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Household Fuel Use in Rural China

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Abstract: The household transition from dirty to clean fuels is important because of its economic, health and environment consequences, locally, nationally and globally. In order to study fuel choices, a non-separated farm household model for fuel demands is developed. Then, discrete choice equations of fuel uses, consistent with this theoretical model, are estimated using microeconomic household panel data from rural China.

The estimation results support the theoretical approach that implies that the fuel demands depend not only on income, fuel prices, and demand-side socioeconomic factors, as would occur in the standard fuel demand models in the literature, but also on food prices, agricultural assets, and original household and community characteristics that shape the household responses to market failures. Finally, we present a few policy simulations that reveal the complex substitution impact of energy price policies in China.

We provide the first evidence on: price sensitivity of fuel stacking, that food prices exert some pressure on the fuel transition, the role of farm work and activity specialization in fuel choices. Policies should incorporate some of the complexity of the non-separated decisions of rural households in this context of market failures. The complex cross-price effects imply that the policy pricing mechanisms should account for all energy types and food prices. Finally, market-based policies should be coupled with policy interventions aimed at increasing the opportunity cost of dirty fuels.

Keywords: Fuel Use, China, Consumption Demand, Energy.

JEL Codes: D11; D12; Q41.

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I. Introduction

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China's energy transition is of vital importance to the world. China has overtaken the United States as the world's largest energy consumer since 2010. Its soaring energy demand has made China increasingly dependent on imported and locally produced fossil fuels. From 2006, China has been the world's largest carbon emitter, which makes its commitment to global climate change mitigation essential.

Chinese households, especially in rural areas, still greatly rely on traditional biomass (for example, firewood, crop residues) and coal for their cooking and heating needs (Pachauri and Jiang 2008; Yao, Chen, and Li 2012). These 'dirty' fuels generate adverse consequences for the environment and the health of Chinese families. Not only does the combustion of these fuels at home lead to high indoor concentrations of air pollutants, but it also causes local environmental damage. In particular, firewood collection accelerates deforestation and crop residue utilization contributes to soil erosion. Coal combustion also produces sulfur dioxide emissions, which yield acid rain and hence acidify soil. Zheng and Kahn (2013, 2017) indicate that 99.6 percent of the Chinese were exposed in 2013 to air pollution levels above the WHO guidelines, while only one percent of China's urban population live in cities that meet the EU air quality standard. Moreover, the consumption of these dirty fuels aggravates the global climate change through the release of greenhouse gases into the atmosphere. Finally, most of these adverse environmental consequences increase the risk of ill health (for example, through respiratory diseases or cardiovascular mortality) and threaten the nutritional health of the populations because of associated damages to crops (McMichael, Woodruff and Hales 2006).

In order to promote the energy transition, the Chinese government has fostered the supply of clean energy through policies directed at rural electrification and biogas development. Several public programs and projects have been developed to foster this transition, including: the 1996 Brightness Program; the 2002 Township Electrification Program; the 2003 Regulations on Rural Biogas Projects supported by the National Bond; and the 2003 National Debt Project for Rural Biogas Construction. In Hebei Province more than two millions of households using coal have been suddenly given access to gas, which contributed to clear Beijing's sky. However, these policy efforts have not been successful in incentivizing most rural households to give up dirty fuels (Gosens et al. 2013; Shyu 2012). Sometimes, the policy methods used are too clumsy and brutal to be efficient. For example, the coal furnaces of some peasant households were destroyed by government agents before these households could access the promised alternative gas resources.

This study explores several questions: Why is the use of traditional fuels in rural households so persistent? What are the driving forces that govern the fuel transition of rural households toward clean fuels? Do rural households move up a ladder of fuel qualities as their income rises? How do rural households respond to fuel prices? Do other neglected factors play a role? Answering to these questions is essential for designing effective policies promoting the fuel transition.

Household fuel choices in China have already received substantial research attention. However, most previous studies are based on descriptive analyses (Cai and Jiang 2008; Pachauri and Jiang 2008; Wang and Feng 1996; Wang, Xiaqing, and Yuedong 2002), although there are also a few reported econometric estimates (An et al. 2002; Chen, Heerink, and van den Berg 2006; Kaul and Liu 1992; Zhang and Kotani 2012). Prior studies have made use of cross-sectional household surveys, either from large nationally representative household surveys (Jiang and O'Neill 2004; Pachauri and Jiang 2008) or with small household samples (An et al. 2002;

Chen, Heerink, and van den Berg 2006).[1] We innovate by using a large micro-household panel dataset. Availing of panel data allows us to control for unobserved individual heterogeneity, which has been neglected so far, and thus to limit estimation biases.

The previous empirical studies mostly highlight the effects on fuel choices of income, of demand-side socioeconomic factors reflecting preferences (age, sex, education, and household size) and of access to forest resources.[2] When focusing on China, one can see that income (An et al. 2002; Jiang and O'Neill 2004; Peng, Hisham, and Pan 2010), education (Démurger and Fournier 2011; Jiang and O'Neill 2004; Zhang and Kotani 2012), household size (Démurger and Fournier 2011; Jiang and O'Neill 2004) and distance to firewood source (An et al. 2002; Chen, Heerink, and van den Berg 2006) are found to affect the transition toward clean fuels. Nevertheless, these analyses are based on simple reduced-form equations or elementary consumer models of fuel consumption, mostly incorporating the few above covariates. In practice, though, household decisions are likely to be much more complex than that, as is argued in this paper.

Indeed, what drives the fuel choice of Chinese rural households has to be a more composite interplay of socioeconomic factors than in the simple fuel consumer model. For one thing, in rural areas, the markets for traditional biomass and credit are typically missing or incomplete. Moreover, markets for commercial fuels,

[1] For other developing countries, the studies that analyze the determinants of fuel choice in rural households are also mainly based on descriptive statistics (Davis 1998; Miah et al. 2011) and cross-section household surveys, whether nationally representative (Gundimeda and Köhlin 2008; Rao and Reddy 2007) or with small samples (Miah et al. 2011). Among the few econometric analyses are Gundimeda and Köhlin (2008) and Jumbe and Angelsen (2011). All these studies show that income (Rao and Reddy 2007), education (Heltberg 2004), household size (Rao and Reddy 2007), self-owned dwelling (Arthur, Zahran, and Bucini 2010), access to electricity (Heltberg 2004) and distance to firewood source (Jumbe and Angelsen 2011) are positively correlated with rural households choosing clean fuels.

[2] Muller and Yan (2018) provide a comprehensive survey of fuel use studies in developing economies.

agricultural products, and labor are also often quite imperfect. Under the presence of such market failures, it seems unrealistic to assume that consumption decisions can be separated from production decisions, at least for rural households. That is, consumption decisions —and fuel choices in particular— cannot be seen as being a pure consumer choice in which all other decisions can be seen as predetermined. In contrast, the non-separation implies that the decisions relating to fuel production and consumption, food supply and demand, labor allocation in fuel collection, and farm and off-farm activities should be considered as made simultaneously. In this sense, fuel consumption decisions may be seen, in a complex optimization setting, as being guided by the household-specific shadow prices of fuel, which depend on household and community characteristics that are associated with both consumption and production decisions (see, for example, Heltberg, Arndt, and Sekhar 2000; Sadoulet and de Janvry 1995). Therefore, a wide range of socioeconomic covariates, which pertains to consumption and production activities and may shape a household's responses to market failures, should receive more empirical attention. In a sense, Chen, Heerink, and van den Berg (2006) and Démurger and Fournier (2011) already assume a kind of non-separated approach of the fuel consumption and production decisions of Chinese rural households, as they estimate effects of farmland size and livestock number on the consumption of firewood and coal, even though their findings are inconclusive with respectively insignificant and positive effect of farmland on firewood consumption.

Obviously, the market prices of commercial fuels should affect fuel choices. In China, rural households allocate a significant fraction of their income to energy. This is partly due to the high prices of commercial fuels in rural areas (Pachauri and Jiang 2008). Still, the empirical evidence on the impact of fuel prices on the fuel choices of Chinese rural households is limited.[3] Furthermore, the empirical evidence on cross-price effects remains ambiguous. For example, Peng, Hisham, and Pan (2010) find that higher coal prices are associated with a significant increase in biomass consumption. In contrast, Kaul and Liu (1992) and Zhang and Kotani (2012) argue that coal prices do not affect firewood consumption.

Even within a basic consumer model framework, food prices may influence fuel choices, although they have generally been overlooked. Moreover, in non-separated settings, changes in food prices affect both food production and general consumption, and thereby contribute to environmental pressure, as pointed out by Angelsen (1999). Even in separated settings, food prices could influence fuel transition through both consumer-side and producer-side effects. On the consumer side, an increase in a purchased food price may incentivize rural households to turn to 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 price of self-produced food products may shift the budget constraint through an extra income (Strauss 1984). The latter income effect may stimulate the fuel transition toward clean fuels if these have larger income elasticities than dirty fuels. Our estimates will shed more light on all these relatively neglected issues.

Ignoring fuel stacking (that is, the simultaneous use of several fuels) is a common misconception in analyzing the fuel transition. This may arise because the energy ladder has traditionally served as a prominent model for thinking about household fuel choices in developing countries (Kowsari and Zerriffi 2011). The ladder model assumes that households, as their income increases, through a fixed hierarchy of

[3] See, however, An et al. (2002), Kaul and Liu (1992) Peng, Hisham, and Pan (2010), and Zhang and Kotani (2012), who produce somewhat conflicting results for price elasticities. More generally, only few empirical studies conducted in other developing countries have investigated the impact of fuel price on rural household fuel use. Some exceptions are: Edwards and Langpap (2005), Gundimeda and Köhlin (2008), and Pitt (1985).

fuels (Hosier and Dowd 1987), by substituting high-quality fuels for low-quality ones. However, it has been argued that the energy ladder model cannot adequately describe households' fuel use dynamics, especially in the rural areas of developing countries, because households often choose a mix of fuels rather than a specific fuel type exclusively (Davis 1998; Guta 2012; Heltberg 2004, 2005; Hiemstra-van der Horst and Hovorka 2008; Masera, Saatkamp, and Kammen 2000). Jiang and O'Neill (2004) and Peng, Hisham, and Pan (2010) address the issue of fuel stacking for Chinese rural households, though without sophisticated econometric estimates. The current work contributes to this rather unexplored issue by providing evidence on the determinants of fuel stacking.

This paper is organized as follows. A non-separable farm household model is presented in section II. Section III describes the data used and the variables, outlines the econometric method, and discusses estimation and policy simulation results. Finally, section IV offers concluding remarks.

II. A Non-Separated Farm Household Model for Fuel Use

The separation property of farm household models holds when markets are perfect. Under the condition for separation, rural households' decision-making is recursive as a two-step process, in the sense that households behave firstly as profit maximizing producers and then as utility maximizing consumers, given the profit realized in the first step (Singh, Squire, and Strauss 1986).

However, the presence of market failures in Chinese rural areas violates the separation assumption. First of all, the markets for straw, biomass, and firewood are very thin or absent in rural China (Chen, Heerink, and van den Berg 2006; Shi et al. 2009), which implies that the rural households are both producers and consumers of these fuels. Moreover, the lack of a reliable supply of modern fuels—that is, liquefied natural gas (LNG)[4] and electricity—in some rural areas restricts households' fuel choices. Under the frequently imperfect and incomplete markets for agricultural goods in China, the rural households may face high transaction costs for selling and purchasing food products. These costs induce the rural households to consume part of their self-produced food, and may prevent the separation of agricultural production decisions from food consumption decisions. Finally, imperfections in labor markets, as noted in Bowlus and Sicular (2003), may make some rural households self-sufficient in labor, and thus limited by the size of their labor force.

In what follows, we outline a stylized non-separable farm household model for cooking fuel demands as a guideline for our empirical specification.[5] The model implies that the household decisions relating to fuel supply and demand, food production and consumption, labor allocation in fuel collection, and farm and off-farm activities are all made simultaneously rather than recursively. In that case, the household-specific shadow prices of fuel, shaped by household and community characteristics beyond the observed prices, guide the household fuel demands.

Our model shares some motivations with other authors dealing with household fuel demands. Amacher, Hyde, and Kanel (1996) study in Nepal the conditions (including market firewood price and labor opportunity costs) under which rural households are willing either only to collect, or both collect and purchase their firewood. Heltberg, Arndt, and Sekhar (2000) highlight that rural households in

[4] Note that it is really LNG, which is popular in China and often delivered by trucks, and not LPG (liquefied petroleum gas).
[5] We do not consider fuel use for lighting and house heating because nearly all the surveyed rural households use electricity for lighting when they can, and information about house heating is not observed in the data. Another reason for not modelling separately the choices of fuels for house heating is that in China the fuel choice for heating depends on the pattern of fuel use for cooking. As a matter of fact, the heat generated by cooking is generally recycled for heating the house. For example, the Chinese Kang is a traditional heating system for house heating via heat recovery from cooking chimney gases.

India substitute private non-marketed fuels (animal dung and crop residues) for purchased firewood in response to increasing firewood scarcity. Chen, Heerink, and van den Berg (2006) extend the latter approach by focusing on the substitution between firewood and coal in three Chinese villages.

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 and dirty sources to modern and clean ones. One novelty is to highlight fuel substitution in response to food price changes.

To concentrate on the interactions of interest, we consider that the household maximizes its utility $(\boldsymbol{U})$, defined over a vector of food consumption $(\boldsymbol{C})$, cooking fuel $(\boldsymbol{F})$, and leisure $(\boldsymbol{l})$: $\boldsymbol{U} = \boldsymbol{U}(\boldsymbol{C}, \boldsymbol{F}, \boldsymbol{l}; \boldsymbol{Z})$, where Z is a vector of household characteristics pertaining to the preferences. The other consumption goods are assumed to be approximately separated in the preferences, so that we can focus on fuel use decisions. Food consumption can be seen as a function of household produced and consumed food $(\boldsymbol{C^h})$ and food purchased in markets $(\boldsymbol{C^p})$: $\boldsymbol{C} = \boldsymbol{C}(\boldsymbol{C^h}, \boldsymbol{C^p};\ \boldsymbol{\theta})$, where θ stands for other predetermined variables relevant for food consumption. These variables may include community characteristics reflecting the infrastructures that reduce the transaction costs in food markets. We assume that the household can choose between dirty $(\boldsymbol{F^d})$ and clean $(\boldsymbol{F^c})$ cooking fuels, or both. The resulting aggregate cooking fuel can be described by a production function: $\boldsymbol{F} = \boldsymbol{F}(\boldsymbol{F^d}, \boldsymbol{F^c}; \boldsymbol{V})$, where V denotes a vector of some relevant predetermined variables.[6] V includes community characteristics associated with the availability of traditional biomass fuels and access to modern clean fuels. The dirty fuels vector F^d

[6] Although it might have been useful, we cannot account for stove characteristics for which no information is available in our data.

consists of firewood ($\boldsymbol{F^{dw}}$), straw ($\boldsymbol{F^{ds}}$) and coal ($\boldsymbol{F^{dc}}$). The clean fuels vector F^c is made of liquefied natural gas, denoted LNG ($\boldsymbol{F^{cl}}$) and electricity ($\boldsymbol{F^{ce}}$).[7] Because of missing market for firewood, firewood consumption is assumed to be equal to the collected quantity of firewood, $q^{dw}(L_{dw})$, where L_{dw} is the household time spent collecting firewood. Similarly, under missing market for straw, the household obtains straw (q^{ds}) only as a byproduct of agricultural production. We allow for the household to be engaged in agricultural crops (Q_c) and livestock (Q_l) production activities. The aggregate agricultural output Q_{AG} can be described as: $\mathrm{Q}_{AG} = Q_{AG}(Q_c, Q_l;\ \phi)$, where ϕ is a vector of household endowments pertaining to land and livestock. The crop output, assumed to depend on both the household labor (L_c) and the other fixed farm inputs (A_c) is given by $Q_c = Q_c(L_c, A_c)$. Livestock production is a function of purchased cattle feed (M^p) and homemade cattle feed (M^h), $Q_l = Q_l(M^p, M^h(L_l))$, where L_l denotes the labor time allocated to the production of cattle feed. To fix ideas, the amount of straw collected by the household, can be seen as the sum of certain proportions of crop production and of cattle feed: $q^{ds} = \alpha Q_c + \beta M^h$, where α and β denote the proportions. Owing to missing market for straw, $F^{ds} = q^{ds}$. In contrast, coal, LNG, and electricity can generally be purchased in markets. However, LNG and electricity are sometimes in short supply, especially in remote rural areas. Thus, we consider the rationing of LNG and electricity: $F^{cl} \leq \overline{F^{cl}}$ and $\boldsymbol{F^{ce}} \leq \overline{\boldsymbol{F^{ce}}}$, where $\overline{\boldsymbol{F^{cl}}}$ and $\overline{\boldsymbol{F^{ce}}}$ are rationing upper bounds for LNG and electricity, respectively. The household budget constraint is:

$$C^h p^h + C^p p^p + F^{dc} p^{dc} + F^{cl} p^{cl} + F^{ce} p^{ce}$$

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

$$= (Q_{AG}p^h - A_c p^{ac} - M^p p^{mp}) + wL_{off} + Y_o = Y,$$

where p^h and p^p respectively refer to the prices of household own-produced food and market purchased food; p^{dc}, p^{cl}, and p^{ce} are the prices of coal, LNG, and electricity, respectively; p^{ac} is the price of other fixed inputs in crop production; p^{mp} is the price of purchased feeding; L_{off} denotes the household labor allocated to off-farm work; w is the wage rate; and Y_o denotes the other exogenous incomes (for example, fuel subsidy or social transfers). The household total budget Y depends on the agricultural production decisions. An increase in the price of a food item produced and consumed by the household may bring about farm profit effects and substitution effects. In addition, the household has limited time available. The total time allocated to firewood collection, agricultural production, off-farm work and leisure cannot exceed the household total time endowment (T): $L_{dw} + L_c + L_l + L_{off} + l = T$. Finally, the Lagrangian of the constrained optimization problem is:

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

where λ , η , μ_1 , μ_2 , μ_3 and μ_4 are Lagrange multipliers. Under the usual hypotheses of convexity of preferences and technology sets, and focusing on interior solutions, the reduced-form demands for cooking fuel can be derived from the corresponding first-order conditions:

$$\left.\begin{array}{l} F^{dw} \\ F^{ds} \\ F^{dc} \\ F^{cl} \\ F^{ce} \end{array}\right\} = f(p^{h},\ p^{p},\ p^{dc},\ p^{cl},\ p^{ce}, Y,\ Z,\ \theta,\ V, \phi),$$

where $f(\cdot)$ is the fuel demand vector function. In these conditions, the fuel demands depend not only on market prices, income, and preferences, but also on household and community variables that may be associated with consumption-production decisions, and determine each household-specific shadow price of fuel. This is in contrast with separated models, in which the consumption decisions do not depend on the production-side characteristics. An additional twist to the model is that some ‘corner conditions’ are of interest, particularly when only one type of fuel is used by the households. To shorten the exposition, we do not explicitly write the form of the demand functions in that case. However, the general conclusion is the same in that case: all exogenous variables related to preferences, production technology, rationing constraint, and environment, including different kinds of prices, may affect the fuel demand and the transition between the fuels. We investigate the empirical effects of these exogenous variables on the fuel choices in the next section.

III. Empirical Analysis

A. The Data

The data are taken from three waves of the China Health and Nutrition Survey (CHNS) in 2000, 2004, and 2006.[8] In the survey, the respondents are asked which fuels they use as their main energy sources for cooking. 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. Four fuel types are most commonly used primary and secondary cooking fuels: wood/straw, coal, LNG, and electricity, as shown in Table 1. 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. Rural households 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 the primary cooking fuel accounted for only 3.6 percent, 5.8 percent, and 15.9 percent of total households in 2000, 2004, and 2006, respectively. The Chinese government has launched a rural power grid improvement program since 1998 to modernize the rural infrastructure and to harmonize rural/urban consumer tariffs and grid networks. The renovation of the rural power grid benefited rural residents as it was accompanied by lower tariffs and improvement in the quality of the electricity supply. Moreover, wood/straw and LNG were found to be non-negligible secondary sources of cooking fuel in the three survey waves. Besides, wood/straw and LNG, electricity tended to be a major

[8] The CHNS is an ongoing longitudinal household survey (http://www.cpc.unc.edu/projects/china) conducted in nine Chinese provinces: Guangxi, Guizhou, Heilongjiang, Henan, Hubei, Hunan, Jiangsu, Liaoning, and Shandong. The panels were collected in 1989, 1991, 1993, 1997, 2000, 2004, 2006, and 2009. We use only the 2000, 2004 and 2006 waves because the information on electricity price is available only from the 2000 wave, while the 2009 data had not yet been released at the time of this analysis.

secondary cooking fuel, as opposed to coal that was less important.

The percentage of households using fuel mixes is reported in Table 2. Relatively few households used an exclusive energy source. However, single-fuel use was still common among coal users (21.0 percent, 13.3 percent, and 9.2 percent in 2000, 2004, and 2006, respectively). The most common mix of dirty and clean fuels over the three survey years is the joint use of wood/straw (primary) and LNG (secondary). Moreover, the proportion of households using the combination of wood/straw (respectively, LNG) and coal (respectively, electricity) declined (respectively, increased) over the studied period. Clearly, rural households have progressively been moving away from the low efficiency dirty fuels towards more efficient clean fuels. Note also that emphasizing mixes of fuels could be misleading if the secondary fuel was only used rarely, which we cannot know from these data, but suspect from our discussions with specialists.

B. The Variables

1. The dependent variables of discrete data models

We investigate the determinants of: (1) the primary clean cooking fuel choices and (2) the primary-secondary cooking fuel choices (that is, fuel stacking) for Chinese rural households. For this, we estimate random effects panel logit models (REPL) and random effects multinomial logit models (REMNL). The choice of these specifications is supported by several reflections. First, the estimation of a fixed-effect multinomial logit turns out to be infeasible with the currently available software and only three periods. Moreover, fixed-effect estimation of discrete choice models with only a few periods can be very biased in small samples. Further, it is known to be very sensitive to the logit distribution assumption of the errors, as even fixed-effect binary choice models are generally unidentified for general errors and small number of periods (Arellano, 2003). In contrast, at the cost of parametric assumptions for the error distribution components, as often in discrete choice modeling, random-effect estimation allows for convergent estimates, even with a small number of period, provided a large number of individual can be observed. In that case, the estimation results are typically relatively little sensitive to the specific distribution assumption made, here logistic. The random-effect approach allows the reduction of the number of parameter to estimate, thereby augmenting the number of degrees of freedom and in our case allowing for multinomial model estimation in a panel data context with individual effects. The numerical estimation is facilitated by the explicit expression of conditional log-likelihood components that can be easily integrated through Gaussian integrals using Hermite polynomial techniques. Random-effect estimation has additional advantages. It allows the researchers to separate out permanent and transitory components of variations, to reach much larger explanatory power than simple logit estimation, and to generate easily policy simulation results. Finally, as for mixed logit models, it allows us to relax the unrealistic property of the independence to irrelevant alternatives that typically plagues multinomial logit estimation.

In the REPL model for primary clean fuel, wood/straw, coal, LNG, and electricity are the four alternatives. The dependent variable is equal to 1 if the primary fuel used is LNG or electricity, and 0 if it is wood/straw or coal. In the REPL model for primary-secondary fuels, fuel switching is specified according to the following three categories, as in Heltberg (2004): (1) 'no switching'—the main fuels are wood/straw-only or coal-only or mixed wood/straw-coal; (2) 'partial switching'—the main fuels are mixed wood/straw-LNG or mixed wood/straw-electricity or mixed coal-LNG or mixed coal-electricity; (3) 'full switching'—the main fuels are

LNG only, or electricity only or mixed LNG-electricity. The dependent variable is equal to 1 if clean fuels are predominantly used, and 0 if dirty fuels are predominantly used.

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

2. The independent variables

We now discuss the independent variables, which are the same for all models since they reflect the theoretical model in Section II. As is often the case, market prices for coal (p^{dc}), LNG (p^{cl}), and electricity (p^{ce}) are included in the regressions. We replace the unavailable prices of household-produced and market-purchased foods with the prices of a few food products that are consumed and produced by many rural households. Household income (Y) is specified as the total annual income, deflated to 2006 prices, using the CPI estimates by the National Bureau of Statistics of China. The electricity and one-child subsidies are also incorporated alongside household income. Since income data are typically contaminated by measurement errors, it may be useful to add such correlated variables as a complement. Moreover, we are specifically interested in the potential effects of these subsidies, which are key policy parameters.

A few characteristics are supposed to affect household preferences $(\boldsymbol{Z})$: household head's age, sex, education, occupation and marital status; household size; dwelling attributes; and lifestyle captured by whether the household head is living with his/her parents and whether the household head prepares food. The household land and livestock endowments (ϕ) are included to account for the possible agricultural specialization of the household.[9] The households specializing in agricultural production are expected to use more often the dirty fuels because they can take advantage of their crop residues. In order to allow for 'producer price' effects, we also interact the land size with the price of unbleached flour, and the livestock size with the price of pork. Other kinds of interaction with prices led to insignificant coefficients.

The other predetermined variables relating to local fuel supply conditions (V) consist of local characteristics. They are: the local proportion of agricultural activities; off-farm employment participation (proxied by: the proportion of migrants, proximity to local enterprise, and economic open area);[10] the degree of rural economic development (described by dummy variables for administrative districts, population size, and community income); and the region. The proportion of agricultural activities and off-farm employment participation may be correlated with the local availability of traditional biomass fuels. Off-farm employment participation may induce a shift from wood/straw towards commercial fuels as it reduces the available labor for on-farm production and firewood collection. The variables describing rural economic development may jointly serve as proxies for easy access to modern clean fuels,[11] and accordingly they should be correlated with a shift toward clean fuels. The dummies for geographic locations also help us to control for local differences in fuel accessibility.[12]

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

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

[11] We cannot include the distance to the closest market where commercial fuels can be bought because this information is missing in the 2006 wave.

[12] The southwest region includes the Guizhou province. The east region includes the Jiangsu and Shandong provinces. The central region includes the Henan, Hubei, Hunan, and Guangxi provinces.

The other predetermined food-consumption variables (θ) include access to telephone and bus services, which reflect the local public infrastructure. This matters because better communication and transportation infrastructure could mitigate transaction costs and thereby assist farmers participating in food crops markets. The additional income generated by sales of food products may induce rural households to prefer commercial fuels, which are believed to be normal goods.

The definition and descriptive statistics for these variables are reported in Table 4. In particular, the fuel prices deserve special attention. The mean coal prices slightly increased from 0.20 yuan per briquette in 2000 to 0.28 yuan in 2004 and 0.31 yuan in 2006. This is also the case for the mean electricity price, which was 0.66 yuan per KWh in 2000, fell to 0.54 yuan in 2004, and remained stable at 0.56 yuan in 2006. In contrast, LNG prices varied a lot across the different waves: from 51.0 yuan per tank in 2000 to 81.6 yuan in 2006. Table A1 reports often substantial increases in the regional consumer energy price indices over the three survey years with a lot of heterogeneity across provinces. Over the period 1999–2006, the movement of the energy prices ranged between a slight fall at 97.1 in Liaoning and a steady increase at 161.7 in Shandong. This dispersion in price levels and movements is a favorable context to study price effect.

Other prices and incomes fluctuated a lot during this period. In particular, the mean pork prices rose from 6.81 yuan per jin in 2000 to 8.91 yuan in 2004, and then fell again to 7.57 yuan in 2006. Finally, the mean household income rose by about 35 percent over the 2000–2006 period, which suggests considerable income effects in consumption.

C. Estimation Methods

The northeast region includes the Liaoning and Heilongjiang provinces. Finally, the southwest region is taken as the reference.

As mentioned before, we estimate a REPL model of clean versus dirty fuels, and a REMNL model for the choice among the different fuels. These econometric models can be connected to the theoretical model. Households are assumed to choose the fuels that maximize their indirect utility $V(p^h,\ p^p,\ p^{dc},\ p^{cl},\ p^{ce}, Y,\ Z,\ \theta,\ V, \phi)$. All the exogenous variables in the theoretical model are included in the estimated models, including the prices of fuels, of foods, and of agricultural products. Let $j = 1,..m...,J$ be the indices of the alternative fuels, and $i = 1,...n$ be the household indices. Then the household i's indirect utility function is proxied as $V_{ij} = \beta_j x_i + \varepsilon_{ij}$, where x_i represents the observed exogenous variables for household i, β_j is the vector of coefficients to be estimated, and ε_{ij} denotes a stochastic error assumed to follow a Gumbel-type distribution. As is well known, the REPL and REMNL models can be derived from such random indirect utility functions by expressing and comparing the probability of choosing a fuel as a consequence of it generating the highest utility level.

The observed dependent variable y_{it} for a clean primary fuel (or for a given fuel) is a dichotomous variable, and extending it to several periods, t = 1,…, T, the corresponding linear latent (utility) variable specification $(y_{it} = 1_{[y_{it}^* > 0]})$, which can be similarly employed for the two models, is of the form:

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

Variable y_{it}^* is the unobserved propensity to use the considered fuel in household i at time t, an unobserved utility level by analogy. X_{it} represents time-varying household variables, including fuel prices, food prices, and household income. H_i is a vector of time-invariant variables related to the household 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 related to local fuel availability (V), and predetermined food-consumption variables (θ). We also include a one-period lag of the variable 'cook', which represents whether the household head prepared food in the previous period.[13] We have also examined the lagged effects of other explanatory variables, such as food prices and fuel prices. However, they are generally statistically insignificant, so we dropped them from the reported specification. The random variable c_i captures the unobserved household-specific and time-invariant characteristics. In the chosen RE specification, which is tested below, c_i is assumed to be uncorrelated with the observed explanatory variables with the Gumbel-type error term u_{it}. The random variables c_i and u_{it} are centered and are assumed to have homogenous variances σ_c^2 and σ_u^2 , respectively. The parameter vectors η, γ, δ, σ_c^2 and σ_u^2 are estimated using simulated likelihood maximization.

D. The Results

We start with a discussion of the estimated marginal effects for the choice of the primary cooking fuel (among clean versus dirty fuels, or among the few distinct fuels), which are significant for most covariates (Table 5). Then, we turn to the estimated marginal effects for the dominance of clean fuels and for fuel switching (Table 6).

[13] Here, the lag is to mitigate possible endogeneity issues arising from simultaneous household decisions about who cooks and which cooking fuel is used.

1. Choice of the primary cooking fuel

a. Fuel price effects

All prices are introduced in logarithms so that the marginal effects can be interpreted in terms of relative changes in price. One first finding is that all fuel prices have highly significant effects for both direct impacts and substitutions across fuels.

In theory, the complementary/substitution relationships between fuels should be derived from a Slutsky equation—for example, using a simple consumer model. However, the relatively simple decomposition of price effects decomposed into substitution and income effects in the consumer model does not extend so easily to more complex household models. First, the prices of other consumed and produced goods may also affect fuel use. Moreover, when consumption and production are not separable—which is the case for rural households under missing markets—the observed prices do not fully summarize the shadow prices that determine household decisions. In that case, it is still possible to exhibit how variations in food prices may affect fuel choices. In particular, an increase in the price of purchased food may cause households to choose cheaper dirty fuels, while an increase in the price of self-produced food may stimulate the switch to clean fuels that are expected to be normal goods. These considerations imply that price effect estimates in the simplest econometric specifications may be, at best, considered only as approximate estimates, especially for rural areas. Therefore, caution must be applied when interpreting the estimated direct and, especially, cross-price effects. However, as a fully structural estimation of the generalized Slutsky equation is infeasible with these data, we mostly discuss the price effects in terms of uncompensated substitution.

In these data, coal prices are found to have a significant impact on all alternatives, at levels of significance varying from one to ten percent, except for electricity in the REMNL model. As expected, an increase in the coal price decreases the probability of choosing coal, which is in line with Gupta and Köhlin's (2006) evidence from India. As a consequence, getting the coal price right by removing subsidies, reflecting production cost, and internalizing externalities could partly help correct the coal-dominated energy structure.

Moreover, a ten percent increase in the coal price increases the probability of using wood/straw by 0.01 (an elasticity of 0.41). This indicates that wood/straw and coal are (uncompensated) substitutes, which makes sense since they can be burned in the same type of furnace. This is consistent with Peng, Hisham, and Pan's (2010) finding that an increase in the coal price induces rural households to choose biomass in the Hubei province. However, this is at odd with Gupta and Köhlin's (2006) result for Indian urban households that fuelwood and coal are (uncompensated) complements, perhaps because of different contexts. In our case, the negative sign of the coal price coefficient also implies that coal and LNG are (uncompensated) complements, since the probability of choosing LNG decreases as the coal price rises. Thus, the combination of the substitutable and complementary relationships of coal with wood/straw and LNG respectively in the REMNL model may explain the effect of the coal price in the REPL model, in which an increase in the coal price reduces the probability of clean fuel adoption.

As expected, electricity use negatively responds to an increase in the electricity price in the REMNL model. A ten percent increase in the price of electricity diminishes the probability of using electricity by 0.007, that is: an elasticity of -0.53. This result supports the conventional wisdom in the literature that the demand for electricity is sensitive to its own price (for example, An et al. 2002; Gundimeda and Köhlin 2008). In addition, the estimates on electricity price from the REMNL model again suggest that electricity and coal are substitutable. Taken together, the substitution effect of electricity with coal, combined with the negative response of electricity use to its own price, corresponds to the effect of the 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 the LNG price on the household willingness to choose clean fuel in the REPL model can be attributed to some kind of uncompensated substitutability of LNG with electricity and complementarity of LNG with coal. The substitutable relationship between LNG and electricity is akin to that in Gundimeda and Köhlin's (2008) result for India, whereas it is contrary to findings by Filippini and Pachauri's (2004) study for the same country. However, in our case the effect of the LNG price is insignificant for the choice of LNG in the REMNL model. A possible explanation for this insignificant response may lie in non-price factors, such as occasional shortages of LNG, long distance to retailers, and high cost of appliances.[14] Finally, changes in LNG and electricity prices do not, or little, affect the price of wood/straw, perhaps in part because the latter is not a marketed product.[15]

b. Other price effects

There are other price effects beyond those of the prices of fuels, especially for the food prices. There are three channels for these prices. Firstly, preferences are not

[14] 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. This may result in large distances from homes to retailers and uncertainties in delivery frequency.

[15] The substitutable relationship between LNG and wood/straw is supported by Gundimeda and Köhlin's (2008) study, whereas it is challenged by Akpalu, Dasmani, and Aglobitse's (2011) work for Ghana.

weakly separated: for example, the cooking fuels matter for the taste of the cooked food. Secondly, profit effects may arise when the prices of some own-produced foods increase. Thirdly, in the non-separated consumption/production context, changes in food prices affect the shadow prices that determine decisions: for example, an increase in the price of some farm products may reduce the shadow price of biomass from agricultural inputs and byproducts.

Most effects of food prices are highly significant, at least for some fuels, in both the REPL and REMNL models. For the first time in the literature, we bring evidence that food prices can play a vital role in fuel choices. Although food items produced and purchased by households cannot be distinguished in the data, the signs of estimated effects suggest possible distinct roles of produced vs. purchased food prices in fuel choices. In general, an increase in the price of some produced foods should raise farm income, since rural households produce more food than they consume and sell the surplus in the market. This positive income effect may generate a rise in willingness to switch to clean fuels if the latter are normal goods. In contrast, an increase in the price of exclusively purchased food may induce rural households to spend more on other components of consumption, including on fuels, and on the other hand to favor cheaper dirty fuels due to a loss in purchasing power.

For instance, a ten percent increase in pork price would imply a rise in clean fuel adoption probability by about 0.01, that is an elasticity of 0.54. This result is confirmed by the REMNL estimates in which an increase in pork price encourages rural households to use electricity more often. These findings may be explained by the fact that pigs are raised in Chinese rural households, both for home food and sale. An increase in pork price may raise some households' cash income through selling pigs, which may further induce households to adopt clean fuels. However, substitution and income effects are not the only mechanism at play when considering pork price effects. An increase in pork price, when interacted with livestock size, also generates a steady rise in wood/straw adoption. This is not surprising, since grain-based feeds (as wheat bran) are commonly used for pigs by pork producers and subsequent crop residues (as wheat straw) can be used as cooking fuels. Here, we have an empirical hint of a mechanism that may connects intimately non-separable production and fuel consumption decisions.

This kind of interaction has been much neglected in the econometric literature on the subject, although it has substantial consequences for policy as pork is likely to remain the dominant meat consumed in China for some time. To meet the sharp rise in pork demand stemming from growing incomes and urbanization, the government has provided subsidies aimed at promoting a shift away from small-scale pig farming toward large-scale commercial pig production. These changes should certainly affect pork prices, which, in turn, may impact on the rural household energy transition.

While the analyses of pork price effects are perhaps the most striking for their originality, we have also included many other food price effects in the model. We only discuss those effects significant at the five percent level. The price of rice has no significant effect whatsoever. As an almost mandatory staple food with almost fixed quantities consumed, rice may allow for little substitution. In contrast, an increase in the cabbage price reduces the use of LNG. Pork is not the only produced animal product that generates profit effects through price rises. A rise in the price of beef is associated with a significantly higher probability of using LNG. Alternatively, a rise in the price of mutton is related to simultaneous increases in the use of coal and electricity, and a reduction in the use of LNG. Complex substitution/complementarity, income, and non-separable effects may be at work, which would explain all these effects, though their decomposition are beyond our identification possibilities. However, it is interesting that the use of two clean and plausibly normal good fuels is stimulated by these price changes, consistently with farm profit effects.

More insight seems to be reachable in the case of unbleached flour, another product of household farms. Again, the price effects are modelled in that case with two coefficients: one for the logarithm of the flour price, and one for the interaction of this logarithm with farmland size. The latter coefficients allow us to get some hints about the specificity of flour producers in their response to variations in flour prices, while the production of flour is not observed. We find that a rise in the price of flour is associated with more frequent use of LNG, although it is smaller for farmland owners with, for the mean of the sample, a marginal effect of 0.179 - 0.022 x 4.14 = 0.0879, i.e. an elasticity of -0.14. This result would contradict an interpretation in terms of income/profit effect, unless flour production is negatively correlated with farm size for an unknown reason. However, the interacted price effect is also in favor of a more frequent use of coal, and a flour price rise reduces the use of wood/straw fuel (by -0.0146, an elasticity of -0.58), less so for farmland owners (by -1.46 + 0.0009 x 4.14 = -0.0109, i.e. an elasticity of 0.04). The latter result is clearly consistent with a tendency towards reusing the straw and other crop residuals from wheat cultivation as fuels, and perhaps with burning coal in the same kind of furnace.

c. Income variables

An increased household income exerts a robust positive influence on the choice of clean fuel. The REPL results show that a ten percent increase in household income increases the probability of using a clean fuel source by 0.006, with an elasticity of 0.29. This result confirms the consensus in previous studies in favor of a positive relationship between income and clean-fuel demand (see An et al. 2002; Farsi, Filippini, and Pachauri 2007; Gupta and Köhlin 2006). Similarly, the exogenous income obtained from electricity subsidy or one-child subsidy significantly affects fuel choices.[16] As expected, the electricity subsidy stimulates the demand for electricity. However, this is also the case for the one-child subsidy. This may result from two causes. Firstly, one-child families may consider that firewood has a high opportunity cost because their only child's labor spent collecting firewood is at the expense of on- and off-farm work time. Secondly, one-child families are often entitled to other subsidies as well, such as extra food rations, health subsidies, and allotments of farmland (Bredenkamp 2009). These allowances may reduce their economic burden and relax liquidity constraints, and thereby help the families to afford electricity through the interplay of consumer income effects.

d. Preference and lifestyle characteristics

Most included characteristics pertaining to household preferences play a significant role in explaining the fuel choices. Older household heads are more likely to choose wood/straw and coal, and less likely to choose LNG and electricity.[17] For wood/straw and coal, a unit change in the age of the household head implies an increase in the fuel choice probabilities of about 0.002 (an elasticity of 0.29) and 0.0006 (an elasticity of 0.09), respectively. For LNG and electricity, a unit change in the age of the household head implies a decrease in the fuel choice probabilities of about 0.002 (an elasticity of -0.44) and 0.0009 (an elasticity of -

[16] We dropped the estimated effects of coal subsidy and gas subsidy because they were always insignificant.
[17] The coefficient of squared age of the household head is statistically insignificant, so we dropped this variable from the regression.

0.55), respectively.

These results are at odds with the findings reported in India by Farsi, Filippini, and Pachauri (2007) and Gupta and Köhlin (2006) that older household heads are more likely to prefer LNG to wood. Our results, however, may be attributed to the fact that older people became familiar, and somewhat attached, to traditional dirty fuels when they were young. Male-headed households prefer wood/straw, which is coherent with Rao and Reddy's (2007) finding for India that households in which women are empowered opt for clean fuels. A higher education level of the household head marginally significantly (at 10% level) favors the use of clean fuels. The increasing opportunity costs of firewood collection with education and the time saved by the use of modern clean fuels could justify this association, suggesting that preferences and economic constraints may combine to explain the role of education.

Lifestyle matters. Firstly, the household heads living with their parents prefer dirty fuels. Intergenerational transmission of the parents' preferences for traditional fuel to the younger generation may explain this result. Secondly, the household heads participating in cooking more often opt for LNG. It may be a choice of personal comfort by the main decision-maker. However, other explanations are possible. For example, 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 an efficient and time-saving fuel out of concern for efficiency.

The housing context is often closely linked to lifestyle, while it also depend on former investment decisions by the household. Obviously, housing features may also be correlated with unobserved income and wealth characteristics, and their interpretation is therefore subject to caution. However, they still seem to be interesting to include in the regressions. Household dwelling characteristics—which are, in these data, only represented by the presence of a toilet and its location, and whether the lighting source is electricity—may condition the fuel choice because they may motivate or limit some fuel uses. In particular, in this context, the cooking fuels are the heating fuels too, and different houses can be heated more or less easily. House ownership has no significant effect at the five percent level. This finding is consistent with Ouedraogo's (2006) evidence from Burkina Faso, but not with Arthur, Zahran, and Bucini's (2010) result of a positive relationship between self-owned dwelling and clean fuel use in Mozambique households.

Household size has a significant positive effect on the choice of clean fuels, notably LNG.[18] At this stage, it would be challenging to propose a definitive interpretation for a variable correlated with most household decisions and characteristics; So, we merely include it as an additional control for household heterogeneity. We now discuss the role of the agricultural capital, an asset distinct from housing, which is a correlate of the availability of burnable byproducts.

e. Agricultural assets and non-separation of decisions

Households fully engaged in agriculture and cattle raising use more often dirty fuels. Inputs and byproducts of these activities can be burned in the same furnace as coal. This may be the consequence of the non-separation of decisions, which is caused by missing markets for some inputs and byproducts.

We only observe two pieces of information on the agricultural assets: the size of farmland and the number of cattle heads. A large farmland is clearly associated with large-scale production of agricultural products, which implies abundant crop residues. Moreover, large farms may employ a larger labor force, which may lower

[18] The other tried household composition variables had insignificant additional coefficients.

the opportunity costs of firewood collection. Therefore, it is not surprising to find that large farm households use relatively more wood and straw, and less LNG.[19,20]

A word of caution is in order. The variable 'farmland size' appears in the model not only in its own right, but also as interacted with the price of unbleached flour. The assessment of the total marginal effect of farmland size therefore involves some computations. At the sample mean, the combined effect of the two coefficients involving farmland corresponds to a marginal effect of 0002 + 0.009 x 0.1 = 0.00299 for the use of wood/straw, which actually reinforces the above comment.

Finally, livestock, provided one only looks at the coefficient for this variable on its own, is found to be negatively correlated with the use of firewood and straw. However, an opposite effect arises through the coefficient of livestock interacted with the price of pork. The total marginal effect combining these two coefficients corresponds to -0.088 + 0.631 x 0.01 = -0.082 at the sample mean, which is hardly significant in the end.

f. Environment and local variables

Most of the community level variables included in the regressions significantly affect the fuel choice. Firstly, the presence of local firms is clearly a sign of better local economic development, which is correlated with substantial progress in the transition toward clean fuels. This may stem from easier access to commercial clean fuels that are likely to be used by these firms. More frequent use of LNG and electricity may also stem from clean fuels being normal goods, jointly with the additional income brought by off-farm employment. Likewise, the proximity to an economic open area, also included as a measure of off-farm employment

[19] In contrast, Heltberg, Arndt, and Sekhar's (2000) evidence from India shows that larger landholders are associated with lower supply of firewood and collection time.

[20] Démurger and Fournier's (2011) evidence from China indicates that a larger landholding size is associated with a significant increase in firewood consumption, while a larger number of livestock is associated with a significant reduction in firewood consumption.

opportunities, is negatively (respectively, positively) and significantly associated with the use of wood/straw (respectively, LNG).

The presence of local collective enterprises is found to induce a shift from wood/straw and coal towards LNG and electricity in the REMNL model. Moving away from wood/straw may be encouraged by the scarcity of the time available for biomass collection in places where much of the labor force is employed in industrial jobs. In contrast, a plentiful availability of traditional biomass, resulting from a large proportion of agricultural activities, induces a clear preference for wood/straw versus LNG and electricity.

A large local proportion of migrants in 2004 is positively and significantly associated with the use of LNG. Indeed, as pointed out by Gu, Zheng and Yi (2007) , migrants often prefer convenient and time-saving cooking technologies in response to their fast-paced and modern lifestyle and this may stimulate the availability of these fuels.

Surprisingly, the variable describing inadequate electricity availability locally has little significant effect.[21] However, local fuel availability still seems to matter. For example, a longer distance to the nearest free market reduces the use of LNG and stimulates the use of coal.

Households living in the northeast region, the central region, and the east region are more likely to use clean fuel than those living in the southwest, and the higher level of development in these regions, which implies easier access to clean fuels, may explain the observed results. In contrast, rural households living in the northeast region, the central region, and the east region are less likely to use coal as

[21] 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, Qiu, and Kuang 2009). The widespread power shortage may limit not only the supply of electricity, but also the availability of coal and LNG in rural areas, because more coal and natural gas are needed to generate electricity.

the primary cooking fuel than those living in the southwest Guizhou province, which is more abundant in coal resources.

2. Determinants of dominance of clean fuels and fuel switching

We finally and briefly examine the determinants of fuel switching by mobilizing the information on both primary and secondary fuel choices. These different alternatives correspond to different kinds of corner solutions of the theoretical model, and therefore should depend on the same set of covariates as before. For this, we first estimate a random-effect logit model of the dominance of clean fuels. Then, we estimate a random-effect multinomial logit model distinguishing between the three alternatives: no switching, partial switching, and full switching.

Partial switching is defined as corresponding to the main fuels used by a rural household, being: mixed wood/straw-LNG, mixed wood/straw-electricity, mixed coal-LNG or mixed coal-electricity. The dummy for the dominance of clean fuels is equal to 0 if only dirty fuels are used or dirty fuels are primarily used with clean fuels used secondarily, and 1 if only clean fuels are used, or clean fuels are primarily used with some dirty fuels secondarily used.

The results presented in Table 6 show that most of the variables affecting the primary fuel choices also matter for primary-secondary fuel choices. On the whole, the results are in accordance with those of Table 5. To save space, we only discuss a few useful additional points.

The estimates of the REMNL model correspond to stronger effects of the household income and the local average income for partial switching, than for full switching. This is consistent with the critique of the energy ladder model wherein the household fuel transition would be systematically driven by increasing income

(Davis 1998; Heltberg 2004; Masera, Saatkamp, and Kammen 2000). What we find in rural China is a general preference for a mix of modern and traditional fuels, rather than a simple ladder of fuel preferences according to income levels. Furthermore, the changes in the fuel adoption probabilities caused by the variations in the fuel prices, in the REPL model for the primary-secondary fuel mixes, is generally smaller, though not substantially, than that in the previous REPL model focusing on the primary cooking fuels. These findings provide, to our knowledge, the first empirical support of the notion that diversifying fuel use can help rural households to reduce their sensitivity to fuel price fluctuations, as argued by Kowsari and Zerriffi (2011), and Masera, Saatkamp, and Kammen (2000).

For comparison purposes, we also estimated pooled logit models and pooled multinomial logit models that do not control for unobserved household heterogeneity. We observe that the magnitude and the sign of the coefficients in some cases vary dramatically. For example, the effect of the electricity price on the probability of choosing clean fuel is divided by two when passing from the REPL model to the pooled logit model. Moreover, the marginal effect of livestock interacted with the price of pork on wood/straw adoption is statistically insignificant in the pooled multinomial logit estimation, while it is very significant in the REMNL model. These elements of comparison show that it is important to account for individual heterogeneity in order to elicit correct estimates. The misspecification brought by pooling has severe consequences in terms of understanding which mechanisms are at play, and notably the nonseparation structure. We now turn to the exploitation of the estimation results for policy analysis.

E. Policy Simulations

In this section, we conduct simulations by using the estimated REMNL model to predict the proportions of households respectively using wood/straw, coal, LNG, and electricity as primary cooking fuel choices, given alternative scenarios of policies on electricity and coal prices. Using simulations based on the estimated model to discuss policy consequences accounts for household observed and unobserved household heterogeneity.

The government-regulated uniform electricity pricing in the residential sector discouraged energy conservation and resulted in excessive electricity consumption. Given this unsustainable situation, the Chinese government implemented in 2012 nationwide tiered pricing system for household electricity (Lin and Jiang 2012). Under this new pricing mechanism, household electricity prices are set into three tiers based on increasing volumes of electricity consumption (Du et al. 2015). When a household's electricity consumption exceeds the upper bound of its tariff block, it is charged a higher price. The guidance issued by the National Development and Reform Commission required that the first block should cover 70–80 percent of households, while the second block is expected to cover 90–95 percent. While the electricity price of the first tier remains unchanged, the electricity price of the second tier must be at least 0.05 yuan higher than the base price, and the electricity price of the third tier must be at least 0.2 yuan higher (Wang, Zhang, and Zhang 2012). Accordingly, most local governments raised the electricity price by 0.05 yuan for the second tier and by 0.3 yuan for the third tier.

In line with the ongoing market reform, the Chinese government gradually deregulated the pricing mechanism for the coal sector in the 1990s and the 2000s. For example, China's central government stopped setting prices for non-electricity related coal in 1993 (Yang, Xuan, and Jackson 2012). The mechanism of a 'guided price' for thermal coal, under which electricity producers and coal suppliers negotiated the prices of thermal coal at the annual Coal Ordering Conference, was cancelled in 2002, except for a few 'important contracts'. Finally, the price setting for thermal coal for the 'important contracts' was entirely abolished in 2013. On the whole, the market-based pricing reforms tended to push coal prices up. The average annual growth rate of coal price over the period 1990–2011 reached 11 percent (NBS 2012).

In this context, three policy scenarios, quantitatively similar to the price changes as observed in the current policies, are explored in this research. Specifically, in Scenario 1, the electricity price increases by 0.05 yuan for all households and, in Scenario 2, by 0.3 yuan; in Scenario 3, the coal price increases by 11 percent. The simulation results presented in Table 7 show the changes in the population of rural households by primary cooking fuel in 2006 in each policy scenario.

The simulation results show that changes in fuel prices, in particular as a consequence of government policies, are likely to have a powerful influence on rural household fuel uses, and as a result on environment and health consequences of fuel choices. However, the features of these changes may be less obvious than expected. Clearly, more attention should be devoted by the government to these changes when designing price policies. The first policy scenario, with only relatively moderate growth in the electricity price (2nd tier tariff), has already substantial consequences on the pattern of uses. The percentage of households using electricity as a primary fuel drops by 6.6 percent, and the coal users are also less frequent (by 2 per cent), while the proportion of gas users is almost unchanged (-0.5 per cent).

The second policy scenario assumes a six-fold increase of the electricity price (3rd tier tariff), as compared to the first scenario. The changes in proportion are much larger, while not exactly in proportions with the previous scenario. The percentage of electricity users falls by 29.6 per cent; that of wood/straw users by 11.4 percent, and that of gas by 1 percent, whereas the proportion of coal users soars by 31.4 per cent. Obviously, raising electricity prices substantially may have dramatic consequences on pollution emissions from coal consumption.

Finally, the third policy scenario, which is in line with the recent trend in coal prices, brings to the fore a more favorable perspective, while the changes in users are only small, and the 1.4 per cent decrease in coal users is more than compensated by a 3.6 per cent increase in wood/straw users, while the percentage of electricity users and gas users also slightly decline. What seems to be happening here is mostly a substitution of wood and biomass for coal, and not a move towards clean fuels; It may be that the household equipment in coal furnaces keep them dependent in dirty fuels.

IV. Conclusion

The household transition from dirty to clean fuels is important because of its economic, health and environment consequences, locally, nationally and globally. In order to study fuel choices, a non-separated farm household model for fuel demands has been developed. Discrete choice equations of fuel uses, consistent with this theoretical model, have been estimated using a large micro-household panel dataset from rural China.

The estimation results support the theoretical approach that implies that the fuel demands depend not only on income, fuel prices, and demand-side socioeconomic factors, as would occur in the standard fuel demand models in the literature, but also on food prices, agricultural assets, and original household and community characteristics that shape household responses to market failures. The commonly employed elementary consumption demand models are rejected by the data, as is the energy ladder model. In particular, rural households in China often adopt a mix of modern and traditional fuels as their income rises.

Secondly, we contribute to the knowledge about price effects by estimating direct and cross-price effects in this general setting, while providing the first evidence on price sensitivity of fuel stacking. Moreover, we offer the first empirical evidence that food prices exert some pressure on the fuel transition. Besides, we point out that, in this general setting, even traditional price effects have different theoretical interpretations from usual.

Thirdly, the fundamental role of the agricultural assets is exhibited in affecting farm households' fuel demand, as a consequence of the non-separation of fuel consumption, and agriculture and cattle raising activities, due to missing markets for the inputs and byproducts of these activities. Notably, we provide new evidence regarding the potential role of farm work and activity specialization in fuel choices.

The findings are relevant to policies aiming at accelerating the transition toward clean fuels. They suggest that policy interventions, exclusively guided by the energy ladder—a stylized extension of consumer economic theory—may only bring about partial switching, and that they partly miss their goal. Furthermore, the design of policies should incorporate some understanding of the complex non-separated decisions of rural households in the context of market failures at least for some fuels, agricultural foods, and labor.

For example, in the early 2000s, the central Chinese government formulated policies to financially support investment in household-scale biogas digesters. However, these policies did not fit well with the local agricultural circumstances. Although the Chinese agriculture has been steadily shifting from smallholders to intensive farms, the government primarily focused on small inefficient biogas digesters. Moreover, off-farm employment opportunities attract agricultural labor locally or through migration to cities. In these conditions, many rural households have to reduce or abandon their production activities in response to labor shortages, which further generates a lack of raw materials for running the biogas digesters.

Furthermore, policymakers could use more rural energy pricing. The estimates show that the electricity demand is strongly responsive to its own price and to electricity subsidies. However, the early policies aimed at rural electrification have ignored that the affordability of electricity is vital. The analysis also demonstrates the importance of the complex cross-price effects in explaining the pattern of fuel uses. This implies that the policy pricing mechanisms for one energy type should be coordinated with the market prices of the alternatives, accounting for substitution effects. In this context, market-based pricing policies should be coupled with policy interventions aimed at increasing the opportunity cost of dirty fuels (for example, by enforcing environment protection measures).

Finally, the findings suggest that the rural energy policy is not independent from the food policy. Instead, the two policies should be integrated. Indeed, rural household decisions relating to the production and consumption of food and fuel are often made simultaneously. This implies that the energy pricing policies should give consideration not only to the price changes in the alternative energy types, but also to the price changes in food products, as well as to the substitutions/complementarities between energy sources and food.

Let us conclude with a few words about a missing dimension in this study for lack of appropriate data. Given that China has made substantial progress in the deployment of new technologies (for example, biomass gasification) and the dissemination of renewable energies (such as biofuel), future research should examine whether new technologies and renewable energies can exert an influence on the energy transition of rural households.

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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	39.05	34.6	29.85
Secondary	23.30	25.78	23.69
Coal			
Primary	34.62	36.48	31.25
Secondary	29.03	16.16	14.26
Liquefied natural gas			
Primary	22.69	23.16	22.99
Secondary	29.59	32.55	28.48
Electricity			
Primary	3.63	5.76	15.92
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

Notes: Dirty fuel dominance: only dirty fuel is used or dirty fuel is primarily used in combination with clean fuel secondarily used; clean fuel dominance: only clean fuel is used, or clean fuel is primarily used in combination with dirty fuel secondarily used.

Table 4
Description of explanatory variables

Variable	Definition	2000		2004		2006	
		Number of observations	Mean (standard deviation)	Number of observations	Mean (standard deviation)	Number of observations	Mean (standard deviation)
Coal price	Price of honey-combed briquette per piece (in yuan)	2285	0.203 (0.105)	2241	0.28 (0.086)	2428	0.314 (0.108)
LNG price	Price of liquefied natural gas per tank (in yuan)	2752	51.05 (8.439)	2970	66.8 (9.419)	3026	81.68 (10.05)
Electricity price	Price of electricity per kWh (in yuan)	2831	0.663 (0.176)	2992	0.545 (0.146)	3026	0.566 (0.166)
Rice price	Price of rice most commonly eaten per jin in free market (in yuan)	2857	0.898 (0.273)	2992	1.284 (0.171)	3026	1.343 (0.216)
Cabbage price	Price of cabbage per jin in free market (in yuan)	2997	0.475 (0.406)	2992	0.515 (0.309)	3026	0.695 (0.397)
Pork price	Price of lean pork per jin in free market (in yuan)	2810	6.815 (2.637)	2972	8.918 (1.359)	3026	7.572 (1.383)
Beef price	Price of beef per jin in free market (in yuan)	2973	7.219 (2.96)	2992	9.102 (2.167)	3026	9.448 (2.239)
Mutton price	Price of mutton per jin in free market (in yuan)	2997	9.888 (4.481)	2992	10.73 (3.822)	3026	10.86 (3.684)
Unbleached flour price	Price of unbleached flour per jin in free market (in yuan)	2851	1.036 (0.778)	2694	1.276 (0.326)	2915	1.271 (0.414)
HH income	Household total annual net income inflated to 2006 (in yuan)	2893	15683 (16990)	2904	18164 (18465)	2926	21211 (27164)
One-child subsidy	1 if household receives one-child subsidy, 0 otherwise	2997	0.048 (0.215)	2992	0.035 (0.183)	3026	0
Electricity subsidy	1 if household receives electricity subsidy, 0 otherwise	2997	0.016 (0.127)	2992	0.008 (0.091)	3026	0

Household preferences (Z)							
Age (HH head)	Age of household head in years	2897	48.76 (12.46)	2783	51.99 (12.5)	2682	53.9 (12.42)
Gender (HH head)	1 if household head is male, 0 otherwise	2897	0.892 (0.31)	2783	0.874 (0.332)	2682	0.856 (0.351)
High education (HH head)	1 if household head's highest education is over upper middle school level, 0 otherwise	2997	0.029 (0.168)	2992	0.035 (0.184)	3026	0.047 (0.212)
Public sector (HH head)	1 if household head's primary occupation is in public sector, 0 otherwise	2997	0.802 (0.398)	2992	0.076 (0.265)	3026	0.074 (0.261)
Married (HH head)	1 if household head's marital status is married, 0 otherwise	2997	0.825 (0.38)	2992	0.776 (0.417)	3026	0.768 (0.422)
Parent-home (HH head)	1 if household head's mother or father lives in the household, 0 otherwise	2997	0.062 (0.241)	2992	0.041 (0.198)	3026	0.038 (0.192)
Cook (HH head)	1 if household head prepared food last week, 0 otherwise	2997	0.304 (0.46)	2992	0.339 (0.473)	3026	0.342 (0.475)
Lagged cook (HH head)	1 if household head prepared food last week in the last survey year, 0 otherwise	2997	0.223 (0.416)	2992	0.265 (0.441)	3026	0.31 (0.463)
HH size	Number of household members	2992	3.751 (1.412)	2988	3.507 (1.431)	3020	3.609 (1.562)
House-owner	1 if household is the owner of dwelling, 0 otherwise	2992	0.929 (0.256)	2988	0.95 (0.218)	3026	0.952 (0.213)
Modern roof	1 if roof made from tile or concrete, 0 otherwise	2992	0.258 (0.437)	2988	0.162 (0.368)	3026	0.103 (0.304)
Modern wall	1 if wall made from brick or concrete, 0 otherwise	2992	0.25 (0.433)	2988	0.162 (0.368)	3026	0.104 (0.305)
Electric lighting	1 if household normally uses electricity for lighting, 0 otherwise	2992	0.974 (0.159)	2988	0.994 (0.08)	3026	0.99 (0.099)
Toilet type							
No toilet	There is no toilet in household	2992	0.018 (0.132)	2988	0.017 (0.13)	3026	0.019 (0.135)

Out-house toilet	Toilet is out of house	2992	0.747 (0.435)	2988	0.686 (0.464)	3026	0.668 (0.471)
Agricultural assets (ϕ)							
Livestock	1 if household specializes in livestock-raising activity, 0 otherwise	2997	0.009 (0.095)	2992	0.017 (0.128)	3026	0.016 (0.124)
Farmland size	Size of land cultivated in household (mu)	2997	4.135 (9.9)	2992	4.276 (8.88)	3026	4.019 (10.49)
Environment (V) **and** (θ)							
Economic open area	1 if community near open trade area or open city or special economic zone, 0 otherwise	2894	0.472 (0.499)	2972	0.425 (0.494)	3026	0.351 (0.477)
Local collective firm	1 if there is collective enterprise run by village or neighborhood in community, 0 otherwise	2841	0.372 (0.483)	2972	0.169 (0.375)	3026	0.165 (0.371)
Electricity supply	Number of days per week electrical power is cut off	2997	0.361 (1.265)	2992	0.254 (0.592)	3026	0.331 (0.845)
Agricultural activities (%)	Proportion of work force engaged in agricultural activity in community	2806	58.94 (27.3)	2906	49.03 (29.76)	3006	45.14 (28.07)
Migrants (%)	Proportion of work force working outside town for more than one month	2825	28.08 (22.24)	2866	30.19 (24.62)	3006	30.16 (22.73)
Northeast region	1 if household lives in northeast region, 0 otherwise	2997	0.221 (0.415)	2992	0.221 (0.415)	3026	0.222 (0.416)
Central region	1 if household lives in central region, 0 otherwise	2997	0.446 (0.497)	2992	0.444 (0.497)	3026	0.443 (0.497)
East region	1 if household lives in east region, 0 otherwise	2997	0.221 (0.415)	2992	0.218 (0.413)	3026	0.216 (0.412)
Distance to free market	Distance to free market for buying meat, poultry, and eggs	2980	1.433 (1.75)	2992	1.694 (2.305)	3026	1.962 (3.198)

Note: jin: half a kilo

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

Independent variables	**RE-logit**	**RE-Multinomial logit**			
	Clean choice	Wood/straw	Coal	LNG	Electricity
Coal price (ln)	-0.013	0.098***	-0.05*	-0.029*	-0.018
	(0.572)	(0.000)	(0.071)	(0.085)	(0.156)
LNG price (ln)	0.095	0.118	-0.311***	0.07	0.122***
	(0.084)	(0.188)	(0.000)	(0.182)	(0.007)
Electricity price (ln)	-0.155***	-0.093*	0.197***	-0.029	-0.074***
	(0.003)	(0.092)	(0.000)	(0.42)	(0.01)
Rice price (ln)	-0.077	0.074	-0.058	-0.028	0.012
	(0.13)	(0.176)	(0.323)	(0.48)	(0.704)
Cabbage price (ln)	-0.022	0.022	0.01	-0.027**	-0.006
	(0.165)	(0.202)	(0.533)	(0.019)	(0.513)
Pork price (ln)	0.111*	-0.088	-0.077	0.047	0.118***
	(0.075)	(0.126)	(0.174)	(0.264)	(0.000)
Beef price (ln)	0.05	-0.081*	-0.042	0.163***	-0.041*
	(0.276)	(0.078)	(0.377)	(0.000)	(0.071)
Mutton price (ln)	-0.022	-0.007	0.052**	-0.081***	0.037***
	(0.398)	(0.77)	(0.037)	(0.000)	(0.013)
Unbleached flour price (ln)	0.119***	-0.146***	-0.065	0.179***	0.032
	(0.004)	(0.001)	(0.139)	(0.000)	(0.133)
Unbleached flour price (ln)* Farmland size	-0.005*	0.009***	0.01***	-0.022***	0.003*
	(0.093)	(0.012)	(0.014)	(0.000)	(0.091)
Pork price (ln)* Livestock	-0.268	0.631**	-0.289	-0.315	-0.027
	(0.266)	(0.052)	(0.273)	(0.224)	(0.876)
HH income (ln)	0.059***	-0.061***	-0.006	0.063***	0.004
	(0.000)	(0.000)	(0.442)	(0.000)	(0.401)
One-child subsidy	0.076**	-0.069	-0.017	0.007	0.079***
	(0.035)	(0.148)	(0.752)	(0.822)	(0.002)
Electricity subsidy	0.197***	-0.091	-0.118	0.053	0.157***
	(0.005)	(0.426)	(0.191)	(0.366)	(0.000)
Household preferences (Z)					
Age (HH head)	-0.003***	0.002***	0.0006	-0.002***	-0.0009**
	(0.000)	(0.000)	(0.327)	(0.000)	(0.019)
Gender (HH head)	-0.022	0.074***	-0.052**	-0.031	0.01
	(0.321)	(0.004)	(0.024)	(0.112)	(0.545)
High education (HH head)	0.055	-0.058	-0.026	0.056*	0.029
	(0.133)	(0.26)	(0.58)	(0.059)	(0.173)
Public sector (HH head)	0.032	-0.009	-0.02	0.005	0.024*
	(0.111)	(0.705)	(0.366)	(0.767)	(0.082)
Married (HH head)	-0.006	-0.036*	0.033*	0.011	-0.009
	(0.784)	(0.096)	(0.104)	(0.545)	(0.54)
Parent-home (HH head)	-0.074***	0.043	0.015	-0.027	-0.031
	(0.011)	(0.152)	(0.607)	(0.319)	(0.164)
Cook (HH head)	0.018	-0.002	-0.037**	0.031**	0.008
	(0.203)	(0.923)	(0.021)	(0.02)	(0.418)
Lagged cook (HH head)	0.03**	-0.013	-0.036**	0.042***	0.006
	(0.036)	(0.45)	(0.026)	(0.001)	(0.536)
HH size	-0.014***	0.007	0.009*	-0.015***	-0.001

	(0.003)	(0.147)	(0.072)	(0.001)	(0.674)
House-owner	-0.02	0.067*	-0.037	-0.021	-0.009
	(0.509)	(0.059)	(0.227)	(0.438)	(0.626)
Modern roof	-0.007	-0.028	0.024	-0.017	0.021
	(0.894)	(0.598)	(0.618)	(0.749)	(0.525)
Modern wall	0.03	-0.01	-0.001	0.015	-0.003
	(0.59)	(0.847)	(0.977)	(0.769)	(0.917)
Electric lighting	0.059	-0.096*	0.058	0.006	0.033
	(0.362)	(0.102)	(0.376)	(0.927)	(0.584)
No toilet	-0.259***	0.132**	0.183***	-0.116**	-0.199***
	(0.000)	(0.015)	(0.001)	(0.034)	(0.011)
Out-house toilet	-0.121***	0.135***	0.037*	-0.153***	-0.019*
	(0.000)	(0.000)	(0.086)	(0.000)	(0.078)
Household endowments (ϕ)					
Livestock	0.524	-1.405**	0.722	0.59	0.092
	(0.301)	(0.043)	(0.191)	(0.283)	(0.803)
Farmland size	-0.00004	0.002***	-0.0003	-0.002***	0.0006*
	(0.95)	(0.003)	(0.71)	(0.000)	(0.094)
Environment Variables (V) **and** (θ)					
Economic open area	0.013	-0.052**	-0.003	0.048***	0.007
	(0.505)	(0.03)	(0.912)	(0.001)	(0.558)
Local collective farm	0.063***	-0.054**	-0.002	0.031**	0.025**
	(0.004)	(0.022)	(0.937)	(0.032)	(0.027)
Electricity supply	0.0003	0.0003	0.015*	-0.013*	-0.002
	(0.977)	(0.977)	(0.06)	(0.098)	(0.685)
Agricultural activity %	-0.001**	0.001***	-0.0002	-0.001***	-0.0004**
	(0.015)	(0.001)	(0.615)	(0.001)	(0.052)
Migrants* Year 2000 %	0.001*	-0.0008	4.47e-07	0.001**	-0.0004
	(0.089)	(0.286)	(1.000)	(0.017)	(0.466)
Migrants* Year 2004 %	-0.0008	0.0009	-0.0003	-0.0003	-0.0003
	(0.176)	(0.153)	(0.663)	(0.544)	(0.367)
Northeast region	0.409***	0.36***	-0.705***	0.287***	0.058**
	(0.000)	(0.002)	(0.000)	(0.000)	(0.015)
Central region	0.147**	0.363***	-0.51***	0.247***	-0.101***
	(0.021)	(0.000)	(0.000)	(0.000)	(0.000)
East region	0.247***	0.572***	-0.807***	0.342***	-0.107***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Distance to free market	-0.006	0.011**	0.003	-0.015***	0.002
	(0.202)	(0.045)	(0.632)	(0.000)	(0.286)
Year 2000	-0.146***	0.226***	-0.204***	0.027	-0.05
	(0.011)	(0.000)	(0.002)	(0.521)	(0.115)
Year 2004	-0.101***	0.057*	0.044	-0.022	-0.078***
	(0.002)	(0.083)	(0.158)	(0.378)	(0.000)
Observations	4990				4990
Variance of random effects	1.81				2.56
Log likelihood	-1978.28				-3910.57

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

Table 6
Marginal effects of RE-logit and RE-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)	-0.011	0.059***	-0.045**	-0.014
	(0.619)	(0.014)	(0.05)	(0.328)
LNG price (ln)	0.121	-0.173**	0.015	0.157***
	(0.153)	(0.029)	(0.832)	(0.001)
Electricity price (ln)	-0.124**	0.128***	-0.144***	0.016
	(0.021)	(0.008)	(0.002)	(0.608)
Rice price (ln)	-0.079*	-0.009	-0.044	0.053
	(0.124)	(0.848)	(0.358)	(0.116)
Cabbage price (ln)	-0.023	-0.06***	0.083***	-0.023**
	(0.149)	(0.000)	(0.000)	(0.028)
Pork price (ln)	0.118*	-0.078	0.003	0.075**
	(0.062)	(0.161)	(0.951)	(0.041)
Beef price (ln)	0.047	-0.041	-0.007	0.049*
	(0.308)	(0.328)	(0.852)	(0.063)
Mutton price (ln)	-0.025	-0.019	0.059**	-0.04**
	(0.345)	(0.455)	(0.018)	(0.015)
Unbleached flour price (ln)	0.106***	-0.075*	0.042	0.032
	(0.011)	(0.064)	(0.279)	(0.183)
Unbleached flour price* Farmland size	-0.005*	0.001	-0.003	0.002
	(0.13)	(0.781)	(0.593)	(0.723)
Pork price* Livestock	-0.196	-0.318	0.22	0.098
	(0.442)	(0.329)	(0.526)	(0.617)
HH income (ln)	0.06***	-0.059***	0.035***	0.024***
	(0.000)	(0.000)	(0.000)	(0.000)
One-child subsidy	0.074**	-0.037	0.027	0.01
	(0.04)	(0.425)	(0.562)	(0.623)
Electricity subsidy	0.198***	0.006	-0.101	0.095***
	(0.005)	(0.94)	(0.232)	(0.013)
Household preferences (Z)				
Age (HH head)	-0.003***	0.004***	-0.002***	-0.002***
	(0.000)	(0.000)	(0.001)	(0.000)
Gender (HH head)	-0.017	0.003	0.005	-0.008
	(0.445)	(0.904)	(0.841)	(0.569)
High education (HH head)	0.051	-0.078	0.03	0.047**
	(0.162)	(0.112)	(0.529)	(0.018)
Public sector (HH head)	0.028	-0.005	-0.029	0.034***
	(0.167)	(0.845)	(0.229)	(0.005)
Married (HH head)	-0.001	0.018	0.001	-0.018
	(0.963)	(0.367)	(0.978)	(0.175)
Parent-home (HH head)	-0.066**	0.024	0.04	-0.064***
	(0.024)	(0.396)	(0.206)	(0.003)
Cook (HH head)	0.015	-0.013	0.008	0.006
	(0.314)	(0.369)	(0.636)	(0.552)
Lagged cook (HH head)	0.03**	-0.016	0.016	0.001
	(0.044)	(0.282)	(0.338)	(0.954)
HH size	-0.016***	-0.006	0.015***	-0.009***
	(0.001)	(0.183)	(0.002)	(0.005)
House-owner	-0.021	0.026	-0.022	-0.004

	(0.487)	(0.412)	(0.517)	(0.837)
Modern roof	-0.006	0.004	0.075	-0.079*
	(0.914)	(0.94)	(0.214)	(0.057)
Modern wall	0.023	0.003	-0.102*	0.099**
	(0.682)	(0.951)	(0.095)	(0.017)
Electric lighting	0.084	-0.107*	0.06	0.046
	(0.22)	(0.102)	(0.414)	(0.342)
No toilet	-0.26***	0.178***	-0.029	-0.149***
	(0.000)	(0.000)	(0.603)	(0.001)
Out-house toilet	-0.133***	0.135***	-0.064***	-0.071***
	(0.000)	(0.000)	(0.001)	(0.000)
Household endowments (ϕ)				
Livestock	0.373	0.593	-0.387	-0.206
	(0.488)	(0.381)	(0.597)	(0.626)
Farmland size	-0.0001	0.002***	0.005***	-0.007***
	(0.915)	(0.001)	(0.001)	(0.000)
Environment Variables (V) **and** (θ)				
Economic open area	0.012	-0.044**	0.055***	-0.011
	(0.561)	(0.022)	(0.004)	(0.405)
Local enterprise	0.062***	-0.046**	0.052***	-0.006
	(0.005)	(0.029)	(0.01)	(0.645)
Electricity supply	0.0003	0.014*	-0.005	-0.008
	(0.97)	(0.094)	(0.551)	(0.263)
Agricultural activity %	-0.001***	0.001	0.0005	-0.001***
	(0.008)	(0.162)	(0.18)	(0.000)
Migrants* Year 2000 %	0.001*	-0.002***	0.003***	-0.001**
	(0.077)	(0.012)	(0.000)	(0.037)
Migrants* Year 2004 %	-0.001*	0.001	-0.0003	-0.0004
	(0.126)	(0.195)	(0.614)	(0.25)
Northeast region	0.416***	-0.592***	0.37***	0.222***
	(0.000)	(0.000)	(0.000)	(0.000)
Central region	0.148**	-0.148**	0.066	0.081**
	(0.02)	(0.015)	(0.11)	(0.029)
East region	0.251***	-0.393***	0.292***	0.1***
	(0.000)	(0.000)	(0.000)	(0.013)
Distance to free market	-0.007*	0.015***	-0.004	-0.01***
	(0.14)	(0.001)	(0.244)	(0.001)
Year 2000	-0.136**	0.198***	-0.223***	0.025
	(0.018)	(0.000)	(0.000)	(0.464)
Year 2004	-0.094***	0.082***	-0.05	-0.032
	(0.004)	(0.005)	(0.113)	(0.145)
Observations	4892			4892
Variance of random effects	1.785			5.293
Log likelihood	-1925.06			-3113.19

Notes: The estimated marginal effects of explanatory variables are reported. P-values are presented in parentheses. Clean-fuel dominance is defined as 1 if clean fuels are predominantly used, and 0 if dirty fuels are predominantly used.
* Significance level of 10%; ** Significance level of 5%; *** Significance level of 1%.

Table 7
Predicted proportions of households by primary cooking fuel

	Wood/straw	**Coal**	**LNG**	**Electricity**
	Change (%)	Change (%)	Change (%)	Change (%)
Scenario 1	-2.01	6.14	-0.49	-6.61
Scenario 2	-11.39	31.37	-4	-29.61
Scenario 3	3.61	-1.4	-0.97	-1.76

Note: The change in the proportion of households compares the predictions under different scenarios and the percentage predicted by RE-MNL models for primary fuel choice. Scenario 1 supposes that electricity price increases by 0.05 yuan. Scenario 2 supposes that electricity price increases by 0.3 yuan. Scenario 3 supposes that coal price increases by 11 percent.

Table A1
Consumer energy price indices by province

Region	**2000**	**2004**	**2006**
Guangxi	111.9	130	148
Guizhou	104.8	116.4	137
Heilongjiang	108.4	133.9	158.2
Henan	104.2	136.4	161.4
Hubei	105	129.8	150.5
Hunan	102.9	120.8	141.9
Jiangsu	107.9	122.7	134.7
Liaoning	97.1	135.1	148.9
Shandong	105.4	140.7	161.7

Source: Authors' calculation from China National Bureau of Statistics
Note: 1999: 100.