120	0.00003	−0.0637	
	(0.0164)	(0.0077)	(0.0021)	(0.0555)	
Fraction of elderly (≥65 years old)	−0.0116*	0.0043	−0.0030***	0.0830***	
	(0.0070)	(0.0036)	(0.0009)	(0.0236)	
d_1 (=1 if the household located in mountainous areas)	−0.0118***	−0.0003	−0.0032***	−0.0132	
	(0.0035)	(0.0018)	(0.0006)	(0.0116)	
d_2 (=1 if the household located in plain areas)	0.0018	−0.0050*	−0.0002	0.0443***	
	(0.0046)	(0.0026)	(0.0007)	(0.0154)	
Sample selection correction (R_b)		−0.0128***			
		(0.0039)			
_cons	−1.3197***	0.0364	0.0153	2.0021***	0.2659
	(0.1671)	(0.0414)	(0.0114)	(0.3133)	
No. of Obs.	394				

Note: The missing dummy for regions is 'Hilly area'. The significance level are *10%, **5% and ***1%. Values in parentheses are standard errors of estimated parameters. The significant coefficient of the IMR (R_b) indicates that sample selection bias would happen if the system of production functions were estimated without taking household participation decisions on biomass collection into consideration.

commercial energy and other marketed goods).

On the production side, the estimated parameters of the translog cost function and the labor share equations (presented in Table 5) are applied to calculate the price elasticities of demand for labor (See Table 6). The own-price elasticity of labor demand for home production is negative (−1.4382), implying that raising the shadow wage will decrease labor allocated to intra-household production activities. The cross-price elasticity of labor in home production is positive (0.2402).Besides, it is worth noting that both the own-price and cross-price elasticities of off-farm labor are positive, but quite small (0.0119 for own-price elasticity and 0.1196 for cross-price elasticity). These results indicate that with the constrained labor market, labor in off-farm work is not allow to increase significantly with an increase in the market wage rate. Household has to turn to its own farm for further employment until it achieves the new equilibrium (Benjamin, 1992). Under this circumstance, the labor allocated to home production increases.

6. Discussions

The estimated price elasticities in Table 6 are used to simulate the impacts of price incentives, such as subsidizing modern fuels, providing farm-gate price support, lowering the price of market commodities and raising the market wage rate, on household traditional biomass use. As suggested by Henning and Henningsen (2007), elasticities for perfect labor market are calculated setting the second term (the indirect effect) on the right hand side of (12a) and (12b) equal to zero. The global elasticities in (12a) and (12b) are elasticities with imperfect labor market. Thus, the effect of imperfect labor market on household biomass energy use equals to the difference in price elasticities between perfect and imperfect labor market regimes, i.e. $E_{q_b, w^*} E_{w^*, p_x}$ on the production side and $(E_{C_b, w^*})^H E_{w^*, p_x}$ on the consumption side. The results are reported in Table 7.

According to Table 7, if the government subsidizes modern fuels, such that the consumer price of commercial energy falls by 1%. With a complete labor market, this does not affect household's labor allocation decision for biomass collection on the production side. In consumption, lowering the consumer price of commercial energy raises its demand and reduces the consumption of biomass energy by 0.0012%. With a binding constraint imposed on off-farm employment, the shadow wage declines with the falling fuel prices, and hence induces an increase in both biomass collection and biomass energy consumption. This offsets the direct negative effect and makes the response of household biomass energy use be sluggish, reflecting the fact that the labor market failures reduce flexibility in the household's behavior. Finally, household biomass energy consumption decreases by 0.0008%. Similarly, lowering the consumer price of the other purchased goods by 1% will reduce biomass energy consumption by 0.0170%.

In the case of providing farm-gate price support, if the producer price of self-consumed agricultural products increases by 1%, there is a positive supply response in agricultural production. This effect is permitted by a substitution of production for biomass collection. Sequentially, biomass energy consumption declines along with the falling amount of collected biomass (by 0.0046%). However, with an imperfect labor market, the shadow wage of household labor increases, resulting in a further reduction in labor supplied to home production. This is to say that labor market failures exaggerate the household's behavior of reducing biomass collection in response to a price increase of self-consumed agricultural products. The consumption of biomass energy then decreases by 0.0054%.

When raising the market wage rate by 1%, its direct effect on household biomass collection is negative (−0.0020%), as labor will transfer to agricultural production and nonfarm sectors to increase the

Table 5
Constrained ITSURE estimation results of translog cost function and labor cost share equations.

Variables	Total cost	Cost share of labor working on home production	Cost share of labor employed off-farm
$\ln p_c$	0.1825***		
	(0.0299)		
$\ln p_f$	0.4885***		
	(0.0523)		
$\ln p_d$	0.3290***		
	(0.0576)		
$(\ln p_c)^2$	0.0278***		
	(0.0047)		
$(\ln p_f)^2$	0.1467***		
	(0.0159)		
$(\ln p_d)^2$	0.0844***		
	(0.0128)		
$\ln p_c$ * $\ln p_f$	−0.0451***		
	(0.0068)		
$\ln p_c$* * $\ln p_d$	0.0173***		
	(0.0062)		
$\ln p_d$ * $\ln p_f$	−0.1016***		
	(0.0127)		
lnY	−0.0523		
	(0.0899)		
$\ln(p_f/p_c)$		−0.1016***	0.1467***
		(0.0127)	(0.0159)
$\ln(p_d/p_c)$		0.0844***	−0.1016***
		(0.0128)	(0.0127)
Areas of arable land	0.0182**	0.0058**	−0.0049
	(0.0092)	(0.0025)	(0.0032)
Ratio of dependence to labor	−0.4305***	0.1752***	−0.1773***
	(0.0873)	(0.0250)	(0.0327)
d_1 (=1 if the household located in mountainous	0.0201	0.0763***	−0.1157***
	(0.0781)	(0.0220)	(0.0285)
d_2 (=1 if the household located in plain areas)	−0.2171***	0.0550**	−0.0522*
	(0.0837)	(0.0232)	(0.0295)
Sample selection correction (R_o')			0.0449***
			(0.0080)
_cons	9.2236***	0.1529***	0.6419***
	(1.0835)	(0.0217)	(0.0342)
Hausman test statistic	37.26***		
No. of Obs.	524		

Note: The missing dummy for regions is 'Hilly area'. The values in parentheses are standard errors, and the significance levels are *10%, **5% and ***1%. p_c represents the price of intermediate inputs; p_d denotes shadow wage rate; and p_f refers to market wage rate. The coefficient of the IMR (R_o') is significant, indicating that sample selection bias would happen if the system of labor share equations were estimated taking households who do not participate in off-farm work into consideration. The hausman test statistic is significant at 1% level, implying that the selected instrument variables are valid to some extent.

cash income when the rural labor market is perfect. However, if the off-farm labor market is constrained, the previously mentioned direct effect is partially allowed. Instead, household labor will all turn to agricultural production for making profit. Therefore, the global elasticity is then enlarged by a further decline in biomass collection. The biomass energy consumption will decrease by 0.0476%.

Existing literature on the price effects on household energy using behaviors mainly focuses on the fuel price subsidies and their roles in fuel choices (Coady et al., 2017; Peltovuori, 2017). Our results show that although providing fuel price subsides to reduce the consumer price of commercial energy can favor the adoption of modern fuels, it is not an effective measure to encourage the abandonment of traditional biomass energy due to the unresponsiveness of households' demand to the price of commercial energy. This finding is consistent with results from Irfan et al., (2018) and Choumert-Nkolo et al., (2019). Besides, our study reveals that the governments and authorities cannot also rely on prices (i.e. the farm-gate prices, market wage rate, or the consumer price of the

Table 6
Full income elasticities and price elasticities calculated based on the LA/AIDS model and the translog cost function system.

	Full income elasticities	Own-price elasticities		Cross-price elasticities									
Household consumption				Self-consumed agricultural products (a)		Biomass energy (b)		Commercial energy (e)		Leisure (l)		Other marketed goods (o)	
		Marshallian	Hicksian	Marshallian	Hicksian	Marshallian	Hicksian	Marshallian	Hicksian	Marshallian	Hicksian	Marshallian	Hicksian
Self-consumed agricultural products (a)	1.7429	−0.8383	−0.7775	–	–	−0.0928	0.0887	0.0098	0.0202	−1.0985	0.3415	0.2073	0.4207
Biomass energy (b)	1.0067	−0.9431	−0.8383	−0.0054	0.0297	–	–	0.0008	0.0069	−0.0410	0.7907	0.0170	0.1403
Commercial energy (e)	0.7450	−1.3982	−1.3937	0.0913	0.1173	0.0415	0.1191	–	–	0.3156	0.9311	0.2287	0.3200
Leisure (l)	0.8327	−0.8335	−0.1455	−0.0146	0.0144	0.0130	0.0997	0.0018	0.0068	–	–	0.0164	0.1184
Other marketed goods (o)	1.9238	−1.3865	−1.1606	0.0527	0.1171	−0.1114	0.0807	0.0041	0.0152	−0.7907	0.7327	–	–
Household production		Own-price elasticities		Cross-price elasticities									
Labor for home production (L)		−1.4382				0.2402							
Labor for off-farm jobs (L_o)		0.0119				0.1196							

Note: all elasticities are calculated using sample mean value.

Table 7
Simulations of household biomass energy use responding to price changes under imperfect labor market.

	Change in biomass energy use under perfect labor market $E_{q_b, p_x}/(E_{C_b, p_x})^H$	Change in the shadow wage E_{w^*, p_x}	Change in biomass energy use under imperfect labor market[a] $(E_{q_b, p_x})^G/(E_{C_b, p_x})^G$
Self-consumed agricultural products (p_a)↑	0.0046%↓	0.0208%↓	0.0054%↓
Commercial energy (p_e)↓	0.0012%↓	0.0103%↑	0.0008%↓
Other marketed goods (p_o)↓	0.0216%↓	0.1122%↑	0.0170%↓
Labor (w)↑	0.0020%↓	1.1601%↓	0.0476%↓

Source: author's own calculation based on simulated effect of a 1% increase in farm-gate price of self-consumed agricultural products and labor, or a 1% decrease in consumer price of commercial energy (modern fuels such as coal, LPG, natural gas and electricity) and other marketed goods.

[a] As households are self-sufficient in biomass energy, when the rising prices of self-consumed agricultural products, commercial energy and other marketed goods increase the demand for biomass energy, households have to depend on themselves to collect more biomass. Under this circumstance, there is a positive supply response in biomass collection. Nevertheless, at equilibriums, as we have $q_b = C_b$, we can infer that $(E_{q_b, p_x})^G$ and $(E_{C_b, p_x})^G$ have the same sign.

purchased goods) to promote the energy transition. Hence, policy reforms targeting the entire energy supply system should be undertaken rather than merely focusing on changing energy prices.

Commercial energy types, including electricity, currently available to households in Sichuan province rely extensively on various fossil fuels. Coal and electric energy produced from fossil fuels lead greenhouse gas emissions causing climate change. For this reason, policies promoting transitions away from biomass-based energy need to be accompanied by investments into renewable sources of modern energy, particularly, solar, hydro and wind-generated electricity in order to generate fully environmentally friendly energy transitions.

7. Conclusions and policy implications

This paper attempted to investigate the effectiveness of fuel price subsidies on energy transition with a particular focus on household biomass energy using behaviors under imperfect labor market based on estimation of a non-separable agricultural household model (AHM) with the survey data from Sichuan Province of China. Our simulation results reveal the unresponsiveness of households to price changes, as indicated by the rather low price elasticities of the demand for biomass energy. Providing a subsidy to decrease the consumer price of fuels by 1% would reduce the consumption of biomass energy by only 0.0008%. Besides, decreasing the consumer price of other marketed goods by 1% would decrease biomass energy use by 0.0170%. Whereas, raising the producer price of self-consumed agricultural products or labor by 1% would reduce biomass energy consumption by merely 0.0054% and 0.0476%.

Particularly, numerous recent studies have shown that governments or local authorities of many developing countries rely on fuel price subsides to promote household energy transition (Granado et al., 2012; Zhang, 2014; Chen and Liu, 2017; Nguyen et al., 2019). However, the efficiencies of fuel subsidies and taxes have been seriously questioned, due to unresponsiveness of households to fuel prices (Sander et al., 2013). The estimates of our study show no significant own-price and cross-price effects on the use of biomass energy in the study areas. This result partly supports the idea that policy interventions changing external prices have minimal effects on promoting fuel shifts. Therefore, non-price policy instruments should be given priority in designing future rural energy policy packages. For example, providing technical support, such as subsiding on energy-efficient and clean equipment, increasing R&D investments in exploring new energy technologies and providing demonstration projects (or planning programs) in rural areas is an effective way to change household energy use behaviors.

Meanwhile, as the results we have obtained indicate that the labor market failure matters great in improving the effectiveness of the existing fuel price incentives, there are several other non-price elements of policy interventions that can be used to improve their impacts on household biomass energy use behaviors. One is the role of measures directed at reducing the incidence of labor market failures for specific households. This includes interventions that have capability to mitigate the binding constraint imposed on off-farm employment such as increasing investments in infrastructure construction, promoting education in rural areas and smoothing circulation of information on wages and job opportunities. Moreover, indirect sources of labor market failure also need to be eliminated by establishing a sound and effective social safety net to provide better access for rural households to services such as public transport system, health care, and landless employment guarantee.

Finally, our results point to the need for further research. Firstly, the impacts of other labor market failures, such as rationing on the labor demand side and differing returns to hired and family labor, on household biomass energy use need more attention. Secondly, according to the real situation, the market for agricultural products is pervasively imperfect in rural areas across the developing world. Thus, the assumption for its completeness should be relaxed. Thirdly, we cannot conduct a full comparison study on household behaviors with and without market failures, because it is difficult to obtain the data with all complete markets. Future research based on experimental methods that might be able to simulate household's behaviors under perfect markets is necessary to improve our current work.

Credit author statement

Qiu Chen: Conceptualization, Methodology, Writing-original draft preparation, Data collection and analysis.

Jikun Huang: Conceptualization, Methodology, Supervision.

Alisher Mirzabaev: Conceptualization, Writing-reviewing and editing.

Declaration of interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. There is no professional or other personal interest if any nature or kind in any product, service and/or company that could be constructed as influencing the position presented in, or the review of, the manuscript entitled.

Inclusion and diversity

We worked to ensure ethnic diversity in the selection of human subjects. We also worked to ensure that the study questionnaires were prepared in an inclusive way. The author list of this paper includes contributors from the location where the research was conducted and those who participated in the data collection and analysis.

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Appendix A

A.1. Household biomass energy using behaviors in a separable agricultural household model

When all markets are perfect, according to the separation property given by Benjamin (1992), household behaves in a recursive process. It firstly maximizes its profits π without any consideration of its consumption or leisure preferences:

$$\text{Max}\pi = p_a q_a + p_b q_b - w(L_a + L_b)\ w.r.t. L, L_a, L_b \tag{A1}$$

The first-order conditions of (A1) show that the equilibrium of household labor allocation is determined by:

$$\frac{\partial p_a q_a + \partial p_b q_b}{\partial L} = \frac{\partial p_a q_a}{\partial L_a} = \frac{\partial p_b q_b}{\partial L_b} = w \tag{A2}$$

The Eq. (A2) indicates that the optimum of household labor allocation will occur at the point where the marginal productivity of the labor allocated to home production activities is equalized to the marginal productivity of the farm labor and labor in biomass collection. It also demonstrates that household labor allocation on agricultural production and biomass collection is determined by market wage rate. Thus, the solution to the maximization problem yields the household labor allocation functions:

$$\left.\begin{matrix} L_a^* \\ L_b^* \\ L^* \end{matrix}\right\} = L^{'}(p_a, p_b, w; B, Z,); L^* = L_a^* + L_b^* \tag{A3}$$

Based on the maximum profits π^*, household then decides how much goods and leisure to consume and how much labor to supply off-farm:

$$\left.\begin{matrix} C_a^* \\ C_b^* \\ C_e^* \\ C_m^* \\ l^* \end{matrix}\right\} = C^{'}(w, p_a, p_b, p_e, p_m, T, E; B, Z, s, u) \tag{A4}$$

$$L_o^* = T - L_a^* - L_b^* - l^* \tag{A5}$$

A.2. The Kuhn-Tucker conditions obtained from solving the optimization problem of the Lagrangian function

In order to obtain the optimal labor allocation and consumption decisions of the household, the Kuhn-Tucker conditions are derived from establishing a Lagrangian function (Eq. 6) subject to the constraints (Eq. (5a) to (5c)) as follows:

$$\frac{\partial U^L}{\partial C_b} = \frac{\partial U}{\partial C_b} - \eta = 0 \tag{A6a}$$

$$\frac{\partial U^L}{\partial C_x} = \frac{\partial U}{\partial C_x} - \lambda p_x = 0, x = a, m, e \tag{A6b}$$

$$\frac{\partial U^L}{\partial L_o} = -\frac{\partial U}{\partial l} + \lambda w - \mu = 0 \tag{A6c}$$

$$\frac{\partial U^L}{\partial L_a} = -\frac{\partial U}{\partial l} + \lambda p_a \frac{\partial q_a}{\partial L_a} = 0 \tag{A6d}$$

$$\frac{\partial U^L}{\partial L_b} = -\frac{\partial U}{\partial l} + \eta \frac{\partial q_b}{\partial L_b} = 0 \tag{A6e}$$

$$\frac{\partial U^L}{\partial L} = -\frac{\partial U}{\partial l} + \lambda p_a \frac{\partial q_a}{\partial L} + \eta \frac{\partial q_b}{\partial L} = 0 \tag{A6f}$$

A.3. Derivation of the elasticities

A.3.1. Fuel price changes and shadow wage

As the elasticity of the endogenous shadow wage w^* with respect to p_x can be expressed as:

$$E_{w^*,p_x} = -\frac{E_{L^*,p_x} + \gamma\left[E_{l^*,p_x} + E_{l^*,Y^*}\frac{p_x}{Y^*}\left(\frac{\partial \pi^*}{\partial p_x}\right)\right]}{E_{L^*,w^*} + \gamma\left(E_{l^*,w^*} + E_{l^*,Y^*}\frac{w^* l^*}{Y^*}\right)}$$

When the consumer price of commercial energy or other purchased goods changes,

$$E_{w^*,p_x} = -\frac{E_{L^*,p_x} + \gamma E_{l^*,p_x}}{E_{L^*,w^*} + \gamma\left(E_{l^*,w^*} + E_{l^*,Y^*}\frac{w^*l^*}{Y^*}\right)}$$

In the case of a change in the farm gate price of agricultural products,

$$E_{w^*,p_x} = -\frac{E_{L^*,p_x} + \gamma\left(E_{l^*,p_x} + E_{l^*,Y^*}\frac{q_xp_x}{Y^*}\right)}{E_{L^*,w^*} + \gamma\left(E_{l^*,w^*} + E_{l^*,Y^*}\frac{w^*l^*}{Y^*}\right)} = \frac{E_{L^*,p_x} + \gamma\left(E_{l^*,p_x} + E_{l^*,Y^*}S_x\right)}{E_{L^*,w^*} + \gamma\left(E_{l^*,w^*} + E_{l^*,Y^*}S_l\right)}$$

If the price that changes is that of labor (i.e. the market wage rate),

$$E_{w^*,p_x} = -\frac{E_{L^*,p_x} + \gamma\left(E_{l^*,p_x} + E_{l^*,Y^*}\frac{wH}{Y^*}\right)}{E_{L^*,w^*} + \gamma\left(E_{l^*,w^*} + E_{l^*,Y^*}\frac{w^*l^*}{Y^*}\right)} = \frac{E_{L^*,p_x} + \gamma\left(E_{l^*,p_x} + E_{l^*,Y^*}\frac{wH}{Y^*}\right)}{E_{L^*,w^*} + \gamma\left(E_{l^*,w^*} + E_{l^*,Y^*}S_l\right)}$$

A.3.2. The effects of price changes on household biomass energy consumption

The global elasticities of biomass energy consumption

$$\left(E_{C_b,p_x}\right)^G = E_{C_b,p_x} + E_{C_b,w^*}E_{w^*,p_x} + E_{C_b,Y^*}\left(l^*\frac{\partial w^*}{\partial p_x} + \frac{\partial Y^*}{\partial p_x}\right)\frac{p_x}{Y^*}$$

When the consumer price of commercial energy or other purchased goods changes,

$$\left(E_{C_b,p_x}\right)^G = E_{C_b,p_x} + E_{C_b,w^*}E_{w^*,p_x} + E_{C_b,Y^*}\left(l^*\frac{\partial w^*}{\partial p_x}\frac{p_x}{w^*}\frac{w^*}{p_x}\right)\frac{p_x}{Y^*}$$

$$\Rightarrow\left(E_{C_b,p_x}\right)^G = E_{C_b,p_x} + E_{C_b,w^*}E_{w^*,p_x} + E_{C_b,Y^*}\left(l^*E_{w^*,p_x}\frac{w^*}{p_x}\right)\frac{p_x}{Y^*}$$

$$\Rightarrow\left(E_{C_b,p_x}\right)^G = E_{C_b,p_x} + E_{C_b,w^*}E_{w^*,p_x} + E_{C_b,Y^*}E_{w^*,p_x}\frac{w^*l^*}{Y^*}$$

$$\Rightarrow\left(E_{C_b,p_x}\right)^G = \left(E_{C_b,p_x}\right)^H + E_{w^*,p_x}\left[E_{C_b,w^*} + E_{C_b,Y^*}\frac{w^*l^*}{Y^*}\right]$$

$$\Rightarrow\left(E_{C_b,p_x}\right)^G = \left(E_{C_b,p_x}\right)^H + E_{w^*,p_x}\left[E_{C_b,w^*} + E_{C_b,Y^*}S_l\right]$$

In the case of a change in the farm gate price of agricultural products,

$$\left(E_{C_b,p_x}\right)^G = E_{C_b,p_x} + E_{C_b,w^*}E_{w^*,p_x} + E_{C_b,Y^*}\left(l^*\frac{\partial w^*}{\partial p_x}\frac{p_x}{w^*}\frac{w^*}{p_x} + q_x\right)\frac{p_x}{Y^*}$$

$$\Rightarrow\left(E_{C_b,p_x}\right)^G = E_{C_b,p_x} + E_{C_b,w^*}E_{w^*,p_x} + E_{C_b,Y^*}E_{w^*,p_x}\frac{w^*l^*}{Y^*} + E_{C_b,Y^*}\frac{q_xp_x}{Y^*}$$

$$\Longrightarrow \mathrm{E}(\mathrm{C_b}/\mathrm{p_x})^{\mathrm{G}} = \left[\mathrm{E_{C_b,p_x}} + \mathrm{E_{C_b,Y^*}S_x}\right] + \mathrm{E_{w^*,p_x}}\left[\mathrm{E_{C_b,w^*}} + \mathrm{E_{C_b,Y^*}S_l}\right]$$

If the price that changes is that of labor (i.e. the market wage rate),

$$\left(E_{C_b,p_x}\right)^G = E_{C_b,p_x} + E_{C_b,w^*}E_{w^*,p_x} + E_{C_b,Y^*}E_{w^*,p_x}\frac{w^*l^*}{Y^*} + E_{C_b,Y^*}\frac{wH}{Y^*}$$

$$\Longrightarrow \mathrm{E}(\mathrm{C_b}/\mathrm{p_x})^{\mathrm{G}} = \left[\mathrm{E_{C_b,p_x}} + \mathrm{E_{C_b,Y^*}S_x}\right] + \mathrm{E_{w^*,p_x}}\left[\mathrm{E_{C_b,w^*}} + \mathrm{E_{C_b,Y^*}S_l}\right]$$

A.4. Estimation of the Cobb-Douglas production system

The Ordinary Least Squares (OLS) estimates of the production system (12) may be biased due to endogeneity problems. Therefore, we firstly include observable household characteristics such as the age, gender and educational level of the household head as proxies for management ability of the household labor. Moreover, as the observed data we collected in our field survey can only reflect the situation of the households who decide to participate in biomass collection, the potential bias should be corrected by using the standard two-stage Heckman sample selection model. The parameter estimates of the production system are finally obtained using seemingly unrelated regression (SUR) method (Zellner, 1962). In the first stage, a probit model which determines the probabilities that a given household will participate in biomass collection or off-farm work is estimated to obtain the inverse Mills ratio for each participant (R_t,∀t ∈ $\{b,o\}$) and non-participant ($R_t{}'$,∀t∈$\{b,o\}$). In the second stage, parameter estimates of the production system are obtained by augmenting the biomass collection equation with the IMR (R_b) using IT3SLS method (Zellner, 1962). Concretely, we select household head characteristics, demographic characteristics, arable land areas, prices, non-labor income, distance to the nearest biomass collecting spot, and location dummies as the independent variables in estimating the selection equation, according to the reduced form of labor allocation function (8). The estimation results are shown in Table A2.

Table A2
Estimation results of the selection equation (probit model).

	Participate in	
	Biomass collection	Off-farm work
Family size	0.11 (0.06)*	0.51 (0.08)***
Age of household head	0.02 (0.01)**	−0.0003 (0.01)
Gender of household head	−0.37 (0.31)	0.35 (0.30)
Educational level of household head	−0.03 (0.02)	−0.01 (0.03)
Fraction of children	0.31 (0.78)	−0.02 (0.81)
Fraction of elderly people	0.94 (0.37)**	−1.14 (0.32)***
Fraction of adult females	−0.79 (0.76)	1.46 (0.84)*
Fraction of adult males	0.07 (0.74)	1.49 (0.81)*
Arable land	0.02 (0.03)	−0.01 (0.02)
Market wage rate (ln)	−0.23 (0.11)**	−0.34 (0.09)***
Non-labor income (ln)	−0.08 (0.05)*	−0.13 (0.05)**
Price index of intermediate inputs (ln)	−0.04 (0.10)	−0.22 (0.09)**
Distance to the nearest biomass collecting spots	0.49 (0.11)***	0.04 (0.04)
Weighted price of self-consumed agricultural products (ln)	0.25 (0.12)**	−0.05 (0.11)
Mountainous areas	0.25 (0.24)	−0.40 (0.24)*
Plain areas	−0.76 (0.17)***	−0.14 (0.20)
_Cons	0.62 (1.03)	0.17 (1.12)
No. of Obs.	524	

Note: The missing dummy for regions is Hilly area. The values in parentheses are standard errors, and the significance levels are *10%; **5% and ***1%.

A.5. Descriptive statistics of variables used in this study

Table A3
Descriptive statistics of the variables used in this study.

Variable	Mean	Std.Dev.
Shadow wage estimation		
Total value of agricultural outputs (CNY)	18,258.50	47,874.38
Total amount of collected biomass (Kgsce)	3736.65	4505.28
Total of intermediate inputs (CNY)	4839.52	16,262.75
Total hours working on agricultural production (Hours)	760.69	489.39
Total hours working on biomass collection (Hours)	241.24	314.07
Arable land areas (Mu)	4.13	3.71
Age of household head (Years)	51.69	11.61
Gender of household head (share of male)	0.93	0.26
Educational level of household head (Years)	6.39	3.45
Distance to the nearest biomass collecting spot (Km)	2.22	4.50
d_1(=1, if the household is from mountainous areas)	0.33	0.47
d_2(=1, if the household is from plain areas)	0.32	0.47
IMR (R_b)	0.43	0.41
Y_{bc} (=1, if household participates in biomass collection)	0.75	0.43
Y_{off}(=1, if household participates in off-farm work)	0.86	0.34
Non-labor income (CNY)	7782.91	16,236.23
LA/AIDS demand system		
Expenditure share of self-consumed agricultural products	0.03	0.04
Expenditure share of biomass energy	0.01	0.02
Expenditure share of commercial energy	0.01	0.06
Expenditure share of leisure time	0.83	0.11
Expenditure share of other purchased goods	0.12	0.10
Weighted price of self-consumed agricultural products (CNY per kg)	4.01	3.27
Weighted price of commercial energy (CNY per kgsce)	3.32	1.01
Price index of other purchased goods (CNY per unit)	596.15	279.83
Linear Stone's price index (P*)	2.73	0.69
Family Size	4.13	1.36
Fraction of children (≤14)	0.11	0.16
Fraction of elderly people (≥65)	0.12	0.23
Fraction of female adults	0.41	0.15
Fraction of Male adults	0.44	0.16
Translog cost function with labor cost share equations		
Total cost for all production (CNY)	45,349.65	33,769.41
Total value of outputs (CNY)	248,679.00	127,585.00
Cost share of labor allocated to home production activities	0.29	0.23
Cost share of labor allocated to off-farm work	0.59	0.31
Ratio of dependence to labor	0.32	0.36
Market wage rate (CNY per hour)	8.48	4.98
Shadow wage rate (CNY per hour)	9.90	4.20

(*continued on next page*)

Table A3 (*continued*)

Variable	Mean	Std.Dev.
Price index of intermediate inputs (CNY per kg)	7.23	14.62
IMR (R_o')	1.91	0.69
No. of Obs.	524	

Note: As the variables used in estimating the selection equation are also included in the three models, they are not listed separately. The missing data of wage rate (for the households who did not participate in off-farm work) are replaced by the regional mean. The average market wage rate is lower than the estimated shadow wage rate, due to the fact that in our field survey, most households understated their wage income levels; In order to unify the units of firewood and crop straw to standard coal equivalent (kgsce), we divide the quantities of them by their conversion coefficients respectively. The data of conversion coefficients for all types of energy are collected from China Energy Statistic Yearbook (2009).
Source: author's own household survey, 2013–2014.

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