Household Fuel Use in Rural China

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Abstract: In order to contribute to the debate on environmental damages generated by carbon emissions and smoke from dirty fuels, we investigate the determinants of fuel choice and fuel switching in Chinese rural households. To this end, we specify a non-separable farm household model, focusing on the substitution of fuels from wood/straw and coal to LNG and electricity, is estimated by using a large micro-household panel dataset. We find that the pattern of fuel use depends not only on income, fuel prices and demand-side socioeconomic factors, as would appear in standard demand models, but also on agricultural production characteristics, food prices, and a set of original household and community characteristics shaping the household responses to market failures.

Keywords: Fuel Use, China, Consumption Demand, Energy

JEL Codes: D11; D12; Q41

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1. Introduction

China's energy transition is of enormous importance to the world. China has overtaken the United States as the world's largest energy consumer since 2010. The soaring energy demand has forced China to be increasingly dependent on imported fossil fuels. This has raised world's energy security concerns. China has become the world's largest carbon emitter since 2006. This has made China's commitment in global climate change mitigation essential. Thus, the transition towards cleaner fuels is more beneficial to global energy supply security and global climate change.

Currently, the energy transition process in Chinese rural households is rather slow. The households still heavily rely on traditional biomass (e.g., firewood, crop residues) and coal for their cooking and heating needs (Pachauri and Jiang 2008; Yao et al. 2012). The heavy reliance on these dirty fuels further produces serious adverse consequences on the environment and health. Incomplete burning of these fuels leads to high indoor concentrations of air pollutants. Extensive use of these fuels also results in regional environmental problems. For example, firewood collection accelerates deforestation. Crop residue utilization potentially contributes to soil erosion. Coal combustion is directly responsible for sulphur dioxide emissions, which yield acid rain and subsequently acidify soil. Moreover, consumption of these fuels together aggravates climate change through releasing greenhouse gases into the atmosphere. The adverse environmental consequences, in turn, pose the risks of ill health (e.g., respiratory diseases, cardiovascular mortality) and threaten the nutritional health of populations.[1]

In order to promote rural household energy transition, the Chinese government has attached great importance to clean energy supply through issuing a number of policies directed at rural electrification and biogas development.[2] However, these policy efforts have not succeeded in motivating most rural households to abandon dirty fuels (Gosens et al. 2013; Shyu 2012).

[1] Climate change may cause extensive losses of crop yields and thus contribute to malnutrition (McMichael et al. 2006).

[2] Brightness Program in 1996; Township Electrification Program in 2002; Regulations on Rural Biogas Projects Supported by National Bond in 2003. National Debt Project for Rural Biogas Construction in 2003.

Motivated by the failure of policy efforts as response to the issues, this study seeks to explore several crucial questions: Why is the use of traditional fuels in rural households persistent? What are the driving forces that govern the fuel transition of rural households to clean fuel types? Do rural households move up the ladder of fuel preferences as their income rises? How do rural households respond to fuel price fluctuations? Do rising other prices play a role in rural household fuel transition? How does off-farm employment exert influence on rural household fuel use? The answers to these questions remain elusive, although they are essential for designing effective policies aimed at promoting rural household fuel transition. In order to investigate these questions, this paper provides empirical evidence on the determinants of fuel choice and fuel switching in Chinese rural households.

Fuel choice in Chinese households has received rather limited research attention. Previous studies are largely based on descriptive analysis.[3] While few studies carry out econometric analysis.[4] In addition, prior studies widely make use of large nationally representative household surveys for some given years (Jiang and O'Neill 2004; Pachauri and Jiang 2008) and cross-sectional micro household surveys with small samples (An et al. 2002; Chen et al. 2006).[5] The use of a large micro-household panel dataset in this paper is new. Availing of panel data allows us to control for unobserved individual heterogeneity and capture dynamic effects, which are neglected in other empirical studies.

The available empirical studies have highlighted the underlying effects of income, demand-side socioeconomic factors reflecting preferences (including age, sex, education and household size) and access to forest resources on the fuel choice. In general, income[6], education[7], household size[8] and distance to firewood source[9] are the driving forces behind the transition to clean fuel types. Despite these common

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[3] Cai and Jiang (2008); Pachauri and Jiang (2008); Wang et al. (2002); Wang and Feng (1996).

[4] An et al. (2002); Chen et al. (2006); Kaul and Liu (1992); Zhang and Koji (2012).

[5] For other developing countries, the studies that analyze the determinants of fuel choice in rural households are mainly based on descriptive statistics (Davis 1998; Miah et al. 2011) and use nationally representative cross-section household surveys (Gundimeda and Köhlin 2008; Rao and Reddy 2007) and cross-sectional micro household surveys with small samples (Miah et al. 2011). Few econometric analyses are also used (Gundimeda and Köhlin 2008; Jumbe and Angelsen 2011). The studies show that income (Rao and Reddy 2007), education (Heltberg 2004), household size (Rao and Reddy 2007), self-owned dwelling (Arthur et al. 2010), access to electricity (Heltberg 2004) and distance to firewood source (Jumbe and Angelsen 2011) motivate rural households to choose clean fuels.

[6] See An et al. (2002); Jiang and O'Neill (2004) and Peng et al. (2010).

[7] See Démurger and Fournier (2010); Jiang and O'Neill (2004) and Zhang and Koji (2012).

[8] See Démurger and Fournier (2010) and Jiang and O'Neill (2004).

[9] See An et al. (2002) and Chen et al. (2006).

findings, there remain controversial empirical issues about the fuel choice.

What drives the fuel choice of Chinese rural households should be a more complex interplay of socioeconomic factors. In rural areas, the markets for traditional biomass, commercial fuels, agricultural food, labor and credit are typically missing or incomplete. Under the presence of such market failures, it is unrealistic to assume that consumption decisions are separable from production decisions in rural households. The non-separability implies that the decisions relating to fuel production and consumption, food supply and demand, labor allocation in fuel collection, farm and off-farm activities are made simultaneously. In this sense, the fuel consumption decisions maybe seen as guided by the household-specific shadow prices of fuel, which depend on household and community characteristics associated with both consumption and production decisions (Heltberg et al. 2000; Sadoulet and de Janvry 1995). Therefore, a wide range of socioeconomic characteristics, which pertain to consumption and production activities and shape household's responses to market failures, should receive more empirical attention. Chen et al. (2006) and Démurger and Fournier (2011) partly deal with the non-separable fuel consumption and production decisions of Chinese rural households through estimating the impacts of some production characteristics (farmland size and livestock number) on the consumption of firewood and coal, while they reach inconclusive empirical findings. Chen et al. (2006) show that farmland size does not affect firewood consumption. In contrary, Démurger and Fournier (2011) report that farmland size is associated with a significant increase in firewood consumption. The present paper attempts to fill the gap by investigating the determinants of fuel demands in a non-separable decision making context.

Obviously, market prices of commercial fuels should matter for fuel choices. In China, the rural households allocate a significant fraction of their income on energy. This is partly due to high prices of commercial fuels in rural areas (Pachauri and Jiang 2008). The households, therefore, may be sensitive to fuel price fluctuations. However, the empirical literature on the impacts of fuel price on the fuel choice of Chinese rural households is scant.[10] Additionally, the empirical evidence on cross

[10] See An et al. (2002); Peng et al. (2010); Kaul and Liu (1992) and Zhang and Koji (2012). Moreover, very few empirical studies conducted in other developing countries have investigated the impact of fuel price on rural household fuel use (Edwards and Langpap 2005; Gundimeda and

price effects remains ambiguous. For example, Peng et al. (2010) find that coal price is associated with a significant increase in biomass consumption. In contrast, Kaul and Liu (1992) and Zhang and Koji (2012) argue that coal price does not affect firewood consumption. This paper, thus, seeks to address this research gap by further exploring how Chinese rural households respond to the fluctuations in fuel price.

Food prices also should be one of key factors underlying the fuel choices of Chinese rural households. The effects of food price hikes on household food consumption have attracted a growing interest in the literature notably after the food crisis of 2007-08, while previous research has disregarded the potential role of food prices in household fuel transition.[11] Indeed, changes in food prices affect food production and consumption of rural households in the non-separable setting, as pointed out by Angelsen (1999). In turn, food prices could influence the fuel transition both through consumer-side and producer-side effects. On the consumer side, an increase in the purchased food price may motivate rural households to choose cheap dirty fuels so as to be able to meet their necessary food needs (Gupta and Köhlin 2006). On the producer side, an increase in the self-produced food price may shift the budget constraint through an extra income (Strauss 1984). This additional income effect may stimulate the fuel transition to clean fuels. We attempt to shed more light on this neglected but crucial issue.

Ignoring fuel stacking (i.e., multiple fuels) behavior is an additional barrier to fully understand the fuel transition. The energy ladder has traditionally served as a prominent model for understanding household fuel choice in developing countries (Kowsari and Zerriffi 2011). This model assumes that households step up the ladder from the bottom (i.e., biomass) to the top (i.e., electricity) of a hierarchy of fuels by perfectly substituting high-quality fuels for low-quality ones as income increases (Hosier and Dowd 1987; Leach 1992). During the past decade, a growing literature has argued that the energy ladder model cannot adequately describe households' fuel use dynamics, especially in the rural areas of developing countries, since the households often choose a combination of fuels rather than one specific fuel type exclusively as their income increases.[12] However, the literature has given much less

Köhlin 2008; Pitt 1985).

[11] See Alem and Söderbom (2012); Ge et al. (2014) and Kumar and Quisumbing (2013).

[12] See Davis (1998); Guta (2012); Heltberg (2004, 2005); Hiemstra-van der Horst and Hovorka

attention to the factors explaining the fuel stacking behavior than to the description of observed multiple fuel patterns (i.e., use a combination of low-quality and high-quality fuels) itself (Masera et al. 2000). Even so, two empirical studies address the issue of fuel stacking for Chinese rural households, while without utilizing sophisticated econometric methods (Jiang and O'Neill 2004; Peng et al. 2010). The current paper, thus, contributes to this rather unexplored issue by providing additional evidence on the determinants of fuel stacking.

This paper is organized as follows. A farm household model is presented in Section
2. Section 3 describes datasets and variables, outlines the econometric method and discusses the estimation results. Finally, Section 4 offers concluding remarks.

2. A farm household model for fuel use

The separation property of farm household models holds when markets are perfect. Under the separation assumption, rural household’s decision-making is recursive as a two-step process in the sense that household behaves firstly as a profit maximizing producer and then as a utility maximizing consumer given the profit realized in the first step (Singh et al. 1986).

However, the presence of market failures in Chinese rural areas violates the separation assumption. The markets for straw and firewood are very thin or absent (Chen et al. 2006; Shi et al. 2009), which explains the dual role of rural household as producer and consumer of these fuels. The lack of reliable supply of modern fuels (e.g., liquefied natural gas (LNG), electricity) could also restrict rural household’s fuel choices. Under incomplete markets for agricultural goods as mentioned in Démurger et al. (2010), rural households may confront high transaction costs for selling and purchasing food products. These costs force rural households to consume part of their self-produced food. The agricultural production decisions of a rural household thus may not be separable from its food consumption behavior. Finally, imperfections in labor markets (Bowlus and Sicular 2003) may make rural household become self-sufficient in labor and have to be limited by the endowment of household labor.

(2008) and Masera et al. (2000).

In what follows, we outline a non-separable farm household model for cooking fuel demands, as a basis of our empirical analysis.[13] The model implies that household decisions relating to fuel supply and demand, food production and consumption, labor allocation in fuel collection, farm and off-farm activities are all made simultaneously, rather than in a recursive fashion. Household-specific shadow prices of fuel, shaped by household and community characteristics, thus guide household fuel demands.

Our model borrows some motivations from other empirical works dealing with household fuel demands. Amacher et al. (1996) place emphasis on deriving conditions (including market firewood price and labor opportunity costs) under which rural households are willing to either only collect, or both collect and purchase their firewood. Heltberg et al. (2000) highlight that rural households substitute private non-marketed fuels (animal dung and crop residues) for firewood in response to increasing firewood scarcity. Chen et al. (2006) extend the model of Heltberg et al. (2000) by focusing on the substitution between firewood and coal.

The model presented below describes the situation of a farm household engaged in crop and livestock production, off-farm work and firewood collection. The main focus of this model is on the substitution of fuels from traditional dirty sources to modern clean ones. One novelty of this model is to highlight the fuel substitution in response to food price fluctuations.

The household maximizes utility (U) defined over food consumption (C), cooking fuel use (F) and leisure (l):

$$U = U(C, F, l; Z), \qquad (1)$$

where Z is a vector of household characteristics pertaining to preferences notably for the pattern of fuel use. Food consumption is a function of household produced and consumed food (C^h) and market purchased food (C^p):

$$C = C(C^h, C^p; \Omega), \qquad (2)$$

[13] We do not consider fuel use for lighting and house heating because nearly all the rural households use electricity for lighting in the household survey used in this study and the information about house heating is not observed in the data. Another reason for neglecting fuel use for house heating is that fuel choice for household heating depends on the pattern of fuel use for cooking. In fact, the heat from cooking could be used for warming the house. For example, Chinese Kang as a traditional heating system is used for house heating via heat recovery from cooking chimney gases.

where Ω stands for other predetermined variables relating to food consumption. In practice, Ω includes a vector of community characteristics reflecting physical infrastructure services in rural areas. Access to infrastructure services could reduce the transaction costs of participating in food markets. This may involve a change in production pattern, switching from self-sufficiency to commercial agricultural production, and thus a change in consumption pattern, shifting from reliance on self-produced food to purchased food. We assume that the household can choose between dirty (F^d) or clean (F^c) fuels, or both for cooking food. The resulting energy input is described by a production function:

$$F = F(F^d, F^c; V), \tag{3}$$

where V denotes other predetermined variables.[14] V is a vector of community characteristics describing the availability of traditional biomass fuels and the access to modern clean fuels. These supply-side factors are taken into account, since it is unrealistic to assume that the household chooses fuels irrespective of the local supply conditions which shape the costs of fuels. Plentiful availability of traditional biomass may become an obstacle to the substitution from dirty sources to clean ones, while access to reliable supplies of clean fuels may imply great potential for fuel transition. Here, F^d consists of firewood (F^{dw}), straw (F^{ds}) and coal (F^{dc}). While F^c is a function of LNG (F^{cl}) and electricity (F^{ce}).[15] Because of the absence of firewood market, the consumption of firewood is assumed to equal to the collected quantity $(q^{dw}(L_{dw}))$, where L_{dw} is household labor time spent collecting firewood. Similarly, under the incomplete market for straw, the household procures straw through its own production output (q^{ds}) which is considered as a physical by-product of agricultural production (Q_{AG}). We suppose that the household is engaged in crop (Q_c) and livestock (Q_l) production activities:

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[14] We do not account for stove characteristics in the energy production function since such information is not available in the data.

[15] Other energy sources for cooking, such as biogas, are not observed in the data used in this study and thus not modeled.

$$Q_{AG} = Q_{AG}(Q_c, Q_l; \phi), \tag{4}$$

where ϕ is a vector of household endowments pertaining to land and livestock. The crop production, assumed to depend on both household labor (L_c) and other fixed inputs (A_c) (e.g., farm equipment) is given by: $Q_c = Q_c(L_c, A_c)$. The livestock production is a function of both purchased feeding (M^p) and homemade feeding (M^h): $Q_l = Q_l(M^p, M^h(L_l))$, where L_l denotes the labor time allocated in feeding production. Thus, the total amount of available straw, produced by the household, is defined as a certain proportion of crop production and of feeding production: $q^{ds} = \alpha Q_c + \beta M^h$, where α and β denote the proportions. Considering the imperfect market conditions for straw, we suppose $F^{ds} = q^{ds}$. In contrast, coal, LNG and electricity could be purchased at the market. However, the household may not be able to buy the desired quantities of LNG and electricity due to the short supply of these energy sources in rural areas, especially in the remote rural areas. Thus, we consider LNG and electricity as rationed goods: $F^{cl} \leq \overline{F^{cl}}$ and $F^{ce} \leq \overline{F^{ce}}$, where $\overline{F^{cl}}$ and $\overline{F^{ce}}$ represent the rationing bounds of LNG and electricity, respectively. The household cannot spend more on the consumption of food and fuel than its total income (Y). Then, the budget constraint is:

$$\begin{aligned} &C^h p^h + C^p p^p + F^{dc} p^{dc} + F^{cl} p^{cl} + F^{ce} p^{ce} \\ &= (Q_{AG} p^h - A_c p^{ac} - M^p p^{mp}) + wL_{off} + Y_0 = Y, \end{aligned} \tag{5}$$

where p^h and p^p respectively refer to the prices of household produced and market purchased food; p^{dc}, p^{cl} and p^{ce} are the prices of coal, LNG and electricity, respectively; p^{ac} represents the price of other fixed inputs in crop production; p^{mp} is the price of purchased feeding; L_{off} denotes household labor allocated in off-farm work; w is wage and Y_0 denotes other exogenous incomes (e.g., fuel subsidy, poverty funds). The household budget here is showed to be endogenous, and it depends on the agricultural production decisions. An increase in the price of a food item produced and consumed by the household could bring about farm profit effects and substitution effects. In addition, the household has limited time available. Thus, the time allocated to firewood collection, agricultural production, off-farm work and leisure cannot exceed the household total time endowment (T):

$$L_{dw} + L_c + L_l + L_{off} + l = T. \quad (6)$$

The Lagrangian of the problem consisting of (1)-(6) can be written as:

$$\begin{aligned}\Gamma = & U\left[C(C^h, C^p; \Omega), F(F^d(F^{dw}, F^{ds}, F^{dc}), F^c(F^{cl}, F^{ce}); V), l; Z\right] \\ & -\lambda\left[C^h p^h + C^p p^p + F^{dc} p^{dc} + F^{cl} p^{cl} + F^{ce} p^{ce}\right. \\ & \left. -(Q_{AG}(Q_c, Q_l; \phi) - A_c p^{ac} - M^p p^{mp}) - wL_{off} - Y_0\right] \\ & -\eta(L_{dw} + L_c + L_l + L_{off} + l - T) \\ & -\mu_1(F^{dw} - q^{dw}(L_{dw})) - \mu_2(F^{ds} - \alpha Q_c - \beta M^h) \\ & -\mu_3(F^{cl} - \overline{F^{cl}}) - \mu_4(F^{ce} - \overline{F^{ce}}), \end{aligned} \quad (7)$$

where λ and η are Lagrangian multipliers associated with income and time constraints, respectively. μ_1 and μ_2 are Lagrangian multipliers attached to quantity constraints on firewood and straw, respectively. μ_3 and μ_4 are Lagrangian multipliers related to inequality constraints on LNG and electricity, respectively. Under usual hypotheses of convexity of preferences and technology sets, and focusing on interior solutions, the reduced-form equations on the cooking fuel demands can be derived from the first-order conditions and form the basis of our empirical work:

$$\left.\begin{matrix} F^{dw} \\ F^{ds} \\ F^{dc} \\ F^{cl} \\ F^{ce} \end{matrix}\right\} = f(p^h, p^p, p^{dc}, p^{cl}, p^{ce}, Y, Z, \Omega, V, \phi), \quad (8)$$

where $f(\cdot)$ is fuel demand function. These are our main equations of interest. The fuel demands depend not only on market prices, income and preferences, but also on a set of household and community variables that may all be associated with consumption-production decisions and thus determine the household-specific virtual price of fuel. This is in contrast with separable models where consumption decision should be independent of production-side household characteristics and quite restrictive assumptions need to be imposed. We investigate the empirical effects of these exogenous variables on fuel choices in the next section.

3. Empirical analysis

3.1 The data

The data used in this study are taken from three waves of the China Health and Nutrition Survey (CHNS) in 2000, 2004 and 2006.[16] In the survey, respondents are asked which fuels they use as their main energy sources for cooking.[17] Four fuel types are most commonly used by the surveyed households as their primary and secondary cooking fuels, including wood/straw, coal, LNG and electricity (see Table 1).[18] Rural households still mostly relied on wood/straw and coal as their primary cooking fuels in 2000, 2004 and 2006. Although there was nearly universal access to electricity in rural areas, the use of electricity as primary cooking fuel accounted for only about 3.55 %, 5.62 % and 15.24 % of total households in 2000, 2004 and 2006, respectively. Moreover, wood/straw and LNG were two important secondary sources of cooking fuel in the three survey waves. Apart from wood/straw and LNG, electricity tended to be a dominant secondary cooking fuel. On the contrary, coal turned into a less important secondary cooking fuel.

The percentage of households using fuel combinations is reported in Table 2. Few households used a unique type of energy. The most important incidence of single-fuel use was among coal users (21.05 %, 13.38 % and 9.20 % in 2000, 2004 and 2006, respectively). In contrast, the majority of households used a combination of cooking fuels. The most common combination of dirty and clean fuels in the three survey years was the joint use of wood/straw (primary) and LNG (secondary). Moreover, the proportion of households using the combination of wood/straw

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[16] CHNS is an ongoing longitudinal household survey conducted in 9 provinces including Guangxi, Guizhou, Heilongjiang, Henan, Hubei, Hunan, Jiangsu, Liaoning, and Shandong. The first round was collected in 1989. Seven additional panels were collected in 1991, 1993, 1997, 2000, 2004, 2006 and 2009. More information is available at http://www.cpc.unc.edu/projects/china. The reasons for using only these three waves are twofold: first, the information on electricity price is available only from the wave of 2000; second, the 2009 data had not yet been released when this analysis was conducted.

[17] When they use more than two energy types, the surveyed households are asked to record the two most often used. There is no information on the quantities used for fuels in the survey.

[18] Only very few rural households chose kerosene, natural gas, charcoal and other type as their primary cooking fuel. Therefore, these fuel types are excluded from the analysis.

(respectively, LNG) and coal (respectively, electricity) declined (respectively, increased) over the study period. Clearly, rural households experienced a shift away from low efficiency dirty fuels towards more efficient clean fuels.

3.2 The variables

3.2.1 The dependent variables

We investigate the determinants of (1) primary cooking fuel choice and (2) primary-secondary cooking fuel choices (i.e., fuel stacking) in rural households by estimating random effects panel logit (REPL) models and multinomial logit (MNL) models.

In the REPL model of primary cooking fuel choice, the dependent variable is defined as 1 if the primary fuel used is LNG or electricity, and it is 0 if the primary fuel used is wood/straw or coal. In the REPL model of primary-secondary cooking fuel choices, the dependent variable is defined as 1 if clean fuels are predominantly used, and it is 0 if dirty fuels are predominantly used.

In the MNL model, wood/straw, coal, LNG and electricity are the four alternative primary cooking fuel choices. In the MNL model of primary-secondary cooking fuel choices, as in Heltberg (2004), we describe fuel switching according to the following three categories: (1) 'No switching'—the main fuels used by rural households are wood/straw-only or coal-only or mixed wood/straw-coal; (2) 'Partial switching'—the main fuels used by rural household are mixed wood/straw-LNG or mixed wood/straw-electricity or mixed coal-LNG or mixed coal-electricity; (3) 'Full switching'—the main fuels used by rural household are LNG-only or electricity-only or mixed LNG-electricity.

The percentage of households in each category is reported in Table 3. Partial switching was still a predominant strategy of fuel use in rural households in 2006. The share of households in the no switching (respectively, full switching) category decreased (respectively, increased) over the study period.

3.2.2 Independent variables

We now discuss our explanatory variables. The definition and descriptive statistics for these variables are reported in Table 4.

Market prices for coal (p^{dc}), LNG (p^{cl}) and electricity (p^{ce}) are included in the regressions. We have to replace the prices of household-produced and market-purchased food with the prices of a few food products generally consumed and produced by rural households, because the data on the self-produced or purchased food items for a given household are not available. Household income (Y) is specified as total annual net income, adjusted to the price level of 2006 based on CPI estimated by National Bureau of Statistics of China.[19] Electricity and one-child subsidies are also incorporated along with household income, as, first, income data is typically contaminated by measurement errors and it is useful to add a variable correlated with it as a complement, and second, we are particularly interested in the potential effects of such subsidies.

The household characteristics affecting household preferences (Z) are: household head's age, sex, education, occupation and marital status, household size, dwelling attributes, and lifestyle types captured by whether the household head is living with his/her parents and whether the household head prepares food. These variables may have either positive or negative effects on fuel demands. The household land and livestock endowments (ϕ) are represented by the agricultural specialization of the household.[20] Household specializing in agricultural production are expected to prefer, relatively, the use of dirty fuels, because they can take advantage of crop residues.

The other predetermined variables relating to local fuel supply conditions (V) consist of % agricultural activity, off-farm employment participation (including % migrants, local enterprise and economic open area), degree of rural economic development (including administrative district, population size, and community income) as well as geographic location.[21] % agricultural activity and off-farm employment participation are used to depict the availability of traditional biomass fuels. % agricultural activity is expected to be an obstacle to the substitution from

[19] Income sources include agricultural production, off-farm wages and diverse subsidies.

[20] The agricultural specialization results from the Household Responsibility System (HRS) introduced at the early stage of China's rural reform since 1978. The implementation of the HRS implies the conversion of collective farming system into decentralized decision-making by peasant households (Kueh 1984) through contracting with individual households (Krusekopf 2002).

[21] The community is considered to be near the economic open area, if it takes less than 2 hours by bus to cover the distance.

wood/straw to cleaner fuels since wood/straw as by-products of agricultural activity are plentifully available. In contrary, off-farm employment participation is expected to induce a shift from wood/straw towards commercial fuels due to a loss of labor available for on-farm production and firewood collection. The variables describing rural economic development serve as proxies for easy access to modern clean fuels.[22] They are thus expected to induce a shift from dirty towards clean fuel demand. The geographic locations also help us to control for differences in energy resource endowments and degree of development across regions.[23]

The other predetermined food-consumption variables (Ω) are represented by access to telephone and bus services that reflect rural public infrastructure. The advance in communication and transportation infrastructure could mitigate transaction costs and hence facilitate farmers to participate in food crops markets. The increased income generated by the commercialization of self-produced food products may induce rural households to prefer commercial fuels.

3.3 Estimation Methods

We first adopt the REPL model, never previously used in this line of research. The panel data model allows us to control for unobserved individual heterogeneity and investigate the dynamic changes in fuel use. Then, we apply the static MNL model in order to compare with prior studies and to better separate the different fuels.

The econometric models can be derived from our theoretical model. Households are assumed to choose the fuel types that maximize their indirect utility $V(p^h, p^p, p^{dc}, p^{cl}, p^{ce}, Y, Z, \Omega, V, \phi)$. Let $j = (1,...m..., J)$ be the indices of alternative fuel choices, and $i = (1,...n..., I)$ be the household indices. Then the household n 's indirect utility function is specified of the random form: $V_{nj} = \beta_j x_n + \varepsilon_{nj}$, where x_n represents exogenous variables for household n, β_j is the vector of coefficients to be estimated and ε_{nj} denotes a stochastic error

[22] We do not consider the effect of distance to the closest free market where buying commercial fuels because the data on this is not available in the 2006 wave.
[23] Southwest region includes Guizhou province. East region includes Jiangsu and Shandong provinces. Central region includes Henan, Hubei, Hunan and Guangxi provinces. Northeast region includes Liaoning and Heilongjiang provinces. The Southwest region is taken as the reference.

assumed to follow a Gumbel-type distribution. The REPL and MNL models can be derived from the random indirect utility function.

3.3.1 Panel logit model with random effects

Household n will choose outcome m if its utility of choosing this outcome is larger than its utility of choosing any of the other alternatives. The logit choice probability is $\Pr(y_{nm} = m \mid x_n) = \frac{\exp(\beta_m x_n)}{\sum_j \exp(\beta_j x_n)}$.

Given the dependent variable y_{it} as a dichotomous outcome variable, the corresponding latent variable specification $(y_{it} = 1_{[y_{it}^* > 0]})$, is of the form:

$$y_{it}^* = X_{it}\,\eta + H_i\,\gamma + W_{it}\,\delta + c_i + u_{it}\,, \tag{9}$$

where i is the household index and t is the period index. Variable y_{it}^* denotes the unobserved propensity to use modern fuels in household i at time t. X_{it} represents time-varying fuel prices, food prices and household income. H_i is a set of time invariant variables in terms of geographic location. W_{it} is a vector of other time-varying factors at household and community levels, which includes household characteristics affecting preferences (Z), household land and livestock endowments (ϕ), predetermined variables relating to local fuel supply conditions (V) and predetermined food-consumption variables (Ω).

To investigate medium-term effect of explanatory variables, we also include the one-period lag of variable Cook, which represents whether the household head prepared food in the previous period. We have also examined the lagged effects of other explanatory variables, such as, food prices, fuel prices. However, they are generally statistically insignificant, so we drop them from the reported specification. The random variable c_i captures the unobserved household-specific and time-invariant variables. This term is assumed to be uncorrelated with the observed explanatory variables. Variable u_{it} is a logistic error term that is uncorrelated with c_i. The variables c_i and u_{it} have means zero and variances of σ_c^2 and σ_u^2, respectively. The coefficient vectors η, γ, δ, θ_0 and θ_1 need to be estimated.

3.3.2 Multinomial logit model

The choice probability is: $\Pr(y_{nm} = m \mid x_n) = \dfrac{\exp(\beta_m x_n)}{1 + \sum_{j=2}^{J} \exp(\beta_j x_n)}$. Then, the log-odds ratios of outcome m vs. outcome j are defined as: $\ln\left(\dfrac{\Pr_{nm}}{\Pr_{nj}}\right) = \beta_m x_n$, where $\Pr_{nj}$ is the probability of household n choosing outcome j.

3.4 The results

We start with a discussion of the estimated marginal effects for the primary cooking fuel choice (Table 5). Then, we turn to deal with the estimated marginal effects for the primary-secondary cooking fuel choices (Table 6). Table 5 reports that the majority of variables have significant effects. In the REPL model, about one third (0.325) of the variance of errors in the latent model is due to the unobserved individual heterogeneity represented by the random individual effects. This result indicates that accounting for such unobserved heterogeneity is essential. Clearly, availing of panel data much contributes to the determination of the effects of regressors in this model. In the MNL model, Mc Fadden's pseudo-R^2 equal to 28.4 % indicates a substantial explaining power of the model, even without capturing unobserved heterogeneity.

3.4.1 Determinants of primary cooking fuel choice

(a) Fuel price effects

Coal prices have a significant impact on all alternatives, except for electricity in the MNL model. As expected, an increase in coal price decreases the probability of choosing coal, which is in line with Gupta and Köhlin's (2006) evidence from India. This result provides an insight that getting the coal price right (removing subsidies, reflecting production cost and internalizing externalities) is responsible for adjusting the coal-dominant energy structure. Moreover, an increase in coal price augments wood/straw adoption probability. This seems to indicate that wood/straw and coal are (uncompensated) substitutes, which makes sense since they can be burned in the same type of furnace. It is consistent with Peng et al.'s (2010) finding that an increase in coal price motivates rural households to choose biomass in Hubei province of China. However, it contradicts Gupta and Köhlin's (2006) result that fuelwood and coal are complements for Indian urban households, perhaps because of different contexts. The sign of the coal price coefficient also implies that coal and LNG are complements since the probability of choosing LNG decreases as the coal price rises. Reduction in LNG supply may be one explanation for the observed result. The increased coal price together with price controls on LNG give less incentives to refineries to produce more LNG in order to cope with the gas shortages appeared in the early 2000s. Thus, the combination of the substitutable and complementary relationships of coal with wood/straw and LNG respectively in the MNL model, may explain the effect of coal price in the REPL model indicating that an increase in coal price decreases the clean-fuel adoption probability.

As expected, the electricity adoption negatively responds to an increase in the electricity price in the MNL model. This result supports the conventional wisdom in literature that the demand of electricity is sensitive to its own price (e.g., An et al. 2002; Gundimeda and Köhlin 2008). In addition, the estimates on the electricity price from the MNL model again suggest that electricity and coal are substitutable, whereas electricity and wood/straw are complementary. These results may be attributed to the widely varying quality of coal and wood/straw used in Chinese rural households. For example, hard coal, which burns longer with high heat content but low pollutant content, may be considered as a desirable fuel. Such complementary relationship is contrary to the evidence from other developing countries suggesting that electricity and wood are substitutable (See Edwards and Langpap 2005; Gundimeda and Köhlin 2008; Kebede et al. 2002). Taken together, the substitution effect of electricity with coal, combined with the negative response of electricity adoption to its own price, is consistent with the impact of electricity price observed in the REPL model where the probability of choosing clean fuel decreases with increasing electricity price.

Likewise, the positive and significant effect of LNG price on households' willingness to choose clean fuel in the REPL model, can be attributed to the substitutability of LNG with electricity and wood/straw, respectively, and the complementarity of LNG with coal in the MNL model. The substitutable relationship between LNG and electricity is consistent with Gundimeda and Köhlin's (2008) result for India, whereas it is contrary to Filippini and Pachauri's (2004) study for the same country. The substitutable relationship between LNG and wood/straw is supported by Gundimeda and Köhlin's (2008) study, whereas it is challenged by Akpalu et al.'s (2011) work for Ghana. However, the effect of LNG price is insignificant for the LNG choice in the MNL model. A possible explanation for this insignificant response may lie in the non-price factors, such as, occasional shortages of LNG, long distance to retailers and high cost of appliances.[24]

(b) Other price effects

The effects of food prices are highly significant in both REPL and MNL models. These findings reveal the perception that food prices can play a major role in fuel choices. This is, to the best of our knowledge, the first time that such effect has been exhibited in the literature.

Although the self-produced or purchased food items cannot be distinguished from the survey, the signs of estimated effects may imply different roles of self-produced vs. purchased food prices in fuel choice. In general, an increase in the price of self-produced food should raise farm income since rural households produce more food than they consume and sell the surplus in the market. This positive income effect, therefore, may generate in a rise of the willingness to switch to clean fuels. In contrast, an increase in the price of purchased food may force rural households to compromise with fuel consumption and additionally to choose cheaper dirty fuels in order to meet their food needs, due to a negative income effect.

For instance, an increase in pork price of 1 % implies a rise of the clean-fuel adoption probability by 0.08 % in the REPL model. This result is confirmed by the estimates of the MNL model showing that an increase in pork price encourages rural households to shift away from coal towards LNG and electricity. These findings could be explained by the fact that pigs are generally raised in Chinese rural households for home food and sale. An increase in pork price may raise household

[24] The piped gas is generally not available in rural areas (Pachauri and Jiang 2008) and the required distribution network for LNG is still lacking especially in remote rural areas, which may result in large distances from homes to retailers and uncertainties in delivery frequency.

cash income through the sales of pigs, which may further motivate the households to shift towards clean fuels. Besides, the estimates of the MNL model indicate that an increase in pork price generates a rise in wood/straw adoption. Indeed, grain-based feeds (e.g., wheat bran) are commonly used for pigs in pork-producing households and subsequently crop residues (e.g., wheat straw) are chosen as cooking fuels. Here, we have exhibited a mechanism that intimately connects production and consumption decisions for explaining rural households' fuel use. This kind of fundamental interactions has been much neglected in the econometric literature on the subject, although it has many significant consequences for policy.

Pork will remain the dominant meat consumed in China. To meet the sharp rise in port demand as a result of growing income and urbanization, the government has provided subsidies aimed at promoting a shift away from small-scale pig farming towards large-scale commercial pig production. These changes may generate increasing volatility of pork prices, which, in turn, may complicate the rural household energy transition.

(c) Income variables

Increased household income exerts a robust positive influence on the choice of clean fuel. This result confirms the consensus of previous studies in favor of a positive relationship between income and clean-fuel demand.[25] Similarly, the exogenous income from electricity or one-child subsidy significantly affects fuel choice.[26] The electricity subsidy fosters the households to demand electricity, which is consistency with the sensitivity of rural households to the electricity price. The one-child subsidy also induces households to choose electricity. This may result from two causes. First, one-child families do not consider that firewood has a low opportunity cost because they may need additional adult labor collecting firewood at the expense of on- and off-farm work time. Second, one-child families are often entitled to other subsidies, such as, extra food rations, health subsidies and allotments of farmland (Bredenkamp 2009). These allowances may reduce economic burden and relax liquidity constraints, and thereby help the families to

[25] See An et al. 2002; Farsi et al. 2007; Gupta and Köhlin 2006

[26] We drop the estimated effects of coal subsidy and gas subsidy because they are always insignificant and badly determined.

afford electricity through the interplay of consumption income effects.

(d) Preference characteristics

Most household characteristics pertaining to preferences included in the regressions play a significant role in explaining fuel choices. Older household heads are more likely to choose wood/straw and coal, while less likely to choose LNG and electricity.[27] These results are at odds with the findings reported by Farsi et al. (2007) and Gupta and Köhlin (2006) that older household heads are more likely to prefer LNG to wood in India. Our results, however, may be attributed to the fact that older people used to use traditional dirty fuels when they grew up. Male-headed households prefer wood/straw, which is coherent with Rao and Reddy's (2007) finding for India that households where women are more empowered opt for clean fuels. The education level of the household head has a significant positive impact on clean-fuel choice in the REPL model, which confirms the previous evidence regarding the positive association between education level and clean-fuel use. The increasing opportunity costs of firewood collection and the advantage of modern clean fuels in terms of time-savings could serve as reasons of this association (Heltberg 2004).

Two original lifestyle measures yield interesting results. First, household heads living with parents prefer to choose dirty fuel in the REPL model. The intergenerational transmission of parents' traditional-fuel preferences to the young generation may explain this result. Second, household heads participating in cooking opt for LNG in the MNL model. Indeed, most surveyed households are headed by males who are also the main household breadwinner. The comparably higher opportunity cost of cooking time may explain the choice of efficient and time-saving fuel type.

Household dwelling characteristics represented by toilet location and lighting source, as expected, condition the fuel choice. On the contrary, the effect of house ownership is insignificant in the regressions. This finding is consistent with Ouedraogo's (2006) evidence from Burkina Faso, while it contrasts to Arthur et al.'s (2010) result of a positive relationship between self-owned dwelling and clean-fuel

[27] The coefficient of age squared of household head is statistically insignificant, so we drop this variable from the regression.

use in Mozambique households.

Household size exhibits a significant positive effect on the choice of wood/straw.[28] This finding may be attributed to the fact that larger households have more labor available for firewood collection and agricultural production, which translates into low opportunity costs of collecting firewood and preparing crop residues (Heltberg et al. 2000; Heltberg 2005).

(e) Technology variable

Household agricultural specialization, as a measure of farm characteristics relevant to production decisions, is found to positively and significantly affect the choice of dirty fuels in the REPL model. This result relates to the fact that households oriented towards agricultural specialization are generally large-scale producers of agricultural products and thereby they may have abundant crop residues. The preference of coal may be attributed to the fact that coal can also be burned in the biomass-fed boilers.[29] Meanwhile, the large-scale and specialized agricultural farms need more on-farm labor for generating income, which implies higher opportunity costs of firewood collection. The households may thus shift away from firewood through reducing collection time in response to the increased opportunity costs.[30] The opposing impacts of household agricultural specialization on the availability of crop residues and on the collection of firewood may explain the insignificant effect of this variable on the choice of wood/straw in the MNL model.[31] This is another piece of convincing evidence demonstrating that farm households' fuel demand is interlinked with their food and fuel production decisions.

(f) Fuel supply variables

The majority of community-level variables relating to fuel supply included in the

[28] Other tried variables for household composition have insignificant coefficients.
[29] Because rural households prefer the fuel type that is compatible with their existing energy service equipment (Kowsari and Zerriffi 2011).
[30] Heltberg et al.'s (2000) evidence from India shows that larger landholders reduce the supply of firewood and collection labor time.
[31] Démurger and Fournier's (2011) evidence from China indicates that the size of landholding is associated with a significant increase in firewood consumption, while the number of livestock is associated with a significant reduction in firewood consumption.

regressions significantly affect the fuel choice. The three variables describing rural economic development yield the expected results, showing rural household fuel transition to clean types in response to easier access to reliable commercial clean fuels. On the opposite, the plentiful availability of traditional biomass, resulting from a larger proportion of agricultural workforces, induces a preference for wood/straw.

Noteworthily, the results provide additional evidence regarding the impacts of off-farm employment participation on rural households' fuel choice, which is a relatively unexplored area. The presence of local collective enterprise is found to induce a shift from wood/straw and coal towards LNG and electricity in the MNL model. Moving away from wood/straw is probably due to the fact that off-farm employment provided by local collective enterprise could absorb a large share of rural labor force, which further results in a loss of labor available for on-farm production and firewood collection. The preferences for LNG and electricity may stem from the fact that clean fuels are considered as normal goods with the increased income level from off-farm employment. Likewise, proximity to economic open area, included as a measure of increased off-farm employment opportunities, is negatively associated with the choice of wood/straw while positively associated with the choice of commercial fuels in the MNL model. Albeit positive, the associations of this variable with the demand of LNG and electricity are not significant. A possible explanation for the insignificance may lie in the high concentration of labor-intensive manufacturing industries in the economic open area that limits the availability of these clean fuels.[32] Contrary to expectations, an increase in the local proportion of migrants in 2004 is positively associated with wood/straw choice in the MNL model. A plausible explanation for this unexpected result could stem from the fact that if there is constraint on access to commercial fuels, farm households may consider biomass as a normal good and increase their biomass consumption when their income from off-farm employment rises (Shi et al. 2009).[33]

[32] The industrial sectors represent a vast potential for electricity consumption. Besides, the large number of migrants may increase the demand of clean fuels because the migrants prefer convenient and time-saving cooking technologies in response to their fast-paced lifestyle and they are eager to pursue modern lifestyle (Gu et al. 2007).

[33] In recent years, China has often faced energy supply shortages. Especially, in 2004 China experienced a severe nationwide power shortage and power breakout covering 24 provinces (Wang et al. 2009). The widespread power shortage may limit not only the supply of electricity, but also the

(g) Food consumption variables

Finally, access to telephone and bus services, as expected, seem to foster rural households to allocate their income to the consumption of commercial fuels. These services may reduce the costs of accessing food markets associated with imperfect information and transportation and, as a consequence, help farmers to sell their self-produced food products and to access to a wide range of food commodities. The incremental earnings induced by agricultural crop sales may enhance the households' ability to afford the commercial fuels in addition to market purchased food.

3.4.2 Determinants of primary-secondary cooking fuel choices

We now turn to the determinants of primary-secondary fuel choices. The results presented in Table 6 show that most of the variables affecting primary cooking fuel choice also matter for primary-secondary fuel choices. To save space, we do not discuss the detailed results. The main purpose of this sub-section is to mention useful complementary information as follows.

First, the estimates of the MNL model in Table 6 report stronger effects of household income and local average income on partial switching (0.031% and 0.079%) than those on full switching (0.025% and 0.045%). These results provide evidence in Chinese context to support the critique of the energy ladder model that rural household fuel transition driven by increasing income is generally characterized as a combination of modern and traditional fuels rather than a ladder of fuel preferences (Davis 1998; Heltberg 2004; Masera et al. 2000).[34] Second, the extent of the fuel adoption probability caused by the variation in fuel price, in the REPL model for primary-secondary fuel combination presented in Table 6, is generally smaller, though not substantially, than that in the REPL model for primary cooking fuel choices showed in Table 5. These findings provide, to our knowledge, the first empirical estimates in support of the common notion that diversifying fuel

availability of coal and LNG in rural areas, because more coal and natural gas are needed to generate electricity.

[34] Davis (1998); Heltberg (2004) and Masera et al. (2000).

use can help rural households to reduce their sensitivity to the fuel price fluctuations (Kowsari and Zerriffi 2011; Masera et al. 2000).

4. Conclusion

We have studied the determinants of fuel choice and fuel switching in rural China. We first develop a non-separable farm household model for fuel demands. Then, we use a large micro-household panel dataset to estimate discrete choice models of fuel uses.

The estimates support the theoretical model indicating that the fuel demands depends not only on income, fuel prices and demand-side socioeconomic factors, as would appear in standard demand models, but also on agricultural production characteristics, food prices, and a set of original household and community characteristics shaping the household responses to market failures. Our estimates provide evidence in Chinese context to support the critique of the energy ladder model arguing that rural households often adopt a mix of modern and traditional fuels instead of moving up a ladder of fuel preferences as their income rises. Our estimates contribute to the ongoing discussion on fuel price effects by showing robust results about the cross-price effects and providing the first evidence on the extent of price sensitivity in case of fuel stacking. Our estimates confirm previous studies by exhibiting the indispensable role of production characteristics in affecting farm households' fuel demand. Our estimates add new evidence regarding the potential role of off-farm work in fuel choice, which should but has not received much attention in the literature (Shi et al. 2009). In particular, our estimates provide the first empirical evidence indicating that food prices exert crucial effects on the fuel transition of rural households.

Our findings are relevant to policy making for accelerating the fuel transition of rural households to clean fuels. First, our estimates suggest that policy interventions, exclusively guided by the energy ladder —— a stylized extension of consumer economic theory (Hosier and Dowd 1987), may bring about partial switching.

Second, our results advise that the design of policies should consider the complex non-separable decision behavior of rural households in a context of imperfect markets. Our study shows that rural households' behavior in fuel use should be understood in the non-separable farm household model under the presence of market failures for fuels, agricultural food and labor. The response of rural households to exogenous policy changes, in the non-separable model, is subject to the failing markets. Therefore, the effective policies need to account for the potential response of rural households exposed to the context-specific market imperfections. From this perspective, the failure of policy efforts directed at promoting the diffusion of biogas in rural areas could be partly explained. In the early of 2000s, the central government has formulated a series of policies to provide financial support for the construction of household-scale biogas digesters. However, these policies have not adjusted to local agricultural circumstances and labor market imperfections. Although agricultural structure has been changing from smallholders to intensive farms, the government has primarily focused on the construction of small biogas digesters that have relatively inefficient operation. The increased off-farm employment opportunities induce agricultural labor to participate in local off-farm work or migrate to cities. Rural households, thus, reduce or even abandon their agricultural production activities in response to the loss of labor, which further leads to a lack of raw materials (e.g., crop straws, livestock manure) for running biogas digesters. Despite this, the government has not paid sufficient attention to establish professional teams in order to make up for the manpower shortage and to provide efficient follow-up services for the stable operation of biogas digesters.

Third, policymakers should give high priority to the issues on rural energy pricing reforms. Our analysis demonstrates that electricity demand is responsive to its own price and to electricity subsidies. This reveals that policy interventions addressing unaffordable electricity prices are crucial for the energy transition of rural households. However, the early policy efforts, aimed at rural electrification, have ignored that the affordability of electricity is of vital importance. Our analysis also shows the importance of cross-price effects in explaining the pattern of fuel use in rural households. This implies that further reforming efforts are required to link the pricing mechanism of one energy type with the market prices of the alternatives, in order to promote the substitution between commercial fuels. The substitution effects are, however, complicated by the rather low opportunity cost of traditional biomass, since the latter may delay the price-induced upward energy transition. Under this circumstance, the market-based pricing policies need to be coupled with the policy interventions aimed at increasing the opportunity cost (e.g., improving education level and creating local off-farm jobs).

Finally, our results suggest that the rural energy policy is not independent from; instead, it should be integrated into food policy. Our research shows the effects of food prices on the fuel use in rural households where the decisions relating to the production and consumption of food and fuel are made simultaneously. This implies that energy pricing policies should give consideration not only to the price changes in alternative energy types, but also to the price changes in food products as well as the complex substitutions/complementarities among energy sources and between energy and food.

Given that China has made substantial progress in the deployment of new technologies (e.g., biomass gasification) and the dissemination of renewable energies (e.g., biofuel), future research should reveal whether new technologies and renewable energies exert influence on the energy transition of rural households. Given that China has committed to fight against global climate change, future research should consider which policies directed at promoting rural household energy transition are more effective for reducing carbon emissions.

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Table 1 Percentage of rural households by primary and secondary types of cooking fuel

Fuel type	Year of survey		
	2000	2004	2006
Wood/straw			
Primary	38.16	33.77	28.57
Secondary	23.30	25.78	23.69
Coal			
Primary	33.84	35.60	29.91
Secondary	29.03	16.16	14.26
Liquefied natural gas			
Primary	22.18	22.61	22.00
Secondary	29.59	32.55	28.48
Electricity			
Primary	3.55	5.62	15.24
Secondary	16.11	23.49	29.80

Table 2 Percentage of rural households by pattern of cooking fuel use

Pattern of fuel use	Year of survey		
	2000	2004	2006
Wood/straw-only	14.05	10.92	7.19
Coal-only	21.05	13.38	9.20
Mixed wood/straw-coal	17.90	17.37	12.54
Mixed wood/straw (primary)-liquefied natural gas (secondary)	11.59	11.62	10.17
Mixed wood/straw (primary)-electricity (secondary)	2.74	4.62	6.50
Mixed coal (primary)-liquefied natural gas (secondary)	4.72	9.52	8.16
Mixed coal (primary)-electricity (secondary)	1.56	3.64	6.90
Mixed liquefied natural gas (primary) - wood/straw (secondary)	6.10	6.16	5.68
Mixed liquefied natural gas (primary) - coal (secondary)	5.38	3.05	3.13
Mixed electricity (primary) - wood/straw (secondary)	0.69	2.21	7.11
Mixed electricity (primary) - coal (secondary)	0.94	0.49	2.01
Mixed liquefied natural gas- electricity	7.32	11.55	15.92
Liquefied natural gas-only	5.83	5.36	4.74
Electricity-only	0.14	0.11	0.75

Table 3 Percentage of rural households by fuel combination and fuel switching

	Fuel combination		**Fuel switching**		
	Dirty-fuel dominance	Clean-fuel dominance	No switching	Partial switching	Full switching
2000	73.60	26.40	53.00	33.71	13.28
2004	71.08	28.92	41.67	41.32	17.02
2006	60.65	39.35	28.93	49.66	21.42

1) 'Dirty-fuel dominance' = only dirty fuel (wood/straw or coal) is used or dirty fuel primarily used is in combination with clean fuel (liquefied natural gas or electricity) secondarily used as the main fuel(s) by rural household.
2) 'Clean-fuel dominance' = only clean fuel (liquefied natural gas or electricity) is used or clean

fuel primarily used is in combination with dirty fuel (wood/straw or coal) secondarily used as the main fuel(s) by rural household.

Table 4 Description of explanatory variables

Variable	**Definition**	**Number of observations**	**Mean (standard deviation)**
Coal price (ln)	Price of honey-combed briquette per piece	6954	-1.414 (0.451)
LNG price (ln)	Price of liquefied natural gas per tank	8748	4.176 (0.246)
Electricity price (ln)	Price of electricity per kWh	8849	-0.562 (0.249)
Rice price (ln)	Price of rice most commonly eaten per jin in free market	8875	0.130 (0.274)
Cabbage price (ln)	Price of Cabbage per jin in free market	9015	-0.803 (0.707)
Pork price (ln)	Price of lean pork per jin in free market	8808	2.021 (0.249)
Beef price (ln)	Price of beef per jin in free market	8991	2.104 (0.318)
Mutton price (ln)	Price of mutton per jin in free market	9015	2.276 (0.405)
Unbleached flour price (ln)	Price of Unbleached flour per jin in free market	8460	0.115 (0.331)
HH income (ln)	Household total annual net income inflated to 2006	8723	9.343 (1.077)
One-child subsidy	1 if household receives one-child subsidy, 0 otherwise	9015	0.028 (0.164)
Electricity subsidy	1 if household receives electricity subsidy, 0 otherwise	9015	0.008 (0.090)
Household preferences (Z)			
Age (HH head)	Age of household head in years	8265	51.538 (12.652)
Gender (HH head)	1 if household head is male, 0 otherwise	8265	0.873 (0.332)
High education (HH head)	1 if household head’s highest education is over upper middle school level, 0 otherwise	9015	0.037 (0.189)
Public sector (HH head)	1 if household head’s primary occupation is in public sector, 0 otherwise	9015	0.317 (0.465)
Married (HH head)	1 if household head’s marital status is married, 0 otherwise	9015	0.790 (0.408)
Parent-home (HH head)	1 if household head’s mother or father lives in the household, 0 otherwise	9015	0.047 (0.212)
Cook (HH head)	1 if household head prepared food last week, 0 otherwise	9015	0.328 (0.470)
Lagged Cook (HH head)	1 if household head prepared food last week in the last survey year, 0 otherwise	9015	0.266 (0.442)
HH size	Number of household members	9000	3.622 (1.474)
House-owner	1 if household is the owner of dwelling, 0 otherwise	9006	0.944 (0.230)

Modern roof	1 if roof made from tile or concrete, 0 otherwise	9006	0.174 (0.379)
Modern wall	1 if wall made from brick or concrete, 0 otherwise	9006	0.172 (0.377)
Electric lighting	1 if household normally uses electricity for lighting, 0 otherwise	9006	0.986 (0.118)
Toilet type			
No toilet	There is no toilet in household	9006	0.018 (0.132)
Out-house toilet	Toilet is out of house	9006	0.700 (0.458)
In-house toilet (reference)	Toilet is in house	9006	0.265 (0.442)
Household endowments (ϕ)			
Agricultural specialization	1 if household is specialized in farming or gardening or livestock activity, 0 otherwise	9015	0.089 (0.284)
Fuel supply (V)			
Suburban/ village	1 if current administrative district belongs to suburban neighborhood or rural village, 0 if current administrative district belongs to town neighborhood or city neighborhood	9015	0.900 (0.299)
Population (ln)	Total population in community	8952	7.548 (0.810)
Community income (ln)	Average income per person measured in yuan in community	8455	7.647 (0.611)
Economic open area	1 if community near open trade area or open city or special economic zone, 0 otherwise	8892	0.415 (0.493)
Local enterprise	1 if there is collective enterprise run by village or neighbourhood in community, 0 otherwise	8839	0.233 (0.423)
% agricultural activity	Proportion of work force engaged in agricultural activity in community	8718	50.880 (28.985)
% migrants* Year 2000	Interaction between proportion of work force working outside town more than one month and dummy year 2000	8697	9.120 (18.263)
% migrants * Year 2004	Interaction between proportion of work force working outside town more than one month and dummy year 2004	8697	9.948 (20.028)
% migrants * Year 2006 (reference)	Interaction between proportion of work force working outside town more than one month and dummy year 2006	8697	10.426 (19.606)
Northeast region	1 if household lives in Northeast region, 0 otherwise	9015	0.221 (0.415)
Central region	1 if household lives in Central region, 0 otherwise	9015	0.444 (0.497)
East region	1 if household lives in East region, 0 otherwise	9015	0.218 (0.413)
Southwest region (reference)	1 if household lives in Southwest region, 0 otherwise	9015	0.116 (0.321)
Food consumption (Ω)			
Telephone service	1 if telephone service is available in	8954	0.875

	community, 0 otherwise		(0.330)
Bus stop	1 if there is bus stop in community, 0 otherwise	8929	0.620 (0.485)
Year 2000	1 if it is in 2000, 0 otherwise	9015	0.332 (0.471)
Year 2004	1 if it is in 2004, 0 otherwise	9015	0.332 (0.471)
Year 2006 (reference)	1 if it is in 2004, 0 otherwise	9015	0.336 (0.472)

1) jin= half a kilo

Table 5 Marginal effects of RE-logit and multinomial logit models for the primary cooking fuel choice

Independent variables	**RE-logit**	**Multinomial logit**			
	Clean choice	Wood/straw	Coal	LNG	Electricity
Coal price (ln)	-0.047***	0.121***	-0.077***	-0.030**	-0.013
	(0.003)	(0.000)	(0.000)	(0.030)	(0.212)
LNG price (ln)	0.154***	0.237***	-0.439***	0.041	0.160***
	(0.003)	(0.000)	(0.000)	(0.325)	(0.000)
Electricity price (ln)	-0.098***	-0.142***	0.227***	-0.013	-0.073***
	(0.004)	(0.000)	(0.000)	(0.639)	(0.003)
Rice price (ln)	-0.173***	-0.124***	0.295***	-0.121***	-0.051**
	(0.000)	(0.000)	(0.000)	(0.000)	(0.044)
Cabbage price (ln)	-0.048***	-0.029***	0.077***	-0.034***	-0.013*
	(0.000)	(0.014)	(0.000)	(0.000)	(0.076)
Pork price (ln)	0.084**	0.275***	-0.394***	0.055*	0.065**
	(0.034)	(0.000)	(0.000)	(0.100)	(0.016)
Beef price (ln)	0.091***	-0.013	-0.066***	0.092***	-0.012
	(0.001)	(0.625)	(0.013)	(0.000)	(0.509)
Mutton price (ln)	-0.061***	0.058***	-0.024	-0.054***	0.020
	(0.001)	(0.002)	(0.186)	(0.000)	(0.106)
Unbleached flour price (ln)	0.151***	0.016	-0.162***	0.111***	0.035**
	(0.000)	(0.572)	(0.000)	(0.000)	(0.050)
HH income (ln)	0.057***	-0.056***	-0.001	0.049***	0.008*
	(0.000)	(0.000)	(0.881)	(0.000)	(0.060)
One-child subsidy	0.064*	-0.046	-0.008	-0.024	0.078***
	(0.066)	(0.293)	(0.872)	(0.355)	(0.001)
Electricity subsidy	0.166***	-0.244**	0.057	0.044	0.143***
	(0.003)	(0.023)	(0.453)	(0.371)	(0.000)
Household preferences (Z)					
Age (HH head)	-0.003***	0.002***	0.0003	-0.002***	-0.001***
	(0.000)	(0.000)	(0.525)	(0.000)	(0.010)
Gender (HH head)	-0.016	0.072***	-0.064***	-0.028*	0.020
	(0.468)	(0.002)	(0.003)	(0.098)	(0.165)
High education (HH head)	0.075**	-0.069	0.012	0.025	0.033*
	(0.049)	(0.150)	(0.788)	(0.387)	(0.092)
Public sector (HH head)	-0.003	-0.010	-0.002	-0.003	0.016
	(0.891)	(0.632)	(0.910)	(0.852)	(0.215)
Married (HH head)	-0.005	-0.022	0.030	0.008	-0.016
	(0.815)	(0.286)	(0.132)	(0.654)	(0.262)
Parent-home (HH head)	-0.052*	0.031	0.024	-0.032	-0.023
	(0.074)	(0.251)	(0.374)	(0.170)	(0.221)
Cook (HH head)	0.030**	0.017	-0.048***	0.024**	0.007

	(0.033)	(0.239)	(0.001)	(0.036)	(0.415)
Lagged Cook (HH head)	0.045***	0.006	-0.045***	0.032***	0.007
	(0.001)	(0.669)	(0.002)	(0.005)	(0.416)
HH size	-0.009**	0.011**	-0.003	-0.008**	-0.0005
	(0.042)	(0.015)	(0.528)	(0.045)	(0.865)
House-owner	-0.016	0.040	-0.018	0.002	-0.025
	(0.574)	(0.210)	(0.544)	(0.930)	(0.136)
Modern roof	0.038	0.010	0.0002	-0.032	0.021
	(0.468)	(0.842)	(0.996)	(0.509)	(0.467)
Modern wall	-0.014	-0.052	0.017	0.032	0.003
	(0.789)	(0.322)	(0.715)	(0.514)	(0.924)
Electric lighting	0.087	-0.164***	0.122*	0.022	0.021
	(0.180)	(0.003)	(0.062)	(0.681)	(0.680)
No toilet	-0.252***	0.156***	0.099**	-0.082**	-0.173***
	(0.000)	(0.001)	(0.046)	(0.047)	(0.010)
Out-house toilet	-0.155***	0.137***	-0.002	-0.120***	-0.015
	(0.000)	(0.000)	(0.901)	(0.000)	(0.113)
Household endowments (ϕ)					
Agricultural specialization	-0.067***	0.029	0.044*	-0.058***	-0.015
	(0.006)	(0.229)	(0.065)	(0.010)	(0.294)
Fuel supply (V)					
Suburban/ village	-0.118***	0.212***	-0.084**	-0.071**	-0.057**
	(0.002)	(0.000)	(0.046)	(0.018)	(0.021)
Population (ln)	0.058***	0.037***	-0.095***	0.032***	0.025***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Community income (ln)	0.062***	-0.053***	-0.009	0.073***	-0.011
	(0.000)	(0.000)	(0.473)	(0.000)	(0.202)
Economic open area	0.012	-0.059***	0.050***	0.001	0.008
	(0.380)	(0.000)	(0.000)	(0.923)	(0.343)
Local enterprise	0.071***	-0.023	-0.036**	0.036***	0.023**
	(0.000)	(0.141)	(0.019)	(0.002)	(0.020)
% agricultural activity	-0.001***	0.001***	-0.0003	-0.001***	-0.0003*
	(0.000)	(0.000)	(0.290)	(0.000)	(0.056)
% migrants* Year 2000	0.001***	0.001	-0.002***	0.001***	-0.001
	(0.008)	(0.151)	(0.004)	(0.001)	(0.333)
% migrants* Year 2004	-0.001**	0.002***	-0.0004	-0.001**	-0.001*
	(0.024)	(0.000)	(0.342)	(0.039)	(0.090)
Northeast region	0.367***	0.279***	-0.608***	0.238***	0.091***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Central region	0.087***	0.263***	-0.357***	0.167***	-0.073***
	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
East region	0.158***	0.504***	-0.664***	0.243***	-0.083***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Food consumption (Ω)					
Telephone service	0.046*	-0.152***	0.083***	0.111***	-0.041***
	(0.068)	(0.000)	(0.000)	(0.000)	(0.003)
Bus stop	0.050***	0.006	-0.047***	0.056***	-0.014*
	(0.000)	(0.655)	(0.000)	(0.000)	(0.089)
Year 2000	-0.120***	0.240***	-0.171***	-0.033	-0.037
	(0.002)	(0.000)	(0.000)	(0.312)	(0.192)
Year 2004	-0.065***	-0.051*	0.085***	0.009	-0.044**
	(0.010)	(0.057)	(0.001)	(0.668)	(0.018)
Observations	4669				4669
Rho	0.325				

LR-test χ^2_{129} (P-value)	3334.17 (0.0000)
Mc Fadden pseudo-R^2	0.284

1) The estimated marginal effects of explanatory variables are reported. P-values are presented in parentheses.
2) Clean choice is defined as 1 if LNG or electricity is chosen, and it is 0 if wood/straw or coal is chosen.
3) * Significance levels of 10%, ** Significance levels of 5%, *** Significance levels of 1%.

Table 6 Marginal effects of RE-logit and multinomial logit models for fuel combination and fuel switching

Independent variables	RE-logit	Multinomial logit		
	Clean-fuel dominance	No switching	Partial switching	Full switching
Coal price (ln)	-0.045***	0.059***	-0.028	-0.031***
	(0.005)	(0.001)	(0.143)	(0.008)
LNG price (ln)	0.149***	-0.189***	0.091	0.098***
	(0.004)	(0.000)	(0.106)	(0.005)
Electricity price (ln)	-0.080**	0.116***	-0.146***	0.031
	(0.022)	(0.001)	(0.000)	(0.189)
Rice price (ln)	-0.175***	0.128***	-0.099***	-0.030
	(0.000)	(0.000)	(0.013)	(0.288)
Cabbage price (ln)	-0.047***	-0.020*	0.059***	-0.039***
	(0.000)	(0.092)	(0.000)	(0.000)
Pork price (ln)	0.097**	-0.120***	-0.003	0.124***
	(0.015)	(0.002)	(0.938)	(0.000)
Beef price (ln)	0.088***	-0.097***	0.087***	0.010
	(0.001)	(0.000)	(0.004)	(0.609)
Mutton price (ln)	-0.059***	0.023	0.035*	-0.058***
	(0.001)	(0.215)	(0.095)	(0.000)
Unbleached flour price (ln)	0.144***	-0.125***	0.045	0.080***
	(0.000)	(0.000)	(0.136)	(0.000)
HH income (ln)	0.059***	-0.056***	0.031***	0.025***
	(0.000)	(0.000)	(0.000)	(0.000)
One-child subsidy	0.061*	-0.056	0.070	-0.014
	(0.079)	(0.223)	(0.131)	(0.546)
Electricity subsidy	0.163***	-0.095	0.013	0.081***
	(0.004)	(0.213)	(0.864)	(0.014)
Household preferences (Z)				
Age (HH head)	-0.003***	0.004***	-0.002***	-0.002***
	(0.000)	(0.000)	(0.003)	(0.000)
Gender (HH head)	-0.010	0.012	0.003	-0.014
	(0.665)	(0.591)	(0.916)	(0.307)
High education (HH head)	0.073*	-0.088*	0.044	0.044**
	(0.056)	(0.058)	(0.348)	(0.036)
Public sector (HH head)	-0.007	0.014	-0.051**	0.037***
	(0.730)	(0.515)	(0.025)	(0.002)
Married (HH head)	0.0001	0.006	0.008	-0.014
	(0.997)	(0.771)	(0.728)	(0.349)
Parent-home (HH head)	-0.048*	0.013	0.037	-0.050**
	(0.101)	(0.625)	(0.220)	(0.016)
Cook (HH head)	0.025*	-0.026*	0.015	0.011
	(0.068)	(0.063)	(0.327)	(0.261)
Lagged Cook (HH head)	0.045***	-0.024*	0.011	0.013

	(0.001)	(0.095)	(0.488)	(0.177)
HH size	-0.010**	-0.005	0.015***	-0.010***
	(0.025)	(0.253)	(0.003)	(0.004)
House-owner	-0.020	0.031	-0.031	0.001
	(0.485)	(0.321)	(0.350)	(0.979)
Modern roof	0.036	0.005	0.071	-0.076*
	(0.499)	(0.926)	(0.237)	(0.083)
Modern wall	-0.016	0.001	-0.105*	0.104**
	(0.766)	(0.991)	(0.085)	(0.017)
Electric lighting	0.105	-0.106*	0.075	0.031
	(0.120)	(0.095)	(0.303)	(0.514)
No toilet	-0.249***	0.191***	-0.056	-0.135***
	(0.000)	(0.000)	(0.292)	(0.002)
Out-house toilet	-0.163***	0.157***	-0.059***	-0.099***
	(0.000)	(0.000)	(0.001)	(0.000)
Household endowments (ϕ)				
Agricultural specialization	-0.069***	0.007	0.074***	-0.081***
	(0.005)	(0.770)	(0.007)	(0.000)
Fuel supply (V)				
Suburban/ village	-0.117***	0.084*	-0.016	-0.068***
	(0.002)	(0.067)	(0.730)	(0.001)
Population (ln)	0.057***	-0.051***	0.013	0.038***
	(0.000)	(0.000)	(0.193)	(0.000)
Community income (ln)	0.067***	-0.124***	0.079***	0.045***
	(0.000)	(0.000)	(0.000)	(0.000)
Economic open area	0.009	-0.039***	0.031**	0.008
	(0.536)	(0.004)	(0.043)	(0.408)
Local enterprise	0.073***	-0.060***	0.028*	0.032***
	(0.000)	(0.000)	(0.087)	(0.002)
% agricultural activity	-0.001***	0.0005*	0.001***	-0.001***
	(0.000)	(0.086)	(0.002)	(0.000)
% migrants* Year 2000	0.001***	-0.002***	0.003***	-0.001***
	(0.004)	(0.000)	(0.000)	(0.011)
% migrants* Year 2004	-0.001**	0.0004	0.0004	-0.001**
	(0.016)	(0.374)	(0.419)	(0.021)
Northeast region	0.368***	-0.376***	0.235***	0.141***
	(0.000)	(0.000)	(0.000)	(0.000)
Central region	0.084***	-0.071***	0.026	0.046*
	(0.002)	(0.001)	(0.365)	(0.055)
East region	0.153***	-0.235***	0.180***	0.055**
	(0.000)	(0.000)	(0.000)	(0.032)
Food consumption (Ω)				
Telephone service	0.046*	0.064***	-0.060**	-0.004
	(0.067)	(0.005)	(0.023)	(0.822)
Bus stop	0.048***	-0.071***	0.041***	0.030***
	(0.000)	(0.000)	(0.006)	(0.002)
Year 2000	-0.120***	0.175***	-0.160***	-0.015
	(0.002)	(0.000)	(0.000)	(0.582)
Year 2004	-0.063***	0.071***	-0.030	-0.041**
	(0.014)	(0.005)	(0.288)	(0.028)
Observations	4575			4575
Rho	0.328			
LR-test χ^2_{86} (P-value)				2706.92 (0.0000)
Mc Fadden pseudo-R²				0.3002

1) The estimated marginal effects of explanatory variables are reported. P-values are presented

in parentheses.
2) Clean-fuel dominance is defined as 1 if clean fuels are predominantly used, and it is 0 if dirty fuels are predominantly used
3) * Significance levels of 10%, ** Significance levels of 5%, *** Significance levels of 1%