Determinants of household energy consumption in India

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Abstract

Improving access to affordable modern energy is critical to improving living standards in the developing world. Rural households in India, in particular, are almost entirely reliant on traditional biomass for their basic cooking energy needs. This has adverse effects on their health and productivity, and also causes environmental degradation. This study presents a new generic modelling approach, with a focus on cooking fuel choices, and explores response strategies for energy poverty eradication in India. The modelling approach analyzes the determinants of fuel consumption choices for heterogeneous household groups, incorporating the effect of income distributions and traditionally more intangible factors such as preferences and private discount rates. The methodology is used to develop alternate future scenarios that explore how different policy mechanisms such as fuel subsidies and micro-financing can enhance the diffusion of modern, more efficient, energy sources in India.

1. Introduction

Providing clean and affordable energy reliably for poor households in developing countries is an important prerequisite in the fight against poverty. Even though rural households often have an easy access to traditional forms of energy—firewood, charcoal and agricultural residues—to fulfill their basic energy needs, these fuels carry adverse effects, such as emissions of particulate matter that are harmful to health, deforestation and environmental degradation. The greater time needed for gathering, transporting and using these fuels also reduces the prospects for using this time in more productive work or education. In addition, as women and children are more likely to suffer from many of these adverse effects, the issue has an important gender and equity dimension (Pachauri, 2004b). The low efficiency associated with the direct combustion of biomass in traditional devices is also sub-optimal from a societal and technical perspective (Reddy, 2003).

A large concentration of people relying on the traditional forms of energy can be found in India, and improving the access of the poor to modern energy has been on the agenda of the government of India since independence. Electrification has especially received much attention within the policy arena, and a summary of past electrification measures can be found in Bhattacharyya (2006). Kerosene and LPG—the main modern cooking fuels in India—have also been subsidized since long, although there has been pressure to limit these subsidies more recently (Gangopadhyay et al., 2005). However, as electricity is rarely used for cooking or heating in India, electrification cannot be seen as an effective solution for reducing the consumption of traditional fuels and the above-mentioned detrimental impacts associated with their use. It should be noted, though, that electricity is required for sufficient lighting and associated with several additional benefits, e.g. improved education and employment possibilities (Kanagawa and Nakata, 2008).

Literature on household energy requirements in developing countries, particularly for the case of India, is extensive. The traditional view on fuel choice has been the “energy ladder” approach (e.g. Leach, 1992), according to which households switch to more convenient energy forms as their disposable income increases. A partial critique of this approach has been presented by Masera et al. (2000), who observed from data on rural Mexican energy consumption that households do not ascend a “ladder” but rather follow a “stacking” procedure, i.e. traditional fuels are not completely discarded with rising income, but rather used in conjunction with modern fuels due to cultural preferences.

The importance of income as a factor affecting fuel use is, however, apparent, even in the case where the switch to modern fuels is not always complete. For Indian consumers, Pachauri (2004a) found that the statistically most significant factors determining households’ energy consumption were income and location, whether rural or urban. However, the factors likely to
affect fuel choices vary by location, financial circumstances and household preferences. Therefore, the energy choices of consumers with different income and location should be assessed separately in energy policy analysis, in contrast to the “representative consumer” approach normally followed in most economic models.

There have been some previous attempts on formal modelling of household energy choices, using a linear cost-minimization solution concept, e.g. by Kanagawa and Nakata (2007, 2008) for the case of India, and by Howells et al. (2005) for an African village. These studies, however, suffer from a number of shortcomings, for instance they disregard consumer heterogeneity, the high discount rates of the poor and differing preferences. A system-dynamic model for India (van Ruijven, 2008, Chapter 6) addresses these issues partially, but does not account fully for all the factors mentioned above. Studies employing logit models of fuel choices have also been conducted. E.g. Reddy (1995, 1996) distinguishes between different income groups in their fuel choice models for Bangalore, India. However, they do not carry out any policy analysis or provide recommendations for the future based on their model results.

This paper therefore intends to establish a stronger framework for modelling the energy choices of households, by explicitly accounting for the heterogeneous economic conditions and preferences of populations living in rural and urban settings, in order to analyze effective policy choices to improve the penetration of modern cooking fuels among the poor. We start by discussing existing energy consumption patterns in Indian households, based on data from a nationally representative consumer survey. A basic, microeconomic choice model is then presented, serving as the backbone of our energy choice model. This is further expanded to incorporate different practical determinants relevant to the choice problem in the model. We also present a sensitivity analysis for certain key parameters included in the model. The choice model developed is then implemented as the MESSAGE-Access model within the MESSAGE linear cost optimization framework (Messner and Strubegger, 1995). As an application of the MESSAGE-Access model, the effect of fuel subsidies and improved financing options on the future adoption of modern cooking fuels in India is assessed in the final section of the paper.

2. NSSO survey on household energy consumption

This study is largely based on a large consumer survey, carried out by National Sample Survey Organisation (NSSO) of India between 1999 and 2000 (NSSO, 2000). In the survey the respondents were asked to state, among others, their energy consumption for different energy forms in energy and expenditure terms in the past 30 years. In addition to expenditure, the survey also includes home-grown fuel sources for traditional fuels. The NSSO surveys, which involve the energy questionnaire every five years, involve a large sample of households and cover the whole of India, and thus can be assumed to be representative of the nation as a whole.

The energy consumption data from the 1999/2000 survey has already been analyzed extensively in a number of papers, and a more in-depth analysis can be found e.g. in Bhattacharyya (2006), Gangopadhyay et al. (2005) and Pachauri (2007). The survey data have also been used to estimate the elasticities of different energy forms by Gundimeda and Köhlin (2008); to identify barriers for improving energy efficiency by Reddy (2003); to construct a measure of energy poverty by Pachauri (2004b) and to model urban fuel choices by Farsi et al. (2007). As households with different socioeconomic status are likely to make differing choices regarding their energy use, the household heterogeneity should be taken into account in models. For this differentiation, the households’ expenditure level and nature of surroundings—whether urban or rural—were used, as these factors were identified to be the statistically most significant determining households’ energy consumption patterns by Pachauri (2004a). The NSSO survey data were therefore split into 10 consumer groups—labelled R1–R5 for the rural and U1–U5 for the urban population, with expenditure rising with the group number—consisting of expenditure quintiles for the urban and rural populations.

From Fig. 1, which portrays the survey data split between the consumer groups, we can see that the energy consumption patterns of the groups are very distinct. The rural population relies largely on traditional fuels. Even though electricity, kerosene and LPG consumption increases with rising expenditure levels, traditional fuel use also increases in absolute terms and dominates the fuel mix of rural households, even after accounting efficiency differences. On the other hand in urban areas the switch from traditional to modern fuels is more apparent as the absolute amount of traditional energy consumption is decreasing with rising expenditure.

An interesting feature can also be seen from an analysis of the sources of firewood, the main traditional fuel source consumed, illustrated in Fig. 2. The figure shows that for some 20% of households even in the lowest expenditure quintile purchase their firewood. This would thus indicate that the market for traditional fuels is functional even within the lowest expenditure

![Fig. 1. Household final energy consumption (MJ/cap/a) of the 10 consumer groups.](image1)

![Fig. 2. Sources of firewood of the 10 consumer groups.](image2)
category. This, in turn, implies that traditional fuel consumption always carries a cost—at least an opportunity cost—regardless of whether collected freely or bought, as the collected firewood could also be sold. In the presence of the opportunity cost, cost minimizing behaviour can then be assumed with all households.

As the NSSO data does not indicate the purpose for which each fuel is being used, the consumption data have to be further divided among the different energy services. For splitting kerosene consumption for lighting and cooking, the approach from Gangopadhyay et al. (2003) was adopted, grouping consumption data have to be further divided among the different energy services. For splitting kerosene consumption for lighting and cooking, the approach from Gangopadhyay et al. (2003) was adopted, grouping consumers by their stated main lighting and cooking fuels in the NSSO survey. The amount of kerosene for lighting was then estimated from the consumption patterns of households that use kerosene primarily only for lighting. The kerosene use for backup lighting was similarly estimated from households not using kerosene primarily either for cooking or lighting. For defining the electricity consumption for lighting, the regression equations from Letschert and McNeil (2007) between the number of electric light points and expenditure, was used. The resulting shares of useful energy from different energy sources are depicted in Fig. 3.

3. The problem of consumer energy choice

In classical demand theory the problem of consumer choice is usually described as a problem of utility maximization under a budget limit, with a utility function characterizing the consumer’s preferences for consuming varying amounts of different types of commodities. As for energy consumption, a consumer benefits from a higher level of useful energy consumption and is likely to prefer more convenient energy forms over inconvenient ones.

In the context of developing countries, the poor households—having a more limited budget for energy consumption—are forced to choose the more inconvenient but less costly alternative as otherwise they would trade off adequate energy consumption levels for convenience. The inconvenience—comprising intangible factors such as higher time consumption and exposure to particulate matter—carries a non-monetary burden or an inconvenience cost for the household and is an essential element in the choice problem.

Let us assume that the consumption of energy can be separated from other consumption to its own consumption problem, i.e. that the utility from energy is separable from other sources of utility and that the consumer has a specific energy budget. If the problem is first simplified to only distinguish a single modern, convenient fuel and a single traditional, inconvenient one, the energy consumption problem is

$$\max_{E_t, E_m} U(\eta_t E_t + \eta_m E_m) - \varphi(E)$$

s.t. \(pTE = B\),

(1)

where \(E_t\) and \(E_m\) are the consumption levels of traditional and modern fuels, \(U\) the utility from energy consumption, \(\eta_t\) and \(\eta_m\) the conversion efficiency for \(E_t\) and \(E_m\), \(\varphi\) disutility from consuming the inconvenient fuel, \(p\) the price vector for \(E_t\) and \(E_m\) and \(B\) the budget limit.

If the preferences are locally non-satiable and the utility function is continuous, a problem of minimizing costs to yield the amount of utility equaling the solution of (1) arrives at the same consumption choice and thus is an alternative formulation to the consumer choice problem (Mas-Colell et al., 1995). For this particular problem, the cost minimization problem can be reformulated by introducing a cost on the consumption of traditional fuels instead of using the disutility function \(\varphi\). In this problem setting the required utility level is then that of the fuel consumption, \(U(\eta^T E)\), where \(E^*\) is the solution vector for the utility maximization problem. With a strictly increasing utility function \(U\), the required utility can written purely in the form of useful energy. Thus an equivalent problem for (1) is a cost minimization problem

$$\min_{E_t, E_m} p^T E + c(E)$$

s.t. \(\eta^T E = \eta^T E^*\),

(2)

where \(c\) is the inconvenience cost with \(c > 0\) and \(c' > 0\), \(\eta\) the efficiency factor vector for traditional and modern energy, and \(E^*\) the solution for (1), which can be obtained in practice from energy consumption statistics.

The situation can also be described graphically, as is done in Fig. 4. The solid lines describe the original utility maximization problem with the optimal solution lying in the point where the budget line \(p^T E\) touches the curve of constant utility \(U(\eta^T E^*) - \varphi(E)\). The same solution \(E^*\) is acquired from the cost minimization problem, presented with dashed lines, at the point where the cost curve \(p^T E + c(E)\) touches the useful energy line \(\eta^T E\).

![Fig. 3. The share of different energy forms in household useful cooking energy consumption for rural and urban expenditure quintiles.](image1)

![Fig. 4. The consumer energy choice problem, formulated as an utility maximization (solid lines) and cost minimization (dashed lines) problems. Both yield the same solution, marked with a cross.](image2)
This formulation yet lacks an explicit form for the inconvenience cost function \( c(E_t) \). Regarding the energy choice problem, however, we are mainly interested in the marginal inconvenience cost \( c'(E_t) \). The first order optimality conditions of (2) require that in the optimum

\[
\frac{c'(E_t)}{\eta_t} = \frac{p_{m_t}}{\eta_{m_t}} - \frac{p_t}{\eta_t},
\]

that is, the marginal inconvenience cost in terms of useful energy equals the difference in the price of useful modern and traditional energy.

In the attempt to construct a linear energy choice model based on cost minimizing behaviour, further assumptions on the functional form of \( c(E_t) \) in (3) will be made in Section 4.3. A linearized version of the cost minimization problem (2) differs only from the original, non-linear model in that the inconvenience cost \( c(E_t) \) is linear \( C - E_t \), and in practice the problem consists of simply selecting the technology with lowest costs per useful energy output.

4. Determinants of fuel choice

Section 3 outlined a basic theoretical framework for analyzing the energy choice problem. The presented framework is very generic and employable to a large number of consumer energy choice settings. In constructing a choice model for Indian households, a number of complementary, practical considerations have to be taken into account.

The most obvious determinants, prices and technological parameters of fuels and appliances, have to be supplemented with assumptions on how different consumers value costs and savings in different points of time, i.e. how costs are discounted, and how their preferences should be represented through the inconvenience cost. It is also important to assess whether there are additional constraints—such as the availability of biomass—that should be taken into account in the model.

4.1. Prices and technological parameters

The costs and efficiencies of different energy technologies are both explicit in the cost minimization problem (2). The total cost comprises the fuel cost and appliance cost, compared across the technology options by either the net present value (NPV) or annualized costs per useful energy of each technology, using an appropriate discount rate. Each technology is thus characterized by its investment cost per unit energy consumption, efficiency (\( \eta_t \)) and appliance lifetime.

The average fuel costs, estimated from the NSSO survey data, are presented in Table 1. From the original fuel division, firewood, dung and charcoal have been aggregated into “Biomass”, and coal and coke into “Coal”. Apart from a slight income bias, the average prices were relatively homogenous across the consumer groups.

Table 1: Average fuel prices (Rs/GJ)\(^a\) as implied by the NSSO survey.

<table>
<thead>
<tr>
<th></th>
<th>Rural</th>
<th>Urban</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Electricity</td>
<td>373</td>
<td>415</td>
</tr>
<tr>
<td>Kerosene</td>
<td>282</td>
<td>282</td>
</tr>
<tr>
<td>PDS kerosene</td>
<td>112</td>
<td>112</td>
</tr>
<tr>
<td>LPG</td>
<td>270</td>
<td>270</td>
</tr>
<tr>
<td>Biomass</td>
<td>62</td>
<td>80</td>
</tr>
</tbody>
</table>


The parameters used are presented in Table 2.

Table 2: Parameters for household cooking technologies.

<table>
<thead>
<tr>
<th></th>
<th>Efficiency (%)</th>
<th>Inv. cost</th>
<th>Life (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooking Biomass</td>
<td>15</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>Coal</td>
<td>15</td>
<td>1.5</td>
<td>5</td>
</tr>
<tr>
<td>Kerosene</td>
<td>40</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>LPG</td>
<td>60</td>
<td>267</td>
<td>15</td>
</tr>
<tr>
<td>Electric</td>
<td>75</td>
<td>833</td>
<td>15</td>
</tr>
</tbody>
</table>

Investment costs are in terms of Rs/GJ input energy.

The groups’ stated prices varied less than 10% around the average, indicating that the average price estimates should be relatively reliable. The average price of firewood and electricity was higher among the urban population, which was interpreted as an actual difference in the prices between urban and rural areas. PDS kerosene denotes subsidized kerosene distributed through the public distribution system (PDS).

Numerous studies have cited different technological parameter sets for the appliances, e.g. Reddy (2003), Masera et al. (2000), Pachauri (2004b) or TERI (2006). The parameters used in this study are based on Reddy (2003), except the efficiencies of biomass and kerosene cookers, which were 5 percentage points higher than in Reddy (2003) and set at the values reported in Masera et al. (2000), Pachauri (2004b) and TERI (2006). The parameters used are presented in Table 2.

4.2. Discount rates

Energy investments, in general, include an upfront investment cost and fuel costs distributed over the lifetime of the appliance. The common solution to this temporal distribution of costs is the calculation of net present values by discounting future costs with the so-called social planner’s discount rate or risk-free interest rate, both often around 5%. An implicit assumption behind this is that there are financing opportunities present with the chosen discount rate and thus cash reserves do not constrain the investment. While this is often true for institutional investors, such opportunities are not always present for households, especially for low-income rural households. Even if the financing would be available for these consumers, the interest rates can be high or borrowing can carry a transaction cost, impeding the efficient use of the financing opportunity.

This lack of funding may result in a scarcity of cash within the budgeting period of the household, which can be considerably shorter for poor households with no savings as compared to more affluent ones. Thus a poor household has to either save in advance for the investment, or to reduce other consumption within the budgeting period when the investment is made. In the former case the net present value of the investment at the time the investment is made is higher than the actual investment cost, as the savings have been made in advance. The latter case might not even permit the investment, as the investment cost might be prohibitively large (Leach, 1992; Gangopadhyay et al., 2005). Even if possible, with a decreasing marginal utility from consumption the disutility from a large investment is greater than the increased utility from smaller savings in the future, deterring the investment.

These facets of the intertemporal choice problem can be incorporated through employing a higher discount rate than the social planner’s discount rate in the analysis. Furthermore, the discount rate should be higher for consumers with lower income, for whom cash is even scarcer. This has already noted by Reddy and Reddy (1994) for Indian households.
The discount rates in Table 3 are remarkably higher than the 5% rate usually used in such studies, and gives considerable weight to the up-front costs associated with purchasing stoves. For comparison, Reddy and Reddy (1994) have also estimated discount rates for households in Bangalore, based on the actual decisions that these households made regarding their fuels choices. With the assumption that the households switch fuels types if the internal rate of return associated with the switching is above their own discount rate, the authors associated the shift from firewood to kerosene to a discount rate of around 200%, and from kerosene to LPG to a rate around 10%. Compared to these estimates, the rates in Table 3 seem relatively moderate in the case of switching from firewood to kerosene, but too high for a shift from kerosene to LPG. However, the IRR estimates by Reddy and Reddy (1994) are obviously very dependent on the parameters employed, which were not presented in their paper. Still, their paper provides additional evidence that Indian consumers are likely to use high rates for discounting.

4.3. Inconvenience costs

A basic formula for the marginal inconvenience cost was given in Eq. (3) as the relation between the optimal amount of traditional fuel consumption and the difference in marginal useful energy costs between the two fuels. For the fuel choice model, a single inconvenience cost reproducing consumers’ real life choices is, however, needed. In other words, it is required that the model would select the main cooking fuel, implied by the statistics, as the fuel of choice with each consumer group. In addition, if the effect of changes in fuel prices—e.g. fuel subsidies—is to be modelled correctly, the inconvenience cost estimates should provide a trigger of the right magnitude for switching the choice of main fuel.

If an additional assumption to (3) is made that the marginal inconvenience cost $c(E_t)$ is linear, i.e. $c(E_t) = \alpha \cdot E_t$, then the marginal inconvenience cost of satisfying the cooking energy demand fully with biomass would be

$$c\left(\frac{\eta^T \varepsilon}{\eta_t}\right) = \frac{\eta \varepsilon^T \varepsilon}{\eta_t} \left(\frac{\eta}{\eta_t} p_{m} - p_{t}\right).$$

(4)

This can be reformulated as

$$C_{\text{full}} = \frac{\eta_t}{\eta_m} p_{m} - p_{t} + \frac{p_{T}^E - p_{T}^m \eta^T \varepsilon \eta_t^{-1}}{E_t},$$

(5)

which gives the inconvenience cost for full biomass consumption as a sum of the marginal cost difference and the price premium that the consumers have paid for their actual consumption.

However, using Eq. (5) to estimate the inconvenience cost would result in the traditional fuel, by definition, always being more costly than the modern one, as the inconvenience cost would exceed the marginal cost difference. Instead, an average marginal cost

$$C_{\text{avg}} = \frac{1}{2} \left(\frac{\eta_t}{\eta_m} p_{m} - p_{t} + \frac{p_{T}^E - p_{T}^m \eta^T \varepsilon \eta_t^{-1}}{E_t}\right)$$

(6)

would have the desired characteristics described above. This is illustrated in Fig. 6, which portrays a consumer using biomass as the primary fuel with useful traditional energy consumption of $\eta E_t$. As can be seen from the figure, the marginal cost difference $\eta_t/\eta_m p_{m} - p_{t}$ exceeds the average inconvenience cost $C_{\text{avg}}$ and the linear choice model would select the traditional fuel as the fuel of choice for this consumer. Also, if the price of the modern fuel would be lowered so that the marginal cost difference would be below $C_{\text{avg}}$, the consumer would choose the modern fuel as the consumer groups’ estimated rates being also explicitly presented in Table 3.

A vast number of studies have attempted to quantify consumer’s discount rates, giving extremely diverging results. For example a review on a large number of discounting studies by Frederick et al. (2002) cites results ranging from negative to infinity. However, if confined only to results from real field studies, as distinct from hypothetical and experimental studies, the range narrows to between 0% and 300%. Even though the review did mention that the relationship between income and discount rates has been observed in a number of studies, it did not cite any explicit income-discount rate correspondence.

This lack is remedied by an older review of 14 studies on different energy-related investments by Train (1985), which also confirms the assumption that consumers with higher income use lower discount rates in their decisions. Selecting the studies on consumers with higher income use different energy-related investments by Train (1985), which also cite any explicit income-discount rate correspondence from IMF (2008). The data from Train (1985) and estimates for consumer groups’ estimated rates being also explicitly presented in Table 3.

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1 The PPP rate might differ between consumers with different consumption patterns. Income-specific PPP rates could also be incorporated in the conversion, but as according to Asian Development Bank (2008) the differences in PPP rates for Indian consumers with different income levels are only minor, a single PPP rate from IMF (2008) was used for simplicity.
main choice, which would also be the result from the use of the linear choice model.

The average inconvenience costs for the consumer groups considered were calculated from Eq. (6), using the minimum of either the price of kerosene or LPG—inclusive of the associated annualized investment cost—as the reference modern fuel price. The results are presented in Table 4. As can be seen from Table 4, the inconvenience cost is increasing with income within both rural and urban populations.

There is no good reference point in the literature for the inconvenience cost values, although, e.g., Reddy and Reddy (1994) have noted the importance of inconvenience in the fuel choice problem. van Ruijven (2008) made an effort to estimate these costs but their method yielded counterintuitive results. However, as van Ruijven (2008) noted, the limited availability of LPG in rural areas might affect the inconvenience cost estimates, and inconvenience costs for rural consumers might be higher in the absence of these availability barriers. When compared to the actual price for biomass, estimated as 62 Rs/GJ in rural and 80 Rs/GJ in urban areas, the estimated inconvenience costs are quite moderate for the entire rural population, less than 50% of the fuel price. For the urban population the inconvenience cost estimates rise sharply with income, almost reaching the actual price of biomass already for the third quintile group.

An interpretation for the observed behaviour of the inconvenience costs can be based on the factors behind the inconvenience. As has been already mentioned, a higher time spent and exposure to particulate matter is associated with the use of traditional fuels. The low income levels of poor households and more limited work opportunities of the rural population—especially with women, who usually gather and use the firewood—involve lower opportunity cost for time (Pachauri, 2004b), and consequently lower inconvenience costs for low-income and rural households. Also, lack of information on the adverse effects of particulate matter among the less educated, lower income households might be an additional explanation. Cultural preferences and traditions have also been reported by Masera et al. (2000) as factors affecting household energy choices. With less empowered women gathering and using the fuels and men making the decision of which fuel to use—a situation more likely to be the case for rural populations—there might be a tendency to undervalue the inconveniences (Cabraal et al., 2005).

4.4. Other determinants

4.4.1. Time consumption and availability of biomass

The time needed to gather a certain amount of fuel might be a constraining factor for consumers, and depends on available biomass resources. A study by Bhagavan and Giriappa (1995) on time used for gathering traditional fuels in eight villages in three different climatic environments in India, estimated the average pace for gathering traditional fuels at the community level as varying from 38 MJ/h in the semi-arid regions to 62 MJ/h in the tropical regions. A pace of 50 MJ/h would equate to roughly as 3.5 kg of firewood per hour. Assuming this gathering pace, the average biomass consumption of the rural population implied by the NSSO survey, 3600 MJ/ha/capita, would require 12 min per day per capita to gather the fuel. Based on this estimate, the time budget requirements needed appear unlikely to be a constraining factor for the population as a whole.

As was noted already in Fig. 2, traditional fuels are also traded. This has two important implications. First, due to the possibility of purchasing some of the fuel, time does not constrain the consumption of traditional fuels on the level of individual consumers, but only possibly at an aggregate level. At this level, based on the calculation above, only a fraction of the workforce appears to be required to gather the fuel and thus time consumption does not seem to be a major constraining factor even at the aggregate level. Second, using freely gathered traditional fuels also carries a monetary opportunity cost due to the presence of the market for traditional fuels. Therefore the monetary value or price of the fuel is also significant for those who collect their own fuel, and should reflect the time needed for gathering the fuel.

4.4.2. Budget

In the preference maximizing choice model, presented in Eq. (1), the budget limit characterizes the solution with the preferences of consumers. In the equivalent cost-minimizing problem of Eq. (2), the budget constraint is met through the cost minimization. This, however, holds in general only when prices are stable, and if changes in (real) prices are assumed, the budget constraint would have to be considered also in the cost-minimizing problem.

The constraining feature of the budget, however, increases only with increasing prices, assuming that the own-price elasticity of aggregate energy consumption is above −1, i.e. the demand is relatively inelastic. This is an appropriate assumption as there are no close substitutes for energy consumption. Gundimeda and Kohlin (2008) also reported that the Hicksian (compensated) own-price elasticities estimated from the NSSO data for different fuels were generally between −0.1 and −0.7.
This study assesses the effect of reduced energy prices due to fuel subsidies, and the resultant potential shift from traditional fuels to modern fuels. A fuel subsidy, based on the reasoning above, then leads to a reduced importance of the fuel budget constraint. Also, the higher efficiency of LPG and kerosene stoves compared to those used with traditional fuels balances out their higher fuel price, either partially or wholly, thus also reducing the effect of the budget constraint. Although the fuel budget constraint was implemented in the MESSAGE-Access model, described in Section 6, the factors mentioned above rendered the constraints mostly non-binding.

4.5. The results from the choice model

A household energy choice model based on the characteristics described above compares the annualized costs of different fuels, taking fuel, investment and inconvenience costs into account, and using the discount rates presented in Fig. 5 individually for each consumer group. The model results in all rural consumers choosing biomass; and among urban population U1 choosing biomass, U2 choosing kerosene and groups U3–U5 choosing LPG. Comparing these results to Fig. 3 reveals that the choices correspond exactly to the main cooking fuels the groups use, suggesting that the model is able to reproduce actual household choices regarding the main cooking energy forms.

It should be borne in mind, however, that the linear cost optimization approach intends to solve the energy choice problem with a single solution, whereas in reality many households in India use multiple fuels for cooking. Therefore the results from the choice model might be slightly unbalanced, and might not portray the whole spectrum of energy forms used, although on the level of the total population the actual energy mix is more accurately represented.

5. Sensitivity analysis of the choice model

The parameters in the choice setting can be divided into technical and price parameters, on which we have relatively good estimates, and more speculative parameters, namely the discount rates and inconvenience costs. Following this division, the sensitivity analysis of the fuel choice model is also divided into two parts.

Given the prices and technology parameters presented in Tables 1 and 2, the choice problem involves choosing a single technology with lowest annualized costs per useful energy implied by the discount rate, and inclusive of the inconvenience cost for biomass. The solution itself therefore gives no indication of how close the costs of other technologies are to the optimal one.

The problem can, however, be expressed as a phase diagram on a discount rate–inconvenience cost plane, explicitly illustrating the proximity of other technologies to the optimal. This is represented in Fig. 7, separately for rural and urban consumers to account for the differences in fuel prices, along with the point estimates of discount rates and inconvenience costs for each consumer group.

As can be seen from the figure, all of the rural consumer groups are well inside the biomass phase, but approach the LPG phase with higher income. Therefore, the rural consumers’ choices are not sensitive to their discount rate and inconvenience cost parameters. The urban consumer groups are scattered on all three phases, with the lowest income group in the biomass phase, U2 in the kerosene phase and three groups with the highest income in the LPG phase. As many of the estimated parameter pairs lie close to the phase boundaries, the model results for the urban consumers appear to be clearly more sensitive to the parameter values than for the rural population.

However, as both the actual values and consumer preferences and technological parameters might vary, there is not a single cost-optimal technological choice to the problem at hand or the consumer might be unable to identify it, and therefore the aggregate choice will be a mix of fuels that are close to the optimum. Then, if we broaden our view away from the decision of selecting a single cost-optimal fuel, the results from the phase diagram compare well with Fig. 3 as the proximity of a group’s parameters to different fuel phases correlate with the each group’s main energy form for cooking implied by the statistics. The rural consumers use predominantly biomass, but the highest quintile also uses LPG to some extent. The lowest urban expenditure quintile uses mostly biomass, but also some kerosene, the second lowest quintile uses approximately equal amounts of kerosene, biomass and LPG. For the three highest expenditure groups the share of biomass declines steeply and the share of LPG rises, reaching over 80% for the highest group.

Although the phase diagram seems to compare well to the observed statistical consumption patterns, the phase diagram is also dependent on the techno-economic parameters. These affect
the location of the triple point, i.e. the intersection of the three fuel phases. The sensitivity to cost, efficiency and equipment lifetime estimates was assessed by deviating each parameter by ±5% and ±10% from the values stated in Tables 1 and 2. The results from this experimentation are presented in Fig. 8. The inconvenience costs also vary depending on the parameter values, and therefore instead of a single cross, a group of 12 crosses represents each consumer group in the figure.

It can be seen from Fig. 8 that the rural consumers are sufficiently deep in the biomass phase so that the results are resilient to changes in all parameters. The figure for urban consumers suggests that the model might not be entirely conclusive, as a 10% change in the price or efficiency of kerosene or LPG would shift the triple point sufficiently to induce a result different from that of Fig. 7.

Should the default parameter estimates be unbiased, however, there should be also no actual bias in the results of choice model. As there are, however, uncertainties and variance in both actual and perceived values of prices and technical parameters, this would add to the distribution of actual choices in reality around the optimum. It should also be noted that the different uncertainties counteract each other to some extent, reducing the sensitivity of the model to the parameter uncertainties as a whole. Therefore, even though the model is relatively sensitive to the parameters used, it should give a good indication of the determinants of fuel choice and what kind of an effect a change in these determinants might have on choices.

6. Scenarios up to 2020

As an extension of the developed energy choice model, the choice framework was implemented in an Indian household-sector demand-side model, MESSAGE-Access, using the MESSAGE energy modelling system (Messner and Strubegger, 1995). The MESSAGE framework uses linear cost optimization as the solution concept for calculating long-term energy scenarios, and the most notable implementation of the system is the global 11-region integrated assessment model (see e.g. Riahi et al., 2007). In addition to producing a baseline scenario for household energy consumption, the model was used to explore policy scenarios aiming to improve the market penetration of modern cooking fuels, especially among the rural poor.

The MESSAGE-Access implementation incorporates multiple consumer groups, each with distinct inconvenience costs and discount rates. The consumers were grouped into expenditure classes corresponding to the rural and urban expenditure quintiles of 2000. Therefore due to economic growth and increasing expenditure levels, households migrate gradually from the lower to the higher expenditure groups.

As an exception to the grouping, however, the highest rural group was split into two parts, R5-1 and R5-2, in a manner that the group R5-2 would have a sufficiently high investment cost for it to only barely prefer LPG to biomass according to the energy choice model. This configuration enables the model to account for the autonomous shift from traditional to modern fuels resulting from economic growth. The share of R5-2 of the rural population was, however, only 1.3% in 2000, which compares well with the NSSO statistics indicating that of the highest earning rural 5%, only 30% used LPG as their main cooking fuel in 1999/2000.

The inconvenience costs and discount rates for the groups R1–R4 and U1–U5 were taken, respectively, from Table 4 and Fig. 5. For R5-1 and R5-2 the inconvenience costs were 29.2 and 43.1 Rs/GJ, respectively, and the discount rates 62% and 59%.

The shift of expenditure distributions—for the rural and urban populations separately—were estimated by extrapolating the parameters of a lognormal curve fitted to the real expenditure distributions from NSSO survey data between 1993 and 2007 with consumer price inflation estimates from IMF (2008). The shares of consumer groups in the MESSAGE-Access model from the total rural and urban populations are presented in Fig. 9. The growth of the total urban and rural population sizes were taken from the B2 scenario by Riahi et al. (2007).

As the MESSAGE model framework, however, operates inherently on a single discount rate, the investment costs were multiplied with a factor representing the effect of a higher discount rate. This factor is the ratio between annualized investment costs for the appliance lifetime T with the model’s discount rate rM and the discount rate r_i of the consumer group i, i.e.

\[
\frac{r_M}{r_i} \left( \frac{1 - e^{-r_M T}}{1 - e^{-r_i T}} \right)
\]

As the cost minimization problems with NPVs or annualized costs are equivalent, using multiplied investment costs and model discount rates yields the same outcome as would minimization with the consumer’s own discount rate.

![Fig. 8. Sensitivity of the triple point in Fig. 7 and inconvenience costs to different assumptions with ±5% and ±10% deviations in the fuel price, investment cost, efficiency and appliance lifetime parameters for rural (top) and urban (bottom) consumers. The lines are slightly displaced to improve visual distinguishability. The black groups of crosses depict the effect of different parameter assumptions to the inconvenience cost, calculated with (6).](image-url)
6.1. Policy measures for improving the adoption of modern fuels

Based on the determinants considered in Section 4, possible measures aiming at a larger penetration of modern cooking fuels should target either the costs, discount rates or the inconvenience costs. Of these three, lowering the costs through fuel subsidies and discount rates, e.g. through micro-financing opportunities, seem more plausible than aiming for policies that lower inconvenience costs, the sources of which are more ambiguous. Subsidizing the appliances is obviously also a possibility, but this might be hard to implement effectively in practice due to the heterogeneity of products available on the markets, and was thus not considered here. Also, the state-owned oil-companies and the PDS currently act as the distribution chain for subsidized LPG and kerosene (Gangopadhyay et al., 2005), which ease the implementation of applying fuel subsidies.

As the discount rate of the poor consumers was estimated to be dramatically larger than the usual assumption of the socially optimal rate, it could be argued that such high rates produce a socially sub-optimal outcome. Thus it would be beneficial to provide a funding scheme for appliance investments with interest rates closer to the social planner’s discount rate. Based on Robinson (1996), micro-financial institutes, which provide loans for the poor in developing countries, generally charge interest rates of 20–35%. This range was used as a reference for discount rates in the improved financing scenarios by associating the high end to the R1 group and a 5% rate to the U5 group and interpolating for the groups in between based on their expenditure levels. The effect of providing improved financing opportunities was assessed both as the only policy measure, and in conjunction with a fuel subsidy.

With the assumed fuel subsidies, the price of LPG or kerosene was reduced by 20%, 33% or 50% from the real price of 2000 in the policy scenarios. For comparison, in 2000 the price of PDS kerosene was roughly only 40% of the market price, but the quantity of PDS kerosene supplied was limited. Thus, especially in the high subsidy scenarios, this may be seen as quite an extreme measure. All of the measures were assumed to be announced in 2010 and to be implemented from 2011 on, so that the household energy scenarios would follow the baseline scenario up to 2009, after which the households could react to the announced policies.

6.2. Results

The baseline scenario for cooking energy consumption, illustrated in Fig. 10, follows closely the results of the basic fuel choice model. Among the rural population, biomass is clearly the fuel of choice for all consumer groups except R5-2, although it is supplemented with the limited supplies of PDS kerosene. Existing LPG stoves are also used for their lifetime, but not replaced. For the urban population, U1 selects biomass, U2 kerosene, and the higher expenditure groups LPG. Similar findings—i.e. the dominating status of biomass in rural areas and an increasing share of LPG in urban areas—in projections up to 2010 have also been made by Reddy (2003).

In the figure, the year 2000 corresponds to the statistical values from NSSO data, and the actual results from the MESSAGE-Access model start from year 2001. As can be seen, the model reproduces the statistical consumption patterns with reasonable accuracy, especially when measured in useful energy terms and taking the uncertainties in the biomass consumption figures into account. Also, as was noted in Section 4.5, the choice model represents only the main fuels used by households, and therefore any secondary cooking energy forms are not represented in the scenarios.

In the baseline scenario with no policy changes, the rural population will continue to use traditional biomass as its main cooking fuel. With the growing rural population, this leads to an increase in the absolute number of people affected by the adverse effects of traditional fuel consumption, e.g. particulate matter exposure. Also, as the energy consumption is likely to rise due to income growth, the consumption of firewood increases even more than the rise in population size, resulting in possibly greater deforestation and forest degradation, as already the current firewood consumption is estimated to be at an unsustainable level (Kaul et al., 2009).

The effect of the policy measures was very straightforward in most cases. Without improved financing possibilities, a partial market penetration of modern fuels occurs within the rural population with a 20% kerosene or 33% LPG subsidy, and a full penetration with subsidies of 33% and 50%, respectively. At the same time, even the low 20% subsidy on LPG prompts the U2 group to switch to LPG, and the 20% kerosene subsidy encourages kerosene consumption so that it gradually becomes the main cooking fuel in urban areas.
Improved financing, in the absence of any additional subsidies, would already cause groups U1 and U3–U5 to switch to LPG as their main fuel. This can also be seen from Fig. 7 by shifting the discount rates of the points to levels below 35%. If this policy is combined with a 20% LPG subsidy, LPG is adopted by the whole population, apart from some groups also using the PDS kerosene in its full availability. Financing, however, does not notably improve the effect of kerosene subsidies, due to the relatively low investment cost of kerosene stoves.

For evaluating the effectiveness of the policies, the net present cost of the policies up to 2020 was calculated to be compared with the market penetration of modern cooking fuels in rural areas in 2012. For the cost calculations, the cost of microfinancing was estimated to be zero, as micro-finance companies cover their activity costs from the interests charged, and can actually even profit from their activities.

The cost-effectiveness of policies is portrayed in Fig. 11. In choosing the pareto-optimal policy with high penetration and low costs, three points emerge: financing only or financing combined with a 20% subsidy on either LPG or kerosene. Of these three, the kerosene option, however, results in only marginally larger penetration levels than in the scenario with only financing measures, whereas the LPG subsidy affects even the poorest consumers. To achieve this with kerosene subsidies, the cost rises rapidly and exceeds that of the 20% LPG subsidy. It should also be noted that this rapid change in the penetration and cost of the kerosene subsidy also produces a source of risk, should the subsidy level be set either too low or too high, as the actual response from the consumers might deviate from that implied by the model.

7. Summary and conclusions

Improving the prospects for modern energy use is an important prerequisite for improving the conditions of poor households in developing countries. In particular, providing access to modern cooking fuels to such populations would reduce their exposure to harmful particulate matter, save their time for more productive activities and mitigate deforestation. Drawing from both the preference and budget constraint approach of classical demand theory and the cost-minimizing solution concept of various energy system models, a fuel choice model was developed in this work, using costs and technical characteristics of appliances and fuels, and discount rates and preferences in the form of inconvenience costs as key determinants. The determinants were specified separately for consumer groups instead of for the population as a whole, differentiating—based on Pachauri (2004a)—between different expenditure levels and whether the households live in rural or urban surroundings.

The fuel choice framework was then implemented as the MESSAGE-Access energy system model for India, which is planned to be integrated with the global MESSAGE model (Riahi et al., 2007) in future work. The novel elements of the model include differentiation of consumer groups, income specific discount rates and the accounting of preferences in the cost minimization framework through the estimation of inconvenience costs associated with traditional fuels. The fuel choice model developed in this work, was able to reproduce the main cooking fuel choices of all consumer groups, as implied by NSSO statistics. As an application, the MESSAGE-Access model was also used for evaluating the implications of policy measures such as fuel subsidies and improved financing in order to promote the adoption of modern cooking fuels in rural India.

Acknowledging the heterogeneity of consumers is a step forward to a more realistic representation of the household sector in energy system models. In existing linear cost-minimizing
models a single energy form is usually used for a given purpose, and a sudden shift to a different one can result from small changes in the underlying parameter values. By differentiating among different consumer groups, even though a single consumer group's decision will still be sensitive to the input values, the aggregate consumption estimates are likely to be more robust and can reproduce a more realistic spectrum of different energy choices.

The actual determinants that distinguish consumer groups from each other in this work were differing fuel costs, discount rates and preference-related inconvenience costs. The prohibitively high investment costs of kerosene and LPG stoves for low income households has already been highlighted in previous literature e.g. by Reddy and Reddy (1994). Gangopadhyay et al. (2005) also noted that the price of a LPG cylinder might also be too high for the poor, though it might result in cost savings for them in the longer term. As income dependent discount rates were employed in this work considerably high discount rates, especially for the lowest income households were used that provided a more realistic estimate of the investment constraints for such households.

The estimation of the inconvenience costs associated with traditional fuels was another novel feature of this analysis. Numerical estimates for these preferences are scarce in the literature. An attempt was made by van Ruijven (2008) but they arrived at a rather counterintuitive outcome, with LPG and kerosene having a higher inconvenience penalty than traditional fuels. The inconvenience cost estimation procedure derived in this paper provided estimates that were higher for households in urban areas and rose with the income of the household. This seems a more intuitive outcome, given the lower opportunity cost of time and limited work opportunities for rural poor households, especially for women.

The model framework taking into account the heterogeneity of households, discount rates and inconvenience costs is of generic nature, and is applicable also for other countries and settings. Case-specific factors—such as prices of different energy forms and appliances, preferences, and expenditure distributions—obviously affect the actual numerical results and responses to different policies. However, the results on consumers’ tendency to disregard energy efficient options with high up-front costs due to the high rates used discounting can be deemed indicative also for other settings.

A sensitivity analysis for the choice model suggested that there are often multiple fuels in close proximity of the cost optimum, but this proximity correlated well with the share of the fuels in the consumption mix of each consumer group. This is also compatible with the findings of Masera et al. (2000), that the households often use multiple energy sources instead of a single one.

A baseline scenario calculated with the MESSAGE-Access model resulted in an approximate continuation of the current consumption patterns. In this scenario, the number of people using traditional biomass in 2020 would rise by almost 100 million compared to the level in 2000. The policy scenarios with either improved financing opportunities, fuel subsidies or a combination of both, suggested that a major obstacle for the adoption of modern fuels, especially LPG, is the high investment cost and the discount rates that the consumers use in their energy related decisions. According to the results, subsidies alone may be inefficient for promoting modern fuels, as the steep up front investment costs are not affected. Improved financing opportunities for the appliance investment alone would already increase the penetration of modern fuels remarkably within the rural population. Combined with a small LPG subsidy, the whole population might be prompted to switch to LPG. With a kerosene subsidy, the effect of improved financing would not be as significant, and a subsidy level sufficient enough to affect choices for those with a very low income level might even induce consumers with higher incomes to shift from LPG to kerosene, raising the cost of the subsidy.

Gangopadhyay et al. (2005) have argued that the current LPG fuel subsidy in India is inefficient, as it benefits the rich more than the poor. However, if the heavy burden of up-front investment costs for the poor is eased through financing, the situation changes as the running costs of LPG are lower than of kerosene due to its higher efficiency. In addition, as Gangopadhyay et al. (2005) also observed, the kerosene subsidy is expensive, as a large share of the kerosene is illegally diverted away from the public distribution system.

At a time when the world is shifting to a low-carbon economy, it might sound odd to promote the adoption of fossil fuels. However, the additional emissions from using LPG in cooking for the entire population of India in 2020 would be only around 50 Mt CO\textsubscript{2}, which is negligible when compared, e.g. to the 2200 Mt CO\textsubscript{2}-equivalent estimate of total Indian emissions for 2005. The shift from cooking with traditional fuels to modern fuels will have a substantial effect on the lives of over 700 million inhabitants in 2020, and is likely to be an important precondition for the eradication of poverty among these households.

Obviously the model developed in this paper, although an improvement on previous modelling efforts, is not a full description of reality, and a number of caveats should be considered. First, fuel consumption is also a matter of physical access to the modern fuels, not only consumer choice. But then again, if the household’s determinants of fuel choice do not imply a switch to modern fuels, improving the access to these fuels will not increase their adoption to its full potential. Second, the supply of biomass was assumed to be at a constant cost or opportunity cost in this work, whereas in reality the potential supply of biomass varies considerably between regions and therefore costs to may vary. Third, in the policy scenarios, the model did not include any own-price elasticity of demand, and the applied subsidies did not therefore affect the total cooking energy demand. The subsidy might in fact increase the fuel consumption and raise the cost of the scheme. Despite these caveats, the overall results from the model are robust, and unlikely to be affected even if these issues were taken into account in more detail.

One may also argue that subsidies are a fiscally unsustainable way of promoting the shift to cleaner fuels, and a strain on government budgets. The case might actually be to the contrary in the longer term, for the subsidy could increase labour productivity, as the time used for gathering and using firewood could be used more profitably. By nourishing economic development among the rural poor, this would also increase the opportunity cost of time—and through this effect, shift the price balance permanently in favour of modern fuels. Therefore the subsidies can be seen as a transitional necessity. Thus, as a conclusion, economic development and the adoption of modern cooking fuels are very likely to go hand in hand and it is hard to imagine improving one without improving the other.

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