Pergamon

www.elsevier.com/locate/worlddev

World Development Vol. 28, No. 12, pp. 2083–2103, 2000
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Printed in Great Britain
0305-750X/00/$ - see front matter

PII: S0305-750X(00)00076-0

From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model

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Summary. — Promoting sustainable development requires evaluating the technical and policy options that will facilitate the adoption and use of energy efficient and less polluting cooking stoves and practices. The transition from traditional to modern fuels and devices has been explained by the "energy ladder" model that suggests that with increasing affluence, a progression is expected from traditional biomass fuels to more advanced and less polluting fuels. In this paper we evaluate the energy ladder model utilizing data from a four-year (1992–96) case study of a village in Mexico and from a large-scale survey from four states of Mexico. We show that an alternate "multiple fuel" model of stove and fuel management based on the observed pattern of household accumulation of energy options, rather than the simple progression depicted in the traditional energy ladder scenario, more accurately depicts cooking fuel use patterns in rural households. The "multiple fuel" model integrates four factors demonstrated to be essential in household decision making under conditions of resource scarcity or uncertainty: (a) economics of fuel and stove type and access conditions to fuels, (b) technical characteristics of cookstoves and cooking practices; (c) cultural preferences; and (d) health impacts. This model also allows better estimates of the expected fuelwood demand and indoor air pollution in rural households. © 2000 Elsevier Science Ltd. All rights reserved.

Key words — fuels, cooking, households, rural development, energy ladder, Mexico

* We would like to thank the comments, suggestions and insights from two anonymous reviewers. We are indebted to Jaime Navia and the rest of the researchers at GIRA. Consuelo Suarez Alfaro, M. D. of the Centro de Estudios Sociales y Ecologicas, A. C. provided essential contacts within Jarácuaro and helped develop the health interviews. Guadalupe Capilla Constantino lent her technical assistance and her friendship to further the project. Ongoing conversations and critical feedback from Daniel Klooster, Burton Singer and Kirk R. Smith are also gratefully acknowledged. We thank René Martinez for his help in the formatting of text and graphs. This work was supported by a Fulbright Garcia-Robles Fellowship to B. D. S., Summer Research Support from the Woodrow Wilson School, grants from the Summit and Compton Foundations, and the Class of 1935 Preceptorship, awarded to D. M. K. Final revision accepted: 16 June 2000.

1. INTRODUCTION

Researchers have often attempted to understand the dynamics of energy use in families of varying incomes by reference to the "energy ladder" as a model for household decisions to substitute or to switch between available fuels (Baldwin, 1986; Smith, 1987; Hosier & Dowd, 1988; Leach & Mearns, 1988, Leach, 1992). In one of its more common interpretations, which we refer here as the "traditional energy ladder," this model proposes that, as families gain socioeconomic status, they abandon technologies that are inefficient, less costly, and more polluting, i.e. "lower" on the energy ladder, such as dung, fuel wood, and charcoal (Smith, 1987; Barnes & Floor, 1996). This dynamic is represented schematically in Figure 1. An increase in available income allows them to leave these fuels behind, and purchase technologies (stoves and fuels) "higher" on the ladder. These "advanced" technologies are usually more efficient and costly, but require less inputs of labor and fuel, and produce less pollution per unit of fuel. Implicit in this model is the notion that the use of each different fuel or stove carries with it a certain status. The energy ladder assumes that more expensive technologies are locally and internationally perceived to signify higher status, and that families desire to move up the energy ladder not just to achieve greater fuel efficiency or less direct pollution exposure [1], but to demonstrate an increase in socioeconomic status. Even when this model is augmented with somewhat more complex dynamics of economic and social factors, the picture that emerges is essentially linear: a simple progression from traditional to modern fuels and from traditional to more efficient, and costly stoves, as a household income increases (Barnes & Floor, 1996).

In this paper we examine the process of fuel switching using an alternate, "multiple fuel", model which requires the consideration of four factors essential in household decision making under conditions of resource scarcity or uncertainty: (a) economics of fuel and stove type and access conditions to fuels, (b) technical characteristics of cookstoves and cooking practices; (c) cultural preferences; and (d) health impacts. Specifically, we use data from three Mexican states and one illustrative village to show that rural households do not "switch" fuels, but more generally follow a multiple fuel or "fuel stacking" strategy by which new cooking technologies and fuels are added, but even the most traditional systems are rarely abandoned. From this perspective, household fuels, rather than pertaining to a ladder of preferences with one fuel clearly better than the others, possess both desirable and undesirable characteristics, which need to be understood

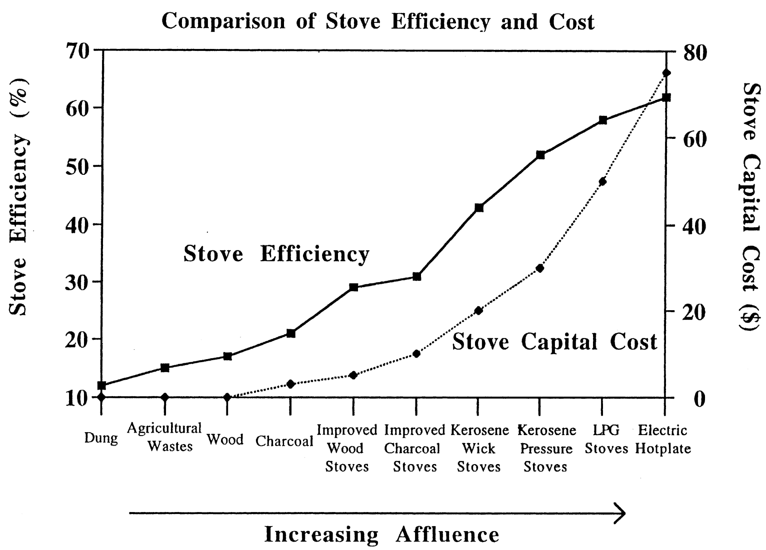

Figure 1. *Schematic representation of the energy ladder hypothesis, which characterizes the general movement towards increased stove and fuel cost associated with increasing affluence. Modified from (OTA, 1991).*

within a specific historic and cultural context. The specific fuel-mix choice and the relative consumption of each fuel is governed by the characteristics of the fuels and end-use devices; specific aspects related to fuel availability, and the local cultural and social context that determines household preferences regarding cooking fuels and lifestyles.

We argue that this change in perspective regarding fuel switching is essential for an improved assessment of future rural energy demand and, specifically, for the framing of policies that will promote sustainable fuelwood use in villages and small towns. A number of policy conclusions relevant to the design and monitoring of stove adoption programs naturally emerge from the multiple fuel model. First, simple measures of household energy use and stove "selection" are often largely inaccurate, with a more complete description of fuel and stove uses required instead. Second, while the health benefits of reduced particulate and trace gas emissions from improved stoves are often compelling, the variety of stoves concurrently used within one household obscures the identification and quantification of these benefits. Third, the particular challenges and opportunities that exist in assisting families that wish to discard energy inefficient or polluting technologies have been largely unaddressed by existing programs.

The multiple fuel model explains a number of features of the adoption or rejection of new technologies and fuel use products generally, as well as patterns of household morbidity, that have previously been ignored or unexplained by the traditional energy ladder. We find that it is unusual for families to make a complete "fuel switch" from one technology to another; rather, they begin to use an additional technology without abandoning the old one. The multiple fuel strategy helps households maximize fuel security and at the same time receive the advantages of different fuels. Contrary to the traditional energy ladder model, when new energy sources are used concurrently with preexisting technologies, the total emissions released and energy used by the household may increase as families move "up the energy ladder." In the case of Jarácuaro and the rest of Mexican villages the primary fuel switch is from biomass fuels to gas.

We utilize a range of longitudinal information from Jarácuaro, a village in the Purepechan Lake Patzcuaro Region of central Michoacan, Mexico, gathered over four years (1992–96) of periodic household surveys and emissions measurements to validate the multiple fuel model of household energy dynamics. We also rely on evidence from other detailed studies of household energy use conducted in the same region and in other Mexican states during 1992–97 (Arias & Riegelhaupt, 1997a; Masera, Navia, Cedeño, Ruiz, & Ochoa, 1997a; López, Cayetano, González, & Riegelhaupt, 1997; Masera & Navia, 1997).

We begin the paper with a description of the methods used for data collection and analysis. The second section examines the main premises of the energy ladder model, with particular reference to rural households and tests this model in Mexican rural households. The fourth section discusses the "multiple fuel" model, including the health impacts related to cooking fuels. The paper ends with a discussion of the policy implications arising from the proposed new perspective on household fuel dynamics.

2. METHODS

(a) *The Jarácuaro study site*

Jarácuaro village was once an island, but is now a peninsula due to the decline in the level of Lake Pátzcuaro. The population is close to 2,500 (approximately 450 households) and includes ~220 hectares of land. Jarácuaro is well suited for an integrated assessment of the impact of fuel and stove substitution on intra- and interhousehold dynamics, health, and economic development. Commercial markets exist for a variety of stoves and fuels. The region around the village is heavily deforested, and a fuelwood market is well established. Fuelwood costs ~0.2 pesos/kg. (As of August 1996, the exchange rate was 7.5P = US$ 1.00, which is used throughout this paper.) Over 90% of the families in Jarácuaro purchase wood weekly. In neighboring communities woodfuel is also used in small pottery, brick-making, and baking industries (Masera *et al.*, 1997a; Fernández *et al.*, 1997; Hibbert, 1997). Household fuelwood use averages 0.8–1.5 m^3 cap^{-1} yr^{-1}. Masera *et al.* (1997a) estimates household wood use in the Patzcuaro Lake region to be approximately 80,000 m^3 yr^{-1} and the commercial demand 46,000 m^3 yr^{-1}. Logging removes in excess of 140,000 m^3 yr^{-1}.

The LPG supply system is also well developed. There has been a regular (weekly or biweekly) LPG supply since the construction of the road to the main land in the early 1980s (Saatkamp, Masera, & Kammen, 1998). An estimated 57% of total households currently use LPG for cooking. LPG is sold in 30 kg cylinders, and costs 53 pesos/cylinder (1.76 pesos/kg). [2] LPG prices have escalated steadily in real terms since 1995. Further, as discussed below, the price of LPG relative to fuelwood has escalated almost four-fold during 1992–96.

The types of stoves available for use in Jarácuaro, listed here from most basic and least expensive to most complicated and costly, are as follows. The simplest of cookstove types, the three stone fire (TSF) consists of three stones on a dirt floor surrounding a fire. The comal, a flat, round clay surface heated over a fire to make tortillas, or any other cooking receptacle, is rested on top of the three stones which serve as "feet" for the comal or pot and raise it above the fire. The fire beneath it can be fed from all angles, and the combustion chamber is not enclosed. The U-type cook stove is slightly more complicated; like the TSF it rests directly on the floor, but the combustion chamber is enclosed on three sides by a "U" of adobe and/or rocks. The comal or pot rests on top of the u-shaped enclosure and the fire is fed from the front. The chimenea is basically an elevated U-type stove, with the combustion chamber surrounded on three sides by an adobe, cement or stone "U" and sitting on a platform of stone or cement so that the entire structure is waist high for the cook. The *lorena* cookstove is an improved biomass cook stove, similar in size and height to the chimenea, but with specific dimensions for a more enclosed combustion chamber and a chimney for drawing smoke out of the room. Finally, LPG stoves are gas stoves from one to four burners, and may either be table top units, free standing, or free standing with an oven below. They are fueled by replaceable LGP tanks.

(b) *The Jarácuaro longitudinal study (1992–1996)*

The longitudinal energy study presented in this paper began in 1992 with the selection of a cohort of 41 families representing four socioeconomic groupings within the village. The household sample gathered is stratified socioeconomically because extensive kinship and exchange networks, and nonmonetary income sources preclude a simple univariate income ranking. A four-tier ranking is used to maintain consistency and build on previous research in the region (Masera, 1993). Households were representative of the local socioeconomic groups, categorized as low (group IV), mid-low (III), mid-high (II), and high (I). Households were assigned to one of the four categories based on survey information, the preliminary interviews, and assessments of the local community perception of family wealth and status. The ranking was in accordance with a variety of local assessments, both subjective and based on resource inventories, with the most direct measures based primarily on family employment and by level of access to land, animal and mechanical resources. The sample included families that cooked exclusively with fuel wood and those that cooked simultaneously with fuelwood and LPG.

These families all responded to a Household Energy Use Survey by answering questions posed to them by the same researcher. Twelve families also participated in a week-long kitchen performance test (KPT) to determine the amount of fuel wood used per capita per week, and controlled cooking tests (CCT) tests were performed on each stove type in several kitchens. In a previous study in the area (Masera *et al.*, 1989), household fuelwood use was found to vary approximately 30% within the year. The measurements for this study were taken in a month where consumption was found to be closer to the year-long average consumption.

The second phase of the study began in 1995, when a new team of interviewers returned to the same forty households to implement a second questionnaire, building on the prior Household Energy Use Survey. One family was lost to follow up, narrowing the overall longitudinal study to 40 families. A two-day energy consumption study was completed in 35 households to serve as a complement to the prior energy consumption study and reported levels of energy consumption from both the primary and secondary surveys.

(c) *Health data surveys*

In addition to the secondary energy survey, the 1995–96 interview team questioned families extensively on the health of each member of the family. They implemented separate survey forms for the mother and father in a traditional household and a joint form for the children which required the respondent to specify which child was involved in each positive response. In this manner, the team collected information on reported illness for 141 individuals.

(d) *Particulate and trace gas data collection and analysis*

Of the original 40 families participating in the Household Energy Surveys and the Health Survey, five were willing to participate in an additional indoor air pollution (IAP) survey. Sixteen other families were then recruited for the IAP study, and were classified using the same socioeconomic status ranking used in the Longitudinal Study. Measurements of both particulates and trace gas emissions were made in these households in both the wet and dry seasons and for a range of food preparations (e.g. *tortillas*, *nixtamal*, and *comida*).

The RSP data were collected by a drawn air filter calibrated to a flow rate of 1.9 l min^{-1} (SKC Inc., Eighty Four, PA). Samples were collected via an SKC cyclone, which removes particles larger than 7.1 mm. The resulting collected particulate matter is roughly comparable to PM_{10}. The exposed filter and a control (matched to within 25 mg) were handled and weighed according to NIOSH (1994) protocol 0600 on a five-digit accuracy electronic balance at the University of Morelia, Mexico (pilot study) and at Texas A&M University. The resulting uncertainty in airborne particulate concentrations is <30 μg m^{-3}. These data consist of 37 ambient control measurements, 24 during the preparation of *nixtamal* (corn base for tortillas), 37 measurements during tortilla preparation, and seven while the main meal, *comida*, is prepared. The measurements lasted for 30–180 min, spanning the period of active food cooking. The pump and filter assembly were worn by the cook, with the air intake valve placed near the right mid-clavicle. To generate a representative concentration parameter for each household, RSP measurements were averaged across food types and data collected during the wet and dry seasons.

Trace gas emissions (CO, CO_2, NO_x, SO_2) were recorded at a set of points around the stove during food preparation: at the location of the stove ($x = 0.0$ m distance, $y = 0.0$ m height above the stove), in the effluent gas column (0.0 m, 1.0 m), at the average location of the cook (0.5 m, 0.5 m), and at grid points extending up to 1.0 m in radius along three cardinal directions. The [CO] data, which are featured in this analysis, and the other trace gas measurements were recorded by an electrochemical sensor manufactured by Energy Efficiency Systems (Westbury, NY). The individual [CO] measurements are accurate to within ± 5 ppm (at standard conditions of 1 atm pressure and 25°C temperature, 1.145 ppm = 1 mg m^{-3}). Measurements were taken every 15 minutes during the cooking of each of the primary foods (*nixtamal*, tortillas, and *comida*). The [CO] cited in this paper is the concentration at the location of the cook (as with the RSP data, averaged over food types, and season). The sample consisted of measurements for: three households using "three stone" fires, four traditional adobe and brick stoves directly on the floor, 13 traditional stoves with the combustion chamber elevated 0.5 m off the floor, two improved efficiency biomass stoves (*lorenas*) with an enclosed combustion chamber and a chimney to vent pollutants outside the home, and one gas stove.

(e) *Additional data*

The research effort at Jarácuaro is part of a long-term regional research strategy aimed at understanding fuelwood use dynamics and developing alternatives for its sustainable use. Within this strategy, several studies have been carried out in neighboring villages, including a longitudinal study in Cheranatzicurin village carried out during 1987–94 (Masera, 1994), and a cross-sectional study in Huancito village (Masera & Navia, 1997). A contemporary study was also carried out in the Patzcuaro Lake Region and in two other regions belonging to two different states of rural Mexico (Arias, Padilla, & Riegelhaupt, 1997; López, Cayetano, González, & Riegelhaupt, 1997; Masera, Navia, Cedeno, Ruiz, & Ochoa, 1997a; Masera, Navia, & Arias, 1997b). Currently, research continues on the design, evaluation, and dissemination of improved cookstoves at the regional level (Puentes & Masera, 1999). All the surveys mentioned included both household interviews as well as direct measurements of household fuel consumption. The methodology used was comparable across studies.

3. THE ENERGY LADDER MODEL: ADVANTAGES AND LIMITATIONS

A number of researchers using the energy ladder model (Baldwin, 1986; Hosier & Dowd, 1988; Smith, 1987; Leach, 1992) have attempted to describe households' energy use dynamics indirectly through the analysis of fuel switching [3] patterns from biofuels to modern fuels. This model has been derived from the empirical evidence that so-called 'modern' fuels are increasingly used as household income increases in urban areas. Preferences for switching include convenience in obtaining, storing, and using the fuels (cleanliness, versatility and a large and easily controlled range of power output) (Leach, 1988) and lower fuel costs (Reddy & Reddy, 1994). The opportunity cost of women's time—particularly for those women who work outside the household—has also being shown to have a major impact in fuel switching (Sathaye & Tyler, 1991).

Fuel switching—from biofuels to modern fuels—is then thought to occur along a preference ladder, the speed and extent depending on factors such as equipment costs, physical access to and network reliability of modern fuels, household incomes, and, to a lesser extent, relative fuel prices. Policy recommendations deriving from the model include increasing the availability of modern fuels to poor households either through subsidies, improvements in the network reliability of modern fuels, better commercialization schemes for alternative stoves, and other measures.

Several authors have noted that the "ladder" hypothesis is a simplified version of the actual fuel switching process, where multiple fuel patterns and switch back processes may occur (Leach & Mearns, 1988; Leach, 1992; Soussan, O'Keefe, & Munslow, 1990). Most research in the area has concentrated, however, on the study of the patterns of adoption and use of modern fuels alone, which has resulted in a tendency to view the energy ladder as a linear process, particularly through the fuel transition approach. For example, in its more extreme interpretation, the process of fuel switching (termed fuel transition) has been equated with a "development path" (Smith, 1987). According to this view, households using different fuels belong to different "development levels," at the bottom of the scale are fuelwood users, and at the top electricity users. In addition, the process of moving from wood to a higher value modern fuel has been interpreted as a linear, unidirectional, or "natural" process driven by increasing household incomes. The implicit premises of this latter interpretation are: that households effectively consider some fuels clearly better than others for all cooking tasks; biofuels are used only because of income and infrastructure constraints. The energy implications of fuel switching are usually estimated using energy efficiency ratios (Appendix A).

A more elaborate version of the fuel preference-ladder approach comes from the studies about interfuel substitution in urban households (Dowd, 1989; Fitzgerald, Barnes, & McGranahan, 1990; Barnes & Qian, 1992). Using neoclassical economics as the basic theoretical framework, these studies derive an econometric energy demand model to find out how demographic, infrastructure-related, and economic variables influence urban households' decisions regarding the use of alternative fuels. [4] In contrast with the fuel transition approach, this model, which we will refer to as the "econometric approach" to fuel switching, accounts for the observed fact that fuels are many times "imperfect substitutes" (Dowd, 1989), with each fuel being used for the specific tasks where it scores the best (Evans, 1987; Tinker, 1980). An interesting result of these analyses is to show that usually fuel savings are not directly proportional to the comparative efficiency of cooking stoves (Fitzgerald *et al.*, 1990). See Appendix B for a description of the mathematical formulation of the model.

(a) *Fuel switching in rural areas*

At the moment, the process of fuel switching in rural areas is very poorly understood (Leach, 1992). On the one hand, there are few studies on the topic (see for example Kaul & Liu, 1992; Davis, 1995; Alberts, Moreira, & Pérez, 1997). On the other hand, the use of conventional approaches like the traditional fuel preference ladder is even more problematic in the rural sector than in the urban sector. To begin with, biofuels are mostly collected, representing zero monetary costs for households; when significant, markets for modern fuels have high transaction costs given the poor access and reliability of supply. Using income categories to examine the process of switching is also difficult as usually a large portion of rural household incomes is nonmonetary. In addition, household cash incomes are, many times, more uncertain and variable than in urban households, thus regular consumption of modern fuels is more difficult. There is a need for a more adequate explanation for the process of partial switching; in particular, regarding the conditions that favor or constrain temporary interfuel substitution among cooking practices.

Finally, the local culture relating to cooking practices and methods tends to be stronger than in urban areas. A large household energy survey conducted in rural China showed, for example, no clear fuel switching patterns across households in terms of conventional explanations like increasing household incomes or shifting fuel prices (Kaul & Liu, 1992).

(b) *The energy ladder applied to Jarácuaro and other mexican villages*

We observe a number of factors in Jarácuaro and other Mexican villages that call the traditional energy ladder model into question. First, families in Jarácuaro add fuels and stove types, but seldom leave any fuel or stove type behind completely. Second, household energy use for cooking as families do adopt technologies that are considered to be "more advanced" is not always decreasing. Finally, economic development does not necessarily lead to less pollution in kitchens or households. In other words, fuel switching may not always result in improvements in energy and household economics.

(i) *Fuel switching is not unidirectional and LPG does not completely substitute fuelwood*

Access to LPG increases in households with higher monetary income due to its high initial investment cost, resulting from the need to purchase a new stove, a gas cylinder and some accessories (see Figure 2 and Table 1).

The process is not simple, however, and does not imply abandoning fuelwood use. We observed that, of the seven families adopting LPG technologies in the period between phase one and two of the longitudinal study, none of the families ceased using fuelwood. Furthermore, the transition between a family using fuelwood alone to using a combination of fuelwood and LPG is not unidirectional. Three families ceased to use their gas stoves and returned to cooking exclusively with fuelwood during the course of the study. The reasons for these changes are complex, and cannot be ascribed to a particular variable. For example, all of the families abandoning LPG showed a reduction in family size and two of them belonged to the lowest income groups, indicating that household economic forces play a role in a families ability to maintain their use of modern fuels (Table 1). On the other hand, families adopting LPG did so in spite of losing some jobs (however, remittances from relatives living in the United States were not accounted for in the survey). Three of the seven families in this category belong to the two higher income groups, while four of them are in the two lower income groups. The adoption of LPG occurred while the price of LPG increased almost four times relative to that of fuelwood. Households that remained as fuelwood-only users or mixed fuelwood-LPG users showed no or a small positive change in household size and a stable main occupational structure; all households also remained in the same income group. Fuelwood consumption was similar for households that relied entirely on fuelwood and those that dropped LPG in the period. Mixed users during the whole longitudinal study showed 10% average savings with respect to fuelwood users, while those households adopting LPG reached 30% average savings (however, differences were not statistically significant among the two groups) (Table 1).

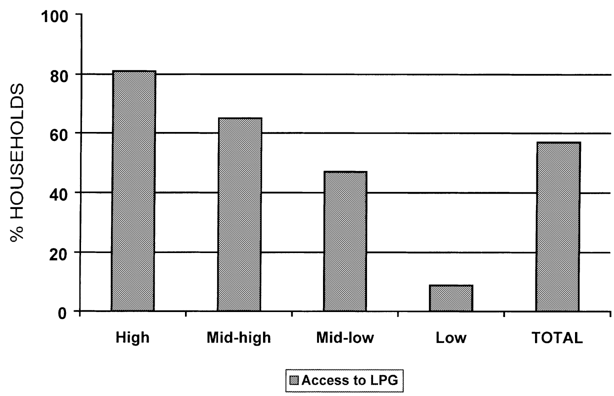

Figure 2. *Percentage of multiple fuel users by income group. The graph shows the percentage of households that combine LPG and fuelwood for cooking by income group and for the village total.*

Table 1. *Selected changes associated with households keeping, adding or dropping cooking fuels, in Jaracuaro village 1992–96*

Category of user	*N*	Average family size changes (1992–96)	Average income group	Changes in main occupation	Fuelwood use (kg/cap/day)[a]	Evolution of relative prices fuelwood/LPG 1992	Evolution of relative prices fuelwood/LPG 1996
Fuelwood-only that remained as such	9	6.8 ± 2.5 (0)	High 22% Mid-high 11% Mid-low 22% Low 44%	None 7 Gained 1 (job in Mexico city) Lost 1 job (mason)	1.9 ± 0.6		
Mixed fuelwood-LPG that remained as such	20	7.2 ± 2.2 (0.6)	High 25% Mid-high 30% Mid-low 35% Low 10%	None 19 Gained 0 Lost 1 (carpinter)	1.8 ± 2.3	3.61	12.96
Added LPG	7	5.3 ± 2.5 (0.6)	High 33% Mid-high 0% Mid-low 33% Low 33%	None 5 Gained 2 Lost 2 (mason, agricultural worker)	1.4 ± 0.6		
Abandoned LPG	3	6.7 ± 2.3 (−1.3)	High 14% Mid-high 29% Mid-low 43% Low 14%	None 3 Gained 0 Lost 0	2.0 ± 0.6		

[a] Data on fuelwood consumption were not precise enough to detect changes over time in the different categories of users. All households stayed in the same income level categories from 1992–96.

Table 2. *Percentage of households by type of cooking fuel used*

	Fuelwood-only users (%)	Mixed fuelwood-LPG users (%)	LPG users (%)
Jarácuaro village (1992)	57	43	<0.5
Huancito village (1992)	73	27	0
Patzcuaro lake survey (1996)[a]	51	42	7
Altos de Mixtepec survey, Oaxaca state (1996)	75	25	0
Tlapa Valley survey, Guerrero state (1996)	19	65	16

[a] The Patzcuaro lake survey included four villages (Masera *et al.*, 1997a). Data for Huancito village from Masera, (1994), for Oaxaca State from López *et al.* (1997) and for Guerrero State from Arias *et al.* (1997). The Guerrero State survey includes a city of 25,000 inhabitants.

In the larger survey conducted in three Mexican states, none of the households in Oaxaca state, only 7% in Michoacan state, and 16% in Guerrero state have completely switched to LPG (Masera *et al.*, 1997b). Within rural areas, virtually all households adopting LPG are multiple fuel users, and this strategy is dominant even in relatively large towns such as Tlapa in Guerrero state (25,000 inhabitants) (Masera *et al.*, 1997b; Arias, Padilla, & Riegelhaupt, 1997) (Table 2).

In addition to the economics of fuel and stove use, two other factors appear to influence a family's switch from one fuel to another, or in the Jarácuaro case, the addition of a fuel or stove type without abandonment of those traditionally used. The first factor is security, defined as the ability of a family to rely on both a constant supply of the fuel and a functional stove. Security is affected by the route and frequency of fuel delivery, the tendency of the stove type to malfunction, and the family member's ability to repair the stove when a problem arises. In Jarácuaro, LPG cylinders are delivered twice a week to once every two weeks. Many families do not have a backup LPG cylinder, and when they run out they must wait until the next delivery day or travel into town by car to retrieve a full cylinder. During the time the family is without LPG, all foodstuffs must be prepared with fuelwood, and because it can take from a few days to a month to receive a full tank (if the family is not in the house on the LPG delivery day), most families rely on their ability to switch from mixed woodfuel/LPG use to exclusive woodfuel use.

(ii) *There are clear fuel preferences by cooking practices*

The second factor influencing stove or fuel-type switching is the culture indigenous to the region. In Jarácuaro, where most people are accustomed to eating tortillas cooked on a clay *comal* over an open wood fire, tortillas prepared over a gas flame are reported to be distasteful. The only family in the survey which uses an LPG stove to cook tortillas "accustomed themselves" to eating tortillas prepared with gas in a nearby town. More important, LPG stove design does not provide a large enough cooking area to prepare tortillas efficiently. Tortillas require a wide, hot surface like that provided by a comal over a wood fire so that many can be cooked simultaneously. To cook tortillas on an LPG stove would require the food preparer to make one tortilla at a time, extending a process that already consumes from one to three hours per day into an all day affair. Traditional foods that are prepared for the frequent village and family parties are also cooked with fuelwood as LPG stoves are also inadequate for these purposes (Figure 3). It should be noted that LPG stove design is much more practical for preparing other foods, such as fried meals or heating water, and all of these are regularly prepared on LPG stoves for families with that option (Masera & Navia, 1997).

(iii) *Fuel switching does not imply improvements in energy use or household energy expenditures*

First, as noted earlier in the text, because fuelwood is very seldom replaced entirely when families adopt LPG, household energy use, rather than dropping by 66% as it would be expected on the basis of energy efficiency ratios and total switching [5] actually increases for multiple fuel users in most villages (Table 3).

Fuelwood savings from partial switching to LPG are on the order of 35% in Jarácuaro to negligible in most other villages (Table 4). One of the main reasons for these low fuelwood savings is that households continue using fuelwood for tortilla making, a task which accounts

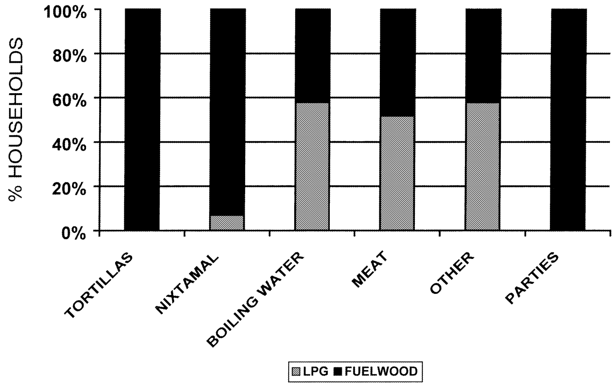

Figure 3. *Percentage of households by type of fuel used for different cooking practices. Only households that combine LPG and fuelwood are included. Thus, the graph illustrates how households having access to more than one fuel for cooking allocate each fuel according to the most important cooking practices. For example, 100% of the mixed fuelwood-LPG users prefer fuelwood for making tortillas, while about 60% use LPG for boiling water. (Source: Adapted from Masera and Navia, 1997.)*

for roughly 50% of total fuelwood consumption (Masera & Navia, 1997).

The economic implication of this pattern of mixed switching is that multiple fuel users tend to spend more on purchasing household cooking fuels than fuelwood-only users. Household expenditures for mixed fuelwood-LPG users almost double those from fuelwood-only users in the surveys of Michoacan and Oaxaca and are 20% higher in Guerrero (Masera *et al.*, 1997b) (Table 5).

(iv) *Economic development does not correlate with pollution reduction*

Technologies higher on the energy ladder tend to be less polluting at the end use level. Therefore, one expects that indoor air pollution levels will decrease significantly as families adopt LPG stoves. To test this hypothesis we first measured the average airborne concentrations of both respirable particulate matter (RSP) and (CO) in the cooking area for a variety of stoves (Figure 4). The data are the averages of wet and dry season measurements. The strong correlation of reduced pollutant concentration with improvement in stove type from three stone to traditional to improved traditional, to *lorena*, to LPG stove is consistent with the findings of a number of other studies (cf. Smith, Apte, Yuging, Wongsekiattirat, & Kulkarni, 1994), and what may be called the "technological component" of the standard energy ladder hypothesis.

Table 3. *Average per capita energy consumption and savings from using LPG (MJ/cap/day)*

	Fuelwood-only users	Mixed fuelwood-LPG users	Energy savings
Purepecha region, Michoacan state			
Jarácuaro village (1992) $N=12$	32.6	26.4	17.5%
Huancito village (1992) $N=12$	29.0	33.2	−4.3%
Pátzcuaro lake survey (1996)[a] $N=139$	34.3	37.1	−8.8%
Other regions of rural Mexico			
Altos de Mixtepec survey, Oaxaca state (1996) $N=114$	42.2	45.6	−7.1%
Tlapa Valley survey, Guerrero state (1996) $N=144$	29.4	33.1	−13-%

[a] The Patzcuaro Lake Survey included four villages (Masera *et al.*, 1997a). Data for Huancito village from Masera (1995), for Oaxaca State from López *et al.* (1997) and for Guerrero State from Arias *et al.* (1997). The following energy contents are used: fuelwood 16 MJ/kg; LPG 51 MJ/kg.

Table 4. *Fuelwood savings from using LPG in other villages of rural Mexico*

	Fuelwood-only users (kg/cap/day)	Mixed fuelwood-LPG users (kg/cap/day)	Fuelwood savings
Purepecha region, Michoacan state			
Jarácuaro village (1992) $N=12$	2.0 ± 0.2	1.3 ± 0.3	35%
Patzcuaro lake survey (1996)[a] $N=139$	2.0	1.8	10%
Huancito village (1992) $N=12$	1.7 ± 0.2	1.8 ± 0.2	6%
Other regions of rural Mexico			
Altos de Mixtepec survey, Oaxaca state (1996) $N=114$	2.6	2.6	0%
Tlapa Valley survey, Guerrero state (1996) $N=144$	1.8	1.6	11%

[a] The Patzcuaro Lake Survey included four villages (Masera *et al.*, 1997a). Data for Huancito village from Masera (1995), for Oaxaca State from López *et al.* (1997) and for Guerrero State from Arias *et al.* (1997). Savings are statistically significant at 95% confidence level only for Jarácuaro village.

Table 5. *Monetary household expenditures in cooking fuels*[a]

Category of user	Expenditures (MEXpesos/month)			Sample size (N)
	Fuelwood	LPG	Total	
Purepecha region, Michoacan state				
Fuelwood-only	44	–	44	28
Mixed fuelwood-LPG	41	48	89	40
Altos de Mixtepec, Oaxaca state				
Fuelwood-only	78	–	78	13
Mixed fuelwood-LPG	103	42	145	17
Tlapa Valley, Guerrero state				
Fuelwood-only	159	–	159	18
Mixed fuelwood-LPG	127	68	195	69

[a] *Sources*: Adapted from Masera et al. (1997a,b).

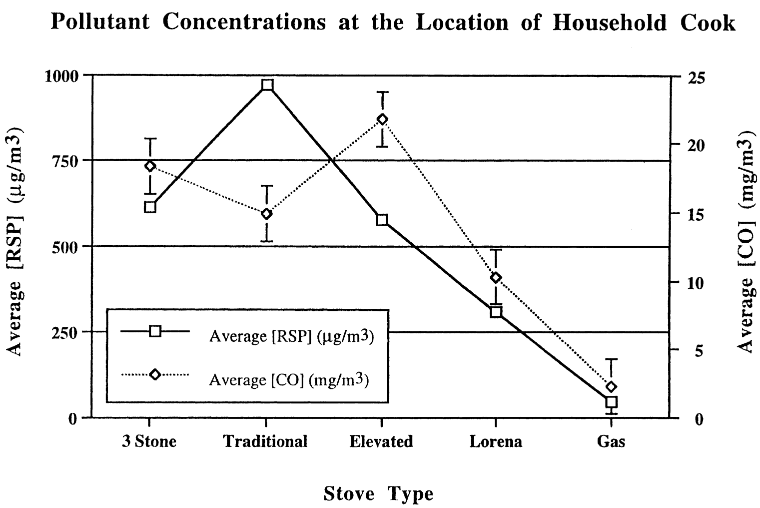

Figure 4. *Pollutant concentration at the location of household cook by stove type.*

When measurements are made at the household level, i.e. including all stoves used and cooking patterns, the average RSP concentration did not decrease consistently as income level rose. The average particulate concentration in the lowest income homes is 449 μg/m3, but almost twice that, 845 μg/m3, in the most affluent households. The absolute comparison of these values is not significant, given the small sample size, but the result is particularly striking in that the highest proportion of gas stove usage were from the most affluent households. In Jarácuaro, mean RSP and CO concentrations from gas stoves are measured to be five to seven times lower than from traditional stoves. The results from this one village stand in contrast with the conventional wisdom that the relationship between stove fuel use and pollutant exposure translates cleanly to a dynamic energy ladder relating improvements in these same parameters to advancing socioeconomic status.

This surprising result is due to a combination of factors. First, the kitchen area can be segregated to a "traditional" section of the home as overall family affluence rises. Thus, while more affluent homes in this study were found to be *generally* cleaner, the neglected kitchen area remained highly traditional, and in fact became more and more marginalized and polluted. Second, in some affluent households, the kitchens are remodeled and the materials used do not permit as much ventilation to the kitchen as traditional materials. For example, cement walls and a wood ceiling below the traditional vented tiles are seen as improvements to the kitchen, but they prevent air efflux to a much greater degree than vented tiles alone and wooden walls, which are often seen in less affluent kitchens.

4. THE "MULTIPLE FUEL" MODEL

The traditional energy ladder, like any such general model, is likely to provide only a limited view of reality in actual households. Due to the failures of the linear energy ladder to describe adequately the fuel use dynamics in Jarácuaro and other Mexican villages, we have used and further elaborated a "multiple fuel" model. Multiple cooking fuel use patterns have been reported frequently in the literature on household energy use since the eighties (Evans, 1987; Leach & Mearns, 1988; Fitzgerald *et al*., 1990). It has even been noted that multiple fuel use constitutes the rule rather than the exception in many urban and rural areas of developing countries (Soussan, O'Keefe, & Munslow, 1990; Davis, 1995, Alberts *et al*., 1997). The description and further explanation of these patterns of fuel use has however received much less attention than the study of the fuel transition process itself.

This pattern of combining traditional and modern technologies has also been observed and well documented in the case of the mechanization of agriculture in developing countries. It has been noted that rather than smoothly switching from animal draught to tractors, farmers often only partially adopt tractors and continue to rely on animal power for a specific set of practices—seeding being one of the most common—where a combination of cultural, technical and economic preferences makes them preferable to tractors (Biswanger, 1984; Masera, 1990).

In the case of rural energy, households rely on multiple cooking fuels to better cope with the variety of methods needed for food preparation (Tinker, 1980) or as a form of "back-up" against policies that can modify the relative prices of fuels (in Africa for example, the escalation of kerosene prices led to extensive switch-back to biofuels) (Leach & Mearns, 1988). Thus, the extent and permanence of multiple fuel use patterns in households are the result of complex interactions between economic factors (such as higly variable fuel prices and unreliability of fuel supply), social factors (such as evolution and security of monetary household incomes) and cultural factors (such as specific cooking practices, habits, and religious beliefs). Therefore, three important questions related to the understanding of fuel switching process are: To what extent is multiple-fuel cooking a transient or a long-term situation (i.e., what is the "strength" of traditions relative to that of modernization)? What is the influence of these patterns in terms of fuelwood demand? What are the implications of multiple-fuel cooking for indoor air pollution in rural households?

To address these questions we argue first that fuel switching should be considered as a process resulting from the simultaneous interaction of factors pushing households away from biofuels and others pulling them back toward biofuel use, a bi-directional process. "Push" factors include more convenience, cleanliness, status, while "pull" mechanisms usually include food flavor, inadequacies of modern devices to fulfill traditional cooking practices, and demand for new skills. Moreover, we discover that, rather than making concise transitions from fuel to fuel, or stove type to stove type, along the energy ladder, families in rural Mexico often show the pattern of "fuel stacking." As stated previously, households will adopt LPG, but rarely (one of 57 households surveyed in Jarácuaro, and very few households in the other villages and rural areas surveyed) abandon fuelwood technologies. This decision is dictated by economic/recourse scarcity, health, and cultural factors, and cannot be modeled in a strict linear framework. We offer the schematic below as a more complete description that reflects both the use of multiple fuel/stove combinations, and the dynamics of shifting between these energy systems as a function of the three factors detailed above.

(a) *The patterns of multiple fuel use: technical, socioeconomic and cultural aspects*

Households adopting LPG present some characteristic features. First, as stated previously, the use of LPG is always accompanied by fuelwood, with a distinctive pattern of preferences across cooking practices. Second, on average, mixed fuelwood-LPG users tend to rely more on the market to get fuelwood. There is, however, no simple relationship between the purchase of fuelwood and the adoption of LPG. This is because, while households purchasing fuelwood may have more economic incentives to begin using LPG, especially if wood is expensive as in Jarácuaro, they have to overcome the gas stove investment cost. In addition fuelwood can be purchased in small amounts, while LPG consumption needs lump payments. Finally, as we have argued earlier in the paper, adoption of LPG cannot be understood in terms of the optimization of households' monetary expenditures.

Technical and cultural factors play an important role in the process of partial fuel switching. The main technical factor preventing total switching to LPG is that these stoves are not well adapted to some traditional cooking practices. Specifically, the burner surface in LPG stoves is too small and only permits the cook to prepare two tortillas at once, dramatically increasing the time and energy burden of this task compared with the traditional *comal*, where it is possible to cook eight to 10 tortillas at a time.

Culture plays an important role in the process of fuel switching, as shown by the type of gas stoves purchased and the changes that accompany the purchase of a cookstove. Regarding cookstoves, most of them correspond to a relatively expensive model (four burners with a cabinet beneath). Some families even purchase stoves with ovens. Ovens, however, are never used by rural households. In fact, ovens serve as additional cabinets for cooking pots. Many gas stoves are gifts of migrants to their mothers or wives, intending to show the "progress" the household is making in their living conditions. Thus besides its utilitarian value, LPG stoves play a role as "status symbols."

The latter assertion is confirmed by observing that the use of LPG is associated with larger changes within the home. [6] An additional kitchen is usually built when the stove is purchased or soon afterwards (see Table 6). The new kitchen often follows the more typical Western-type structure, with a large table and chairs. Some households use this kitchen only for guests or for very special occasions. The old kitchen, with the three-stove fire (TSF) or "chimenea" usually continues to play an important role for the families' daily social interactions.

The use of LPG also implies purchasing new cookware, and households increasingly replace the traditional ceramic pots by porcelain glazed pots (Table 6). In summary, LPG is accompanied by a notion of "modernization" or progress, which, at least at the beginning, is far more important than a pure economic rationale. Interestingly enough, rather than completely "modernizing" when switching to LPG, households continue to keep their traditional socializing spaces (e.g., the old kitchen) and their most important traditional cooking practices built around the use of fuelwood. From a cultural perspective, this multiple cooking fuel strategy in rural areas can be regarded as a tension between the increasing adoption of western values and the maintenance of what Bonfil-Batalla (1990) has described as "the autonomous culture" of indigenous people, i.e., those material, symbolic, ideological, and organizational elements that indigenous groups consciously maintain to keep control over their own cultural spaces.

Table 6. *Changes associated with the use of LPG (% households)*[a]

Features	Jarácuaro (%)	Huáncito (%)
Additional kitchen		
Fuelwood users	1	0
Fuelwood-LPG users	50	62
Type of cookware (pots and vessels)[a]		
Fuelwood users		
Pottery	65	89
Aluminum and pottery	32	4
Fuelwood-LPG users		
Pottery	13	40
Aluminum and pottery	68	54
Items bought when LPG stove was purchased		
Table and chair	15	17
Cookware	32	83
Other home modifications		
Kitchen was re-located	5	23
Another kitchen was built	27	8

[a] In some cases percentages do not add to 100% because people use other types of cookware or because households didn't answer the question. The features noted are not simply income-driven but are characteristic of the process of LPG adoption. This assertion was examined estimating the percentage of mixed fuelwood-LPG households at each income level that have an additional kitchen, have determined type of cookware, etc. For example, regarding the use of an additional kitchen, the analysis shows that 40% and 50% of high-income households, 75% and 71% of mid-high income; 67% and 29% of mid-low income and 100% and 67% of low-income households using LPG have an additional kitchen in Huancito and Jar*á*cuaro, respectively. As there are no significant differences in the percentage of households owning an additional kitchen among income groups of LPG using households, it can be concluded that having an extra kitchen is mostly the result of LPG adoption and not of increasing incomes. Similar results are obtained with the remaining features listed in the table.

(b) *Health impacts*

Increases in socioeconomic status do commonly lead to household improvements such as improved access to health care, potable water, sufficient food supplies. In addition, increasing affluence resulted in the installation of vented tiles and cement floor in the main living spaces of the homes. But, a rise in income level does not necessarily lead to an equivalent increase in kitchen quality. Almost every household classified as high or mid-high invest in cement or improved floors (100%) and vented tile roofing (83% for high income households) for the main dwelling area. By contrast 33–50% of these households still have dirt floor kitchens (33%) or poor unventilated kitchen roofs (50%) (Table 7). Kitchens are often overlooked as families make household improvements, and relatively wealthy families choose to invest their income in other areas. When questioned why their kitchen was constructed without any vent for smoke, one woman said that, "we keep meaning to fix the kitchen, but *no one comes in here anyway*, and we have just not done it."

Important health issues relating to the use of LPG stoves become clear in the light of the multiple fuel energy model. As with studies elsewhere (Ezzati, Kammen, & Mbinda, 2000), health concerns (e.g., acute respiratory infection (ARI), asthma, eye infections, burns) that have been shown to correlate with emissions exposure in Jarácuaro (Saatkamp *et al.*, 1998; Saatkamp, Masera, & Kammen, 1999) are generally not sufficient motivation for families to switch to new stove/fuel combinations. This may be ascribed to the long latency of clear adverse effects of these ailments in adults, but also is likely a result of the fact that families using multiple fuels are unlikely to perceive or to experience discernible benefits from only partial improvements of indoor air quality.

(c) *Implications for future fuelwood demand: combining improved cookstoves and modern fuels*

Due to patterns of multiple fuel and stove use in rural Mexico, fuelwood and energy savings

Table 7. *Comparison of the material investment in the living areas of homes versus the kitchens in the surveyed households in Jarácuaro*[a]

	Construction material	High ($n = 6$) (%)	Mid-high ($n = 6$) (%)	Mid-low ($n = 6$) (%)	Low ($n = 3$) (%)
House	Cement floor	67	67	17	0
	Mixed floor	33	33	66	67
	Dirt floor	0	0	17	33
	Vented tile roof	83	33	17	0
	Mixed roof	17	67	83	33
	Carton roof	0	0	0	67
Kitchen	Cement floor	67	50	0	0
	Mixed floor	0	0	0	33
	Dirt floor	33	50	100	67
	Vented tile roof	50	50	0	0
	Mixed roof	33	0	33	0
	Carton roof	17	50	67	100

[a] Figures indicate percentage of households in the income category indicated.

from adopting LPG are much less than expected from a purely technical perspective, and families continue relying on both fuels for a very long time. Both these outcomes of fuel stacking result in a fuelwood demand strikingly higher than the demand expected from the traditional energy ladder. This situation has definite environmental and social implications and opens new perspectives for improved fuelwood cookstoves.

An example from Jarácuaro serves to illustrate the point. The longitudinal study in Jarácuaro permitted a detailed examination of the process of LPG penetration in the village. The rate of LPG adoption was very slow at the beginning, until a critical number of users was reached in the village and a reliable system of LPG delivery became economically profitable. The adoption process fit well into a logistic or "S" shape curve, with the first stove purchased in the late 1960s and the overall saturation expected to reach 80% by the year 2000. Combining the LPG adoption curve with the village population growth and the measured fuelwood unit consumption for fuelwood-only and mixed fuelwood-LPG users, we constructed the fuelwood demand curve for the entire village for 1970–2010 (Figure 5). By 1996, the demand reached 1,340 t/yr, a figure 15% lower from that expected from a fuelwood-only scenario, but also 47% higher than a process of complete fuel substitution. Under a multiple-fuel situation we expect the total fuelwood consumption in the village to be several times higher than that expected from a complete fuel substitution scenario by 2010. This exercise highlights the importance of adequately describing the process of fuelwood switching.

Given the expected sustained fuelwood demand, even in the presence of fuel switching, options to increase the efficiency of fuelwood consumption merit careful attention. One alternative that has proved promising in the region is improved cookstoves. A series of tests conducted in different villages showed that improved fuelwood stoves (*lorena* type) do provide both fuel savings and reduced emissions, even as measured in the more realistic setting of a household kitchen with the stove user preparing the food. For example, within the Patzcuaro Lake region, Lorena stoves have shown to provide an average of 40% fuelwood savings when compared to traditional three-stone fires, and 30% savings compared to the dominant U-type stoves (Masera *et al.*, 1997a). It should be noted that savings were estimated on the field under actual cooking conditions of local households (Figure 6). Lorenas also help to reduce average RSP and CO by more than 30% with regards to traditional stoves (Figure 4).

Lorenas are particularly efficient for tortilla making, where they reach average savings of 50% compared with the tradtional stoves (Masera & Navia, 1997). These savings are very significant as tortilla-making accounts for approximately 40% of total fuelwood consumption. The stoves, which have been substantially modified and improved from the original design, are well adapted to local cooking practices and have been well accepted

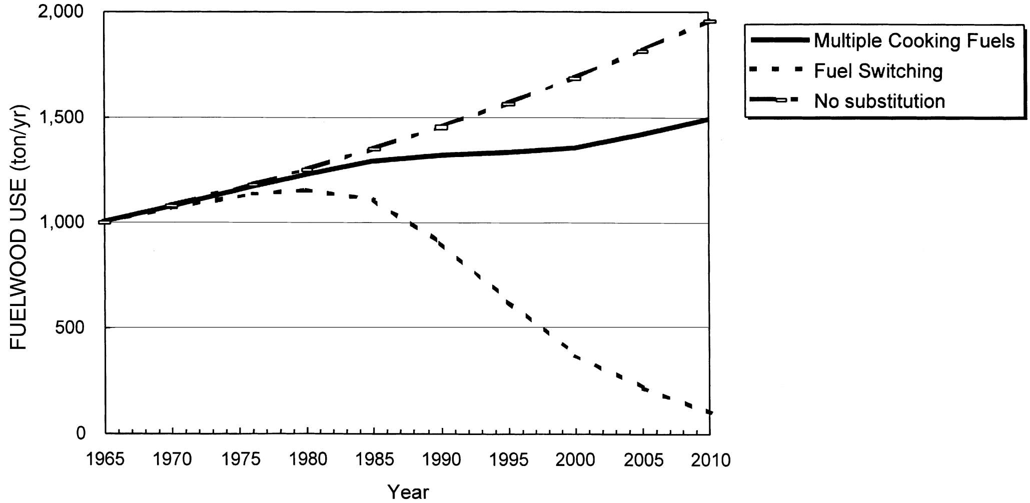

Figure 5. *Actual and estimated fuelwood demand according to different models in Jarácuaro village (1965–2010). The graph illustrates the evolution of fuelwood use in Jaracuaro village according to three different models: (a) no substitution of fuelwood, (b) multiple cooking fuels, i.e. households rely both on fuelwood and LPG, and (c) total substitution of fuelwood for LPG.*

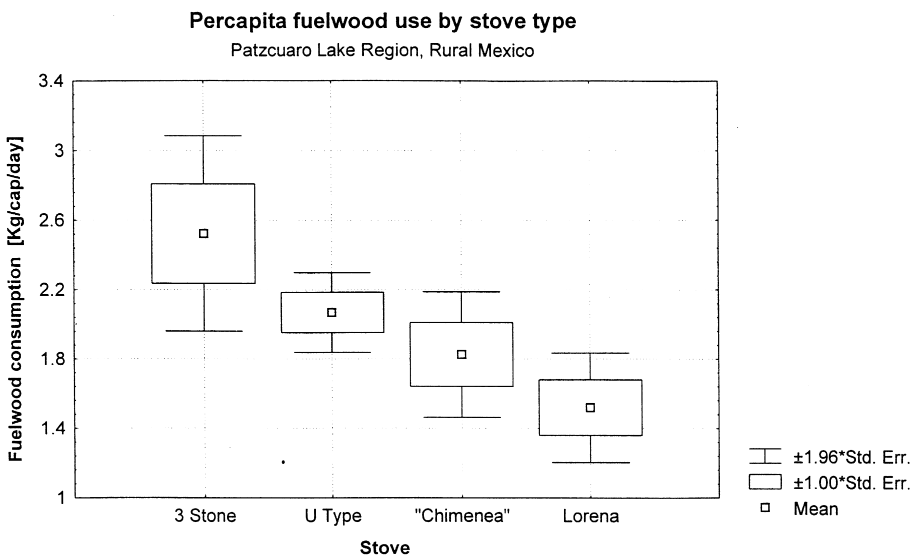

Figure 6. *Per capita fuelwood consumption associated to households using different wood burning stoves common in the Patzcuaro Lake region.*

by local women. Average stove life time reaches 3.8 years, which is quite a longtime taking into account that they are made out of mud, cement, and sand (Puentes & Masera, 1999). Mixed fuelwood-LPG users have been particularly keen on adopting the stoves in several villages of the Patzcuaro Lake region, as they add to the advantages of modern fuels the benefits of continuing cooking their traditional meals with less smoke and a significant reduction in fuelwood consumption.

These observations lend credence to the importance of the general policy goal of utilizing improved fuel/stove combinations to reduce adverse health, economic, and environmental impacts of household energy use.

5. CONCLUSIONS

The analysis conducted in this paper suggests that, in Jarácuaro and more generally in rural Mexico, the so-called fuel switching is actually a step toward "multiple fuel cooking" or "fuel stacking" of both fuelwood and LPG. Examination of the different dimensions of the adoption of modern cooking fuels shows it as a complex process—well beyond a simple change in the end use efficiency of cooking-where economic aspects are interlinked with social and cultural issues. Table 8 outlines the main aspects that should be included in a detailed study of fuel switching and multiple fuel cooking.

Rather than a smooth process driven by increasing household incomes, the rate and pace of interfuel substitution is the result of the interplay between structural macroeconomic conditions, like government investment in rural road and service infrastructure, and the local cultural and economic circumstances of households. At the village level, fuelwood scarcity, the increasing monetization of the household economy, and the influence from urban centers, motivate households to look for other cooking options.

At the household level, the adoption and use of LPG appears as a two-step process. First, households must overcome the LPG stove investment barrier. Because LPG stoves are often regarded as "status symbols," the barrier is much higher than the one represented by the cheapest LPG stove. Also, households' determinations about purchase of a new LPG stove are usually part of larger decisions involving the building and furnishing of a new kitchen, buying new table and chairs, and purchasing new cookware. Given the income constraints, this process is still uneven, and occurs mostly in the mid-high to high-income groups.

Once the gas stove is purchased, LPG unit consumption and the associated fuelwood savings depend on demographic conditions, on the energy requirements of local cooking practices, and on broader cultural issues related to preferences and traditions. Partial switching to LPG appears to be faster in villages with increasing fuelwood scarcity, provided there is also a trend toward increasing rural cash incomes (either from the local economy or through remittances from migrants).

We have shown that *very rarely is fuelwood replaced completely*, even in households that have been using LPG for many years. Fuelwood is still considered essential for tortilla making—both for technical and cultural reasons—and for traditional parties. Therefore, it is seen as a fuel with advantages that go beyond price. Multiple fuel users are even willing to pay a "premium" for continuing to use fuelwood. Wood savings from adopting

Table 8. *How to analyze the process of fuel switching and multiple fuel cooking*

The broader analysis of fuel switching and multiple cooking fuel patterns proposed in this paper implies examining the following aspects
—The technical characteristics of modern cookstoves, in particular, their ability to fulfill traditional rural cooking practices and energy end uses
—The technical potential vs. the realized fuelwood and energy savings from switching. This task involves the examination of the differences between fuel savings estimated through controlled cooking tests and savings based on actual household behavior
—Physical and economic access conditions to modern fuels, including stove investment and O&M costs, and the characteristics of the modern fuel delivery system
—The relative costs and benefits associated to different cooking devices and combination of fuels
—The social aspects of the process of modern fuel penetration. In particular, the analysis of differences in the rate of modern fuel adoption by social group and the identification of "niches" for the process of switching
The health implications of alternative stove types and fuel combinations
—Cultural aspects involved in the process of switching; here it is important to investigate the notions associated to modern fuels (e.g., status) and fuelwood. These issues can be analyzed through the types of stoves purchased, the changes in kitchen structure that accompany the purchase of gas stoves, the particular cooking practices in which fuel substitution occurs, and women's stated preferences for fuelwood and modern fuels

LPG are strikingly lower than the technical potential, and reach from a maximum of 35% to negligible, depending on the village. As only a fraction of village households has the economic power to switch to LPG and only partial substitution occurs, total fuelwood demand is unlikely to drop substantially in the short term.

Regarding indoor air pollution, we have shown that that even if all families possessed the economic resources to purchase less-polluting stove technologies and kitchen refurbishments, the benefits of doing so are either not recognized or devalued compared to other investments. The result is that even as families purchase LPG stoves there is often little attention paid to stove placement, kitchen ventilation, and construction materials. Thus, the availability of modern stove technologies is not sufficient to combat health risks due to indoor air pollution and should be accompanied by general education regarding these risks. Further studies are critical to determine what types of design improvements in fuel type, stove, and kitchen can reduce the morbidity associated with indoor air pollution.

Improved *lorena* stoves, present an important and interesting alternative to the options modeled in the energy ladder. They help save 30 to 40% fuelwood when compared with traditional stoves, and also show pollution reductions of 30% or more. These reductions depend on careful training, installation, and stove management education. In communities with active improved cookstove promotion and construction programs, the *lorenas* have been quite successful and are in considerable demand among all socioeconomic groups. In addition, *lorena* stoves allow local households to continue preparing their traditional foods (such as tortillas). Targetting multiple fuel users for *lorena* stove programs is a good option for reducing fuelwood consumption even further.

This study suggests, and we strongly recommend, that research on multiple cooking fuels be strengthened and the entire process of linear fuel switching be re-examined, particularly under the conditions of uncertain household incomes, highly varying prices of cooking fuels, unreliable fuel supplies, and non-Western cooking habits, prevalent in most regions—particularly rural and peri-urban areas of developing countries.

NOTES

1. An increasing number of studies have found that while many individuals, primarily women, feel that changing the domestic environment can be particularly difficult, the health benefits of doing so can be dramatic (Saatkamp, Masera, & Kammen, 1998).

2. Between August 1996 and December 1997 the price of a LPG cylinder almost doubled, reaching 97 pesos/cylinder (an increase of 64%, from US$7.10 to US$11.70/cylinder).

3. The terms fuel switching, fuel substitution (also named interfuel substitution) and fuel transition are commonly used in the literature to refer to the process by which households change from fuelwood or other biofuels to modern fuels. Because this change of fuels might be total or only partial, strictly speaking, the term "interfuel substitution" is the more appropriate.

4. Reddy (1990) presents an alternative model for interfuel substitution that is based on a dynamic system of the Lotka-Volterra type. The model assumes that fuels "compete" through their appropriate cooking devices (stoves) for adoption by households, and predicts the rate at which fuels should be substituted for different income levels.

5. Assuming that stove efficiencies are 50% and 17%, for LPG and fuelwood, respectively, we get an energy efficiency ratio of $(50/17) = 2.94$ or, in percentage terms, an expected reduction of $100*(1 - 1/2.94) = 66\%$ in energy use for cooking from total switching.

6. In fact, the use of LPG currently represents the culmination of a series of changes that have been happening within local homes since early in this century. These changes involve improvements in the cooking devices—specifically the increasing use of *chimeneas* instead of TSF, the height of the cooking device—traditionally on the floor, but now increasingly on top of a table, particularly in Jarácuaro. Larger changes include the use of Western-type furniture (table and chairs) instead of *petates*, which have modified the traditional kitchen structure.

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APPENDIX A. MATHEMATICAL DESCRIPTION OF THE "ENERGY EFFICIENCY RATIO" APPROACH TO FUEL SWITCHING

This approach is the simplest and the most extensively used in technical analyses of fuel switching. The model assumes that useful energy is constant across households using different fuels. Hence, household energy consumption is only a function of the end-use device efficiencies. The energy implications of switching can thus be estimated mathematically as follows. With $E_u = \text{constant}$ is the useful energy needed by a particular household, E_i is the household energy consumption for fuel "*i*," η_i the efficiency of the end use device used for fuel "*i*," and E_j, η_j the energy consumption, and efficiency of the end-use device used for fuel "*j*"—used here as the fuel substitute—, respectively, we can express E_u as:

$$E_u = E_j \times \eta_j = E_i \times \eta_i = k$$

then

$$E_j = \eta_i/\eta_j \times E_i.$$

Because typical end use efficiencies for fuelwood are in the range of 15%, and those for LPG around 50%, the model predicts that a household using LPG will consume 0.15/0.50 or 3.3 times less energy than a fuelwood-using household. In practice, household energy use rarely accommodates to these efficiency ratios, particularly when switching from traditional to modern fuels.

APPENDIX B. MATHEMATICAL DESCRIPTION OF THE "FUEL SUBSTITUTION RATIO" APPROACH TO FUEL SWITCHING

This approach is used by energy economists. The model acknowledges that fuel switching is not mechanistic but may be accompanied by changes in lifestyles, the quality of life and in the demand for fuels (very particularly in the change from fuelwood to modern carriers). Therefore, fuels cannot be compared in terms of a process involving the *same energy service* (i.e., useful energy). In order to avoid the previous assumption, a multiple regression model is constructed, expressing household energy demand-calculated separately for each fuel and major end-use-as:

$$Q_i = f(Y_i, N_i, P_{ij}, P_{ik}, M_{ik}, M_{ik}, H_i)$$

or, more specifically,

$$Q_i = N_i^a \times Y_i^b \times P_{ij}^c \times P_{ik}^{dk} \times e^{g\ Mij} \times e^{hk\ Mik} \times e^{m\ Hi},$$

where Q_i is the energy use by end-use per household (includes all fuels and is estimated separately for each end-use), Y_i the household income, N_i the family size, P_{ij} the fuel price for fuel *j*, P_{ik} the prices of competing fuels, M_{ij} an index of resource availability for fuel *j*, M_{ik} an index of resource availability for fuels *k* ($k = 1 \ldots n$), and H_i cooking practices (Fitzgerald *et al.*, 1990). The energy implications of substituting one fuel for another is estimated thorugh fuel substitution ratios (FSR). In order to do that a regression model of the kind:

$$\log(Q_i) = a\log(Y_i) + b\log(N_i) + c\log P_{ij} + {}_k\,(d_k \log P_{ik}) + \cdots + f\ C_i + m\ H_i$$

is fitted to the data, where C_i are dummy variables representing the fuel or combination of fuels used by the household, leaving out those households that cook only with the reference fuel. The coefficients $(a \ldots f)$ are directly elasticities. The coefficient "f" for C_i indicates how much more or less energy is used by households using a particular fuel as compared to those not specified by the fuel choice dummy, and the FSR becomes

$$\text{FSR} = \exp(f).$$

For example, if FSR equals 0.60, then users of fuel "*j*" consume only 60% of the energy used by fuel "k_1" using households. It should be noted that FSR is estimated based on actual behavior of households with similar socioeconomic profiles. Only if FSR = 1 is the energy substitution ratio equivalent to the energy efficiency ratio. In practice, however coefficients for FSR greater or smaller than one are obtained. For example, Fitzgerald *et al.* (1990) found that household energy savings from switching from fuelwood to kerosene were less than those expected by energy efficiency ratios alone.