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The drivers of sustained use of liquified petroleum gas in India

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Abstract

Ninety-five per cent of Indian households now have access to liquified petroleum gas (LPG), with 80 million acquiring it under the *Pradhan Mantri Ujjwala Yojana* (PMUY) since 2016. Still, having a connection is not enough to eliminate household air pollution. Studying panel data from rural households in six major states from 2014–2015 and 2018, we assess the determinants of cooking energy transition from solid fuels to LPG. We find that PMUY beneficiaries have much lower odds of using LPG as the primary or exclusive fuel compared with general customers, irrespective of their economic status. Village-level penetration of LPG as a primary fuel and the years of LPG use positively influence its sustained use, while ease of access to freely available biomass and reliance on uncertain and irregular income sources hinder LPG use. The findings highlight the need to interlace cooking fuel policies with rural development, to enable a complete transition towards cleaner cooking fuels.

India is in the midst of the largest household energy transition to date, with about one hundred million households acquiring a liquified petroleum gas (LPG) connection since 2016[1]. In 2011, three-fifths of Indian households-primarily in rural areas-relied on solid fuels to meet their daily cooking and heating needs[2], resulting in substantial negative impacts on health[3], the economy[4] and the environment[5]. The Government of India's flagship

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Author contributions

A.J. conceptualized the study and led the design of the work. A.J., S.T. and S.M. contributed to the collection of data. S.M. and A.J. led the data analysis, with input from all team members. S.T. led the interpretation of results and the writing of the manuscript, with input from all team members. C.F.G. contributed to writing the manuscript, led reviewing of the literature and designed the figures. All authors discussed the results and commented on the manuscript. Please direct any comments or requests for data used in the figures or analysis to S.M. (sunil.mani@ceew.in).

Data availability

The data that support the findings of this study (both of panel and cross-sectional analysis) are made available through Figshare at https://doi.org/10.6084/m9.figshare.9810170.

Code availability

The Stata.do files that format, clean and analyse the merged and appended datasets are available through Figshare at https://doi.org/10.6084/m9.figshare.9810167, while the R scripts that produce the figures are available at https://doi.org/10.6084/m9.figshare.11838963. Information on unique identifiers between the datasets is available in the Stata.do file.

Competing interests

The authors declare no competing interests.

Additional information

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cooking energy programme-Pradhan Mantri Ujjwala Yojana (PMUY)-has sought to alleviate the public health burden of household air pollution by providing a subsidy and loan for the upfront cost of adopting an LPG connection, which typically includes a double-burner gas stove, a 14.2-kilogram gas cylinder, a gas regulator and a hose pipe. Although over 80 million households have benefited from PMUY[6], steep recurring expenses and the poor availability of LPG in rural areas continue to hinder the extent to which households use LPG for all cooking needs[7,8].

Following the connection-oriented approach of PMUY, most evaluations of the programme have discussed enrolment rates using government-provided data[9–11]. Few studies have examined LPG use after adoption, and most of these have focused on average cylinder refill rates[10,12–14]. Government records indicate that about one-quarter of PMUY beneficiaries purchased five or more refills each year, suggesting the use of LPG as their primary cooking fuel, while another one-quarter did not purchase any refills in the first year, suggesting sparing use[10,14]. Recently, researchers used refill records in Karnataka to show that the average annual LPG consumption for PMUY customers was 2.3 cylinders (32.7 kg per year), compared with 4.7 cylinders (66.7 kg per year) for general (non-PMUY) customers[15]. According to a government audit, PMUY customers averaged 2.98 cylinder refills per year (42.3 kg per year) and general customers averaged 6.73 cylinder refills per year (95.6 kg per year) across India between March 2018 and March 2019[1].

Adoption of a clean cooking fuel like LPG is a necessary first step in ensuring smoke-free kitchens and reducing the drudgery of biomass collection. However, both sustained use of cleaner fuels[16,17] and cessation of solid fuel use are required[18] to achieve the stated health outcomes of PMUY. Many households simultaneously use multiple fuels-termed fuel stacking-rather than moving step-by-step along an energy ladder towards cleaner fuels[19].

Using panel data collected from the rural areas of six major energy access-deprived states in India in 2014–2015 and 2018, we assess the determinants of upward shifts in LPG use-from use as a minority fuel for cooking only, to the primary fuel and then as the exclusive cooking fuel. By examining dynamic fuel stacking instead of LPG consumption, this study identifies factors that help households to transition away from solid fuel use and towards cleaner fuels. We report a number of important findings. First, PMUY beneficiaries have considerably lower odds of primary and exclusive use of LPG than general customers. Second, the village-level penetration of LPG as a primary fuel and the age of the LPG connection are both positively associated with sustained use. Third, we find that easy access to free-of-cost biomass is a major deterrent to the exclusive use of LPG. Finally, households depending on agriculture and labour as the primary source of income have much lower odds of increased use of LPG.

Review of the literature on household cooking fuel choice

The body of research characterizing the determinants of household cooking fuel choice has been summarized elsewhere[20–22]. We outline a few econometric approaches that have explained the determinants of cooking fuel use in India. Previous work-while employing rigorous analytical approaches-has been limited, primarily owing to two main gaps.

First, studies seeking to understand the drivers for adoption and use of clean cooking fuels, as well as enablers of the reduction and cessation of solid fuel use, are primarily based on cross-sectional data. Such studies are inherently unable to observe household-level transitions. Many studies of cooking fuel choice in India have also been geographically limited, with relatively limited sample sizes[23,24]. Other studies have employed nationally representative microeconomic survey data that benefit from large sample sizes, such as those from the National Sample Survey (NSS)[25–27], the India Human Development Survey[28–30] and the National Family Health Survey[30–33]. All three of these surveys have multiple waves, enabling researchers to leverage multiple rounds of data[34–36]; although, only the India Human Development Survey has a panel structure.

Two recent studies using multiple NSS rounds are notable. The first study separately analyses the 50th round (1993–1994), the 61st round, (2004–2005) and the 66th round (2009–2010) to assess the determinants of multiple cooking fuel use, and, separately, the exclusive use of clean cooking fuels[37]. The authors find a strong association between increasing household expenditures and clean cooking fuel use. However, this study neither models the data in a panel structure, nor models household-level fuel switching. The second study creates a synthetic panel of 100,000 households using the 55th NSS round (1999–2000) and the 68th round (2011–2012), by matching households on the basis of state, urban/rural and caste[38]. The authors model the extent to which LPG has offset firewood use to estimate the change in carbon dioxide emissions due to increasing LPG adoption and use. This study does not primarily study the determinants of fuel switching or fuel stacking. Taken together, these studies have contributed to our understanding of the differences between LPG adopters and non-adopters, but have not assessed household-level cooking fuel transitions.

Second, many previous analyses have focused only on the household's primary cooking fuel as the variable of interest. Current evidence suggests that the full health benefits of clean cooking fuel use are only obtained when used nearly exclusively[16,18]. Yet, many surveys have collected data only on households' primary cooking fuel; although this may be changing with recent efforts to incorporate multiple fuel use into surveys, worldwide[39]. Previous studies have assessed cooking fuel choice using several different outcomes: ownership of a clean cooking fuel; clean cooking fuel as the primary cooking fuel; and, in some cases, ordered fuel choice[25,40].

Two additional studies employing panel multinomial logit models using multiple rounds of survey data are noteworthy. The first uses three rounds of surveys to assess the socio-economic factors that determine cooking fuel choice in urban households in Ethiopia[41]. The authors find that household expenditures, fuel prices and education are key determinants of fuel stacking behaviour. The second study uses three waves of panel data in Tanzania to model fuel choice for cooking and lighting[42]. This study takes several approaches to assessing fuel stacking and incorporates important contextual covariates, such as fuel prices and local luminosity data. However, neither study directly models households switching fuels, and both include kerosene as a clean cooking fuel, despite evidence of substantial health risk from kerosene combustion due to its polluting emissions[43]. Still, efforts to formally model fuel stacking in India are limited[28].

Research design

Our analysis is based on two waves of household surveys carried out in six historically energy-poor states in India-Bihar, Jharkhand, Madhya Pradesh, Odisha, Uttar Pradesh and West Bengal-collectively representing 40% of the Indian population (Supplementary Table 1). The first wave covered 8,563 households and was collected between November 2014 and February 2015. The second wave covered 9,072 households-7,317 of which were also surveyed in wave 1-and was gathered between March and June 2018. The survey design is described in full in Supplementary Note 1.

To simultaneously study increased LPG use and displacement of solid fuel use, we specify a categorical outcome variable: LPG as a minority cooking fuel (secondary to solid fuels), LPG as a primary cooking fuel (with solid fuels retained as secondary options) and LPG as the exclusive cooking fuel.

We use two approaches to model the determinants of increased LPG use. In the first approach, we use a generalized-ordered logistic regression to study the cross-section of LPG-owning households in wave 2. We consider 4,102 households that reported LPG use in wave 2, but that may or may not have used LPG in wave 1. We only include households that were surveyed in both waves despite analysing the cross-section of wave 2, owing to the inclusion of certain lagged (wave 1) covariates. We identify covariates from the literature, including socio-economic and demographic contextual factors and household experience with cooking fuels (discussed in full in Methods).

In the second approach, we use a panel-ordered logistic regression to assess the household-level determinants of increasing the share of LPG in a household's cooking fuel mix. We consider 1,411 households that reported LPG use during both survey waves (distribution by category in Supplementary Table 2). While the focus of this study is understanding the factors for upward movement, we include movements up, down and across to account for all variation in household-level changes between the two survey waves.

We also undertake subsample analyses to assess whether the explanatory factors influence households differently depending on their starting point of LPG use (minority users versus primary users in wave 1) (Supplementary Table 3).

Increases in LPG use between 2015 and 2018

The overall sample (n = 17,635) witnessed a dramatic increase in LPG adoption between 2015 and 2018-from 22% LPG users in wave 1 to 58% in wave 2. PMUY has been an important driver of this shift: 43% of new LPG owners in wave 2 were enroled through PMUY. However, a lower proportion of PMUY beneficiaries were exclusive LPG users compared to general customers (Fig. 1).

In addition to a greater number of households having LPG in wave 2, we also observe an upward progression of LPG-use category. Among the panel subset, exclusive use was the smallest category in wave 1, but the largest in wave 2 (Fig. 2). Still, there was some

downward movement from primary to minority use, and from exclusive use to primary or minority use.

Determinants of LPG use and fuel stacking

Cross-sectional generalized-ordered logistic regressions show that households acquiring their LPG connections through PMUY have significantly lower odds of being primary users compared to general customers (odds ratio (OR), 0.64; 95% confidence interval (CI), 0.52–0.78) (Table 1). The odds drop further still for exclusive use (OR, 0.56; 95% CI, 0.45–0.71). The lower odds of PMUY households using more LPG is neither a factor of their relatively poor socio-economic status, nor of the infancy of their connection, as both of these factors are controlled for in the model. Rather, we suggest that households that made a decision to spend the upfront cost and effort to procure an LPG connection are probably more willing and more financially prepared to use LPG for the majority of their cooking needs than those who have been provided with a free connection.

We also observe village-level popularity of LPG as a primary fuel influencing LPG use. The fraction of households in a participant's village using LPG as their primary cooking fuel is significantly positively associated with that household being a primary or exclusive LPG user (Table 1). Our panel model corroborates this finding. Households in a village where the percentage of primary LPG users increased by one percentage point had 1.046 (95% CI, 1.041–1.052) times higher odds of moving to primary or exclusive LPG use than households in villages where there was no change in percentage of primary LPG users (Table 2). The positive effect of village-level penetration of LPG as a primary cooking fuel suggests a possible peer effect of LPG use and the importance of community norms in influencing LPG use. Although we account for geographic heterogeneity at the state level, higher percentages of primary users of LPG may also be related to village-level variation in the cost and availability of biomass, infrastructure quality or LPG availability.

As hypothesized, we find that households relying on agriculture or on labour as their primary source of income had lower odds of using LPG as their primary and exclusive fuel compared to households getting their primary income from salaried employment (Table 1). Agriculture-dependent households may have lower odds due to the unpredictability and irregularity of cash flow, which may make the large, 'lumpy' LPG refill payments a challenge. Indeed, households where the primary income changed to agriculture or labour between wave 1 and wave 2 had lower odds of increasing their LPG-use category than those whose occupation stayed the same or changed away from agriculture or labour (Table 2).

Years of owning LPG was positively associated with higher use category in both models. This effect of time may be because households get used to the convenience of LPG-based cooking, have more time to adjust their cooking habits and practices to LPG and/or have more time to align their household expenditures and cash flows with the recurring expense of LPG refills.

Counterintuitively, we did not find involvement of women in household decisions to purchase durable goods to be a reliable predictor of household use of LPG after adoption.

Further research on the involvement of women in cooking energy-related decision-making and its impact on fuel choice is warranted.

Distance travelled to procure LPG was not significantly associated with higher odds of using LPG for primary or exclusive use. However, households that travelled one kilometre less to procure LPG in wave 2 than in wave 1 had somewhat higher odds (OR, 1.04; 95% CI, 1.01–1.08) of moving up from minority use than those for whom distance did not change (Supplementary Table 3).

As hypothesized, households that owned cattle had considerably lower odds of being primary and exclusive users of LPG, probably because of easy access to dung cakes (Table 1). The magnitude of the association was higher for exclusive use compared to primary use, implying that the push towards complete cessation of solid fuel use is likely to face strong resistance from households that have easy access to biomass. Furthermore, households that acquired cattle between the two waves had lower odds of shifting to primary and exclusive use than other households (Table 2).

We find that households that collected firewood daily or a few times a week (a proxy for easy availability of biomass) in wave 1 had lower odds of exclusive use of LPG in wave 2 than those who collected firewood less frequently (Table 1). While easier availability of free-of-cost firewood impedes exclusive use of LPG, we did not find it hindering use of LPG as a primary fuel. Surprisingly, the effect of weekly expenditure on traditional biomass for cooking in wave 1 on the odds of increased use of LPG in wave 2 was not statistically significant (Table 1). This finding is contrary to our hypothesis and warrants further research.

Respondents' perceptions that LPG affected their health less than traditional cook stoves in wave 1 was not associated with LPG use in wave 2 (Supplementary Table 4). However, their perceptions in wave 2 were positively associated with LPG use in wave 2 (Supplementary Table 5). It is possible that knowledge of the health benefits of LPG is a consequence of LPG use, as opposed to a driver of its use, suggesting that health-related awareness in isolation may not be sufficient to nudge sustained use of LPG.

Limitations and future work

Before concluding, we note some limitations of our research. We rely on primary survey data for our analysis, including self-reported information on quantitative variables, which could be affected by typical limitations and biases of survey-based reporting. However, on the basis of a couple of robustness checks for our dependent variable (Supplementary Table 6–9), we can still claim that our self-reported variable is reasonable for this analysis. While approaches such as stove-use monitors and in-field fuel measurements can potentially lead to even more precise estimates, these measurement strategies are costly and can be prone to the Hawthorne effect, where participants behave differently to usual because they are being observed[44].

In addition, we focused on fuel stacking, but only pertaining to cooking. Future studies may investigate the end uses for each stove or fuel in the household. At times, solid fuels are also

used for other heating applications-space heating, water heating or food preparation of animals-that are not easily replicated by LPG or other clean cooking fuels. Elsewhere, such non-cooking end uses-or even preparation of specific dishes-have been motivators for sustained solid fuel use, even after long-term LPG adoption and use[45,46]. The specific nature of household solid fuel uses can potentially inform locally targeted interventions to facilitate complete transitions to clean household energy.

Recommendations and conclusions

India has witnessed a revolution in clean cooking energy adoption between 2016 and 2019 owing to the Pradhan Mantri Ujjwala Yojana programme. With 95% of households now having access to LPG, the policy focus in India is shifting from initial adoption to the sustained use of LPG to reduce air pollution exposure. Using cross-sectional and panel analyses, we examine and identify factors between and within households that drive sustained use of LPG and result in the complete cessation of solid fuel use.

Our results show that PMUY beneficiaries have systematically lower odds of using LPG for primary and exclusive cooking needs than general customers, even after controlling for socio-economic differences. Without targeted support for their energy transition, meaningful reductions in household air pollution among the majority of 80 million PMUY households will probably remain out of reach. A common notion worth assessing in future quantitative and qualitative studies is that the decision and effort to procure an LPG connection by general customers meant their greater preparedness (behaviourally and financially) to use LPG as their primary fuel for cooking.

Given that village-level penetration of LPG as the primary fuel has a strong positive association with household-level LPG use, we suggest that policies with community-level targeting could effectively increase LPG use. Thanks to the age of the LPG connection having a positive influence on its use, we may witness increasing use of LPG among recent adopters over time. However, targeted policies to further improve affordability of LPG refills for poor households can accelerate the transition.

Ownership of cattle and a high frequency of firewood collection-both indicators of easy access to free-of-cost biomass-considerably lower the odds of exclusive LPG use. Creating opportunities for households to sell the biomass for commercial purposes-such as alternative transport or industrial fuel-could create an opportunity cost for biomass to facilitate greater use of modern cooking fuels.

Reduction in the distance travelled to procure LPG increases a minority user household’s odds of moving to primary or exclusive use of the fuel. While the government has taken steps to improve fuel accessibility in recent years, further efforts are required to increase the density of distribution outlets in rural areas. To reduce the distance travelled in remote areas, the government and oil marketing companies could pilot locally tailored business models, such as extending LPG distribution to village-level entrepreneurs and local cooperatives.

Finally, the underlying economic transitions of India’s rural economy cannot be ignored. Households relying on agriculture and labour as the primary source of income need

livelihood support that enables predictable and regular cash flow to facilitate sustained use of clean cooking fuels. Convergence across government schemes on rural livelihoods and employment guarantees with clean cooking fuel promotion could become an important driver of the transition away from polluting solid fuels.

Our findings underscore that there is no ‘silver bullet’ that will yield exclusive clean cooking fuel use in rural India. PMUY has resulted in a tremendous national transition towards LPG, and we need multipronged approaches to accelerate its sustained use over time. Only by going beyond cooking fuel policies, and interlacing them with overall rural development priorities, can India move forward in enabling a complete transition towards clean cooking fuels for all.

Methods

Response variable.

We report here on the specifications of the response, explanatory and control variables. Data collection in wave 1 (refs.[47,48]) and wave 2 (refs.[49,50]) of ACCESS have been described previously, and in further depth in Supplementary Note 1. The survey questionnaire used is available in Supplementary Note 2.

We define three mutually exclusive categories of LPG use to assess factors that determined progression towards exclusive use of LPG amongst rural households in India between 2014 and 2018. These categories are used as the response variable in the panel and cross-sectional analysis: LPG as a minority cooking fuel (secondary to solid fuels), LPG as a primary cooking fuel (with solid fuels retained as secondary options) and LPG as the exclusive cooking fuel.

These categories are based on self-reported responses. Households are classified as exclusive users if they report LPG use but do not use any other fuel source for cooking. Primary users are those that state that LPG is their ‘primary cooking fuel’, but also report using other cooking fuels. Minority users are the remaining households, which use LPG but report some other fuel as their primary cooking fuel.

Elsewhere, continuous variables have been used to model LPG consumption after adoption. While outcomes such as ‘refills per year’ or ‘kilograms of LPG consumed per year’ capture overall LPG use, they are limited because they do not directly account for solid fuel use. Intuitively, increases in LPG use have been shown to yield decreases in solid fuel use; however, the extent to which there is perfect displacement is unknown. Furthermore, continued solid fuel use may not be a function of needing to meet household energy demands exclusively, but is probably also about preferences and meeting household end uses, such as cooking specific dishes or non-cooking energy demands such as space or water heating. Therefore, we use the three categories outlined above to capture dynamic shifts in cooking fuel stacking patterns. As a first-degree check, we assessed our dependent variable among 1,411 panel households by observing the changes in the amount of firewood (kg per person per month), dung cakes (pieces per person per month) and LPG (kg per person per year) used for cooking within households by each LPG category shift. This fuel

displacement analysis is reported in Supplementary Table 6, and clearly shows that all the upward (downward) movements in LPG category among panel households also come up with reduction (increase) in traditional biomass consumption.

To further ensure robustness of our choice of dependent variable, we assessed the deviation between self-reported primary fuel and the primary fuel based on useful energy analysis (considering quantity of fuel and stove efficiencies). We found the self-reported variable to be reasonable for our analysis (Supplementary Tables 7–9).

We noticed some downward movement across the categories between the two waves. There were few systematic differences between households that regressed and those that made lateral or upward movement. Among those that moved down from exclusive use, the proportion that owned cattle increased from 45% to 58%, while cattle ownership declined for all other households in the panel subset. Furthermore, those that moved down from exclusive and primary use had a sharper drop in their asset index score than those that did not regress. Last, among those that regressed, the proportion relying on agriculture for primary income increased, whereas that statistic decreased for the households that remained in the same category or moved up a category between the two waves.

Explanatory variables.

Here, we outline the specification of explanatory variables included in our models, as well as discuss their inclusion in previous studies. The variables were chosen on the basis of the existing literature on cooking energy adoption and use. Supplementary Table 10 (cross-section subset) and Supplementary Table 11 (panel subset) contain descriptive summaries of all explanatory variables, along with the hypothesized direction of association between the covariate and LPG-use category.

We include an indicator variable for whether a household is a PMUY beneficiary. Elsewhere, PMUY beneficiaries have been shown to utilize LPG after adoption differently from general consumers; often purchasing fewer refills relative to their peers[15]. Some PMUY beneficiaries may be financially unable to support regular cooking with LPG, and without the programme may not have purchased an LPG connection. In addition, it is possible that PMUY beneficiaries have different perceptions, attitudes or abilities compared to general customers, although this remains unexplored. We found that PMUY households were generally from the same rural villages as general customers (Supplementary Fig. 1), indicating no geographical bias in sampling. In the cross-section subset, 45% of minority users, 26% of primary users and 13% of exclusive users of LPG were PMUY households. In this subset, we found 134 households that identified as PMUY beneficiaries in wave 2, while also having reported LPG use in wave 1. Since PMUY only started after wave 1 of the survey, we force-coded these households as general (non-PMUY) customers to maintain internal consistency. We note the specific timing of data collection in both wave 1 and wave 2 in relation to when PMUY enroled the beneficiaries in each state in Supplementary Table 12.

We include the percentage of households in a village using LPG as their primary cooking fuel as a potential measure of local popularity of LPG, which, as a community norm, could

influence household use of LPG. In addition to the peer effect, we also expect this covariate to capture unobserved village-level variations, such as local road infrastructure and availability of LPG. Empirical evidence regarding the associations between LPG penetration in a community or community norms is otherwise limited, but there is some positive evidence for increased probability of LPG ownership with higher LPG community penetration[51]. There are ongoing trials testing the effects of peer effect and community norms[52,53].

We include the natural log of total weekly expenditure on biomass procurement in wave 1. We expect that households that spent a higher amount on biomass in wave 1, might have higher odds of increased use of LPG in wave 2 because they would find LPG to be relatively cheaper[54]. We find that households that are primary or exclusive users of LPG in wave 2 had a higher mean spending on biomass in wave 1 than minority users of LPG. Of the households in the cross-section subset, 57% did not spend any money on procuring biomass in wave 1, which made the natural log calculations impossible. Therefore, before converting the values into their logarithmic form they were increased by one. In the cross-section analysis, we use the lagged (wave 1) value of this covariate instead of the wave 2 value because we expect it to be endogenous with LPG-use category. For the same reason, we do not consider this covariate for the panel analysis.

To capture historical availability of biomass, we also include whether firewood was collected multiple times a week in wave 1 as a binary variable-where ‘1’ is assigned to households that collected firewood daily or a few times in a week, and ‘0’ is assigned for any other frequency. High frequency may indicate ease of firewood collection, and the resistance a household is likely to face in transitioning to the exclusive use of LPG. As above, we use the lagged (wave 1) value of this covariate instead of the wave 2 value in the cross-section analysis because we expect it to be endogenous with LPG-use category. Similarly, we do not consider this covariate for the panel analysis.

The involvement of women in household decision-making may be an important determinant of LPG use. We asked respondents who made the decision to purchase durable goods; responses were categorized as (1) a woman was involved in household decision-making (woman alone or joint with male household head), or (2) a woman is not involved in household decision-making. In the panel subset, there is a net increase in the proportion of households where women were involved in household decision-making between the two waves, from 20 to 28%. Women are often the primary cooks and, as such, may understand the benefits of transitioning to modern fuels, such as LPG, better. If women are involved in household decision-making, then their opinions can influence cooking fuel choice. A previous study showed that households where women were involved in decision-making had higher odds of owning LPG among the first wave of ACCESS[55]. Elsewhere, it has been relatively uncommon to directly model women’s decision-making power in studies of cooking fuel choice[20,56]. However, in some cases households headed by a woman have been more likely to have a clean cooking fuel[25,57], and in others less likely, compared with households headed by a man[58,59].

We include the natural log of the number of years that a household has had LPG to capture shifts in attitudes or in abilities for using cooking gas efficiently due to increased familiarity with the fuel over time. Increased ability is often cited as an important aspect of behavioural change[52,60]. This covariate required changes similar to those in the biomass expenditure covariate. While studying data for all households that were surveyed in both the waves, we came across internal inconsistencies in this covariate. First, for households that had an LPG connection in both waves, the reported age in wave 1 and wave 2 should have differed by no more than 3.5 years-the time between the two waves of surveys. However, the difference was off for most of the households. Therefore, we assumed the age reported in wave 1 to be true and added 3.5 to that to arrive at the estimated age in wave 2. Second, for households that did not use LPG in wave 1 but did so in wave 2, the age of connection-as reported in wave 2-could not be higher than 3.5 years. However, for 22% of the households that reported a higher value, age of connection was capped at 3.5.

We asked participants whether they considered LPG to be better than traditional cook stoves from the viewpoint of impact on health, coding responses into a binary variable where ‘1’ is assigned to households that found LPG better, and ‘0’ to those that thought LPG was not better. Positive perceptions of LPG and an understanding of the negative health impacts of traditional solid fuel cooking practices may indicate a household valuing the benefits of LPG adoption and use. Elsewhere, such positive perceptions have been observed among LPG owners. We use this covariate twice in the cross-section subset-first, the response in wave 1 to assess the causal impact on LPG category in wave 2, and second, the response in wave 2 to confirm if perception is endogenous with use. This covariate is only used in the alternate cross-section specifications (Supplementary Tables 4 and 5).

To account for the difficulty associated with accessing LPG cylinders in rural areas, we include the self-reported one-way distance covered by households to procure LPG cylinders (in kilometres). Fuel accessibility is a well-defined constraint to LPG adoption and use[8]. There is increasing empirical evidence for direct associations between fuel accessibility and use[51,61,62] and interventions testing potential solutions[52]. In the cross-section subset, we find that 43% of households received doorstep delivery of LPG cylinders, and while 22% of households travelled up to 3 km (one-way) to procure LPG, 24% travelled more than 5 km. We also find that the proportion of households receiving doorstep delivery has increased unevenly across categories of LPG use between the two waves-from 12% to 29% for minority users, but from 24% to 57% for exclusive users-even as the distance travelled to procure LPG for those who do not receive doorstep delivery has declined evenly across all three categories. We acknowledge the potential for measurement error, since not all households may accurately report the distance in kilometres. Although we cannot quantify the extent of this error in the cross-section subset, we expect a degree of self-correction in the panel subset, where respondents might have committed a similar random error in both waves, balancing out the error in the observations.

To capture easier availability of free-of-cost biomass, we include two binary variables-ownership of cattle and ownership of land. In the cross-section, 68% own land and 57% own cattle. Literature suggests that these may be significant predictors of continued biomass

use[24]. We account for access to land because many households cooking with firewood or crop residue obtain it from their own land[63].

Control variables.

We use a set of variables to control for socio-economic factors that are likely to impact regular use of LPG by rural households, and include state-level fixed effects to account for variation in unspecified state-level factors that could affect household consumption of LPG[48,64]. Supplementary Table 10 (cross-section subset) and Supplementary Table 11 (panel subset) also contain descriptive summaries of all control variables, along with the hypothesized direction of association between the covariate and LPG-use category.

We utilize an economic status index as a measure of a household's relative wealth and economic status, based on the Filmer and Pritchett[65] approach. Such indices are commonly used across studies in regions where fixed incomes are uncommon[65–67]. Overall measures of wealth and income, including asset indices, have been predominately positively associated with ownership and use of clean cooking fuels[57,68,69]. The list of variables included in the economic status index can be found in Supplementary Note 3 and summarized in both survey waves in Supplementary Table 13.

The level of education of the household head is used as a measure of general awareness in the household and the ability to make informed decisions on clean cooking energy. Higher levels of education of the household head have often been positively associated with adoption of clean cooking energy[27,70,71]. We use four categories of education: (1) no education, (2) up to 5th standard, (3) between 5th and 10th standard and (4) 12th standard and above (the base category). A significantly lower proportion of households where the household head has not received a formal education are exclusive users of LPG than those where the household head has studied beyond the 5th standard.

The caste of the respondent is used as a categorical control variable to account for the impact of longstanding social hierarchies on access to LPG connections and refills. Caste is a social stratification system that has been negatively associated with clean cooking energy adoption[66]. The sample has households belonging to four caste categories: (a) scheduled caste (SC), (b) scheduled tribe (ST), (c) other backward classes (OBC) and (d) general. We assess the likelihood of sustained use of LPG for SCs and STs, against the combined base category of OBCs and general, because SCs and STs are historically considered to be the more systematically disadvantaged communities.

The primary source of income of the household is used as a categorical control variable for the varying impact of different cash-flow structures on a household's ability to pay for the recurring cost of cooking gas. We use five categories: (1) agriculture on own or leased land, (2) labour (agricultural or daily wage), (3) salaried employment, (4) own business and (5) others, with salaried employment as the base category. 'Other' sources of primary income mostly included cattle rearing, employment in religious institutions, driving and pension. A larger proportion of households with salaried employment and business as primary sources of income are using LPG as an exclusive fuel, while a larger proportion of those reliant on agriculture and labour are using LPG as a minority fuel. Dependence on agricultural or

daily-wage labour has been negatively associated with clean cooking energy access, which is probably attributable to lower socio-economic status or inconsistent cash flow[21,72]. In other cases, the primary source of income has not been statistically significantly associated with fuel choice or is absent from the analyses[20]. In the panel model, we change this covariate by including binary variables for the three most theoretically relevant primary sources of income from an affordability (cash flow) perspective on LPG uptake: agriculture on own or leased land, labour (agricultural or daily wage) and salaried employment.

The natural log of household size is included to account for its potential impact on LPG use. In previous studies, household size has been both positively[23] and negatively[40,68] associated with clean cooking energy use. In some cases, larger households may seek faster or more cooking options (a positive association with cleaner cooking), while in others it is possible that larger households require the substantially greater capacity of traditional stoves to handle large quantities of food, and are less likely to see the benefit of a possibly limited cleaner cook stove, or have more available labour for fuelwood collection (negative association). There are other studies that have found no association between household size and cooking fuel choice[73]. This covariate required changes similar to those in the biomass expenditure covariate.

Tests of model assumptions, multicollinearity and robustness.

The generalized-ordered logistic regression enables us to relax the parallel lines assumptions of ordered logistic regressions because we do not see a theoretical justification to impose the parallel lines restriction. However, we also use an autofit script in Stata that uses a Wald test to determine which covariates have different beta coefficients by outcome category. Then, the autofit script relaxes the parallel lines assumption for these covariates only. Supplementary Table 14 shares the results from the Wald tests for parallel lines applied to each covariate. Supplementary Table 15 shows results from the regression no autofit script and parallel lines assumption imposed (Supplementary Table 15). While general directions and magnitudes of the associations are similar to our main findings presented in Table 1, we note that our main results with relaxed assumptions show meaningful variation in the coefficients by outcome for some variables, such as household size, education of the household head and primary source of income.

We also tested for the assumption of multicollinearity after finalizing variables by estimating the variance inflationary factor for each covariate. We found acceptably low levels of multicollinearity in our model (Supplementary Tables 16 and 17). To account for potential residual spatial autocorrelation at the village level (beyond what we have captured using state-level fixed effects in the cross-sectional model and other village-level covariates), we carried out an additional generalized-ordered logistic regression clustering standard errors at the village level (Supplementary Table 18). Coefficients are similar to those presented in Table 1.

Reporting Summary.

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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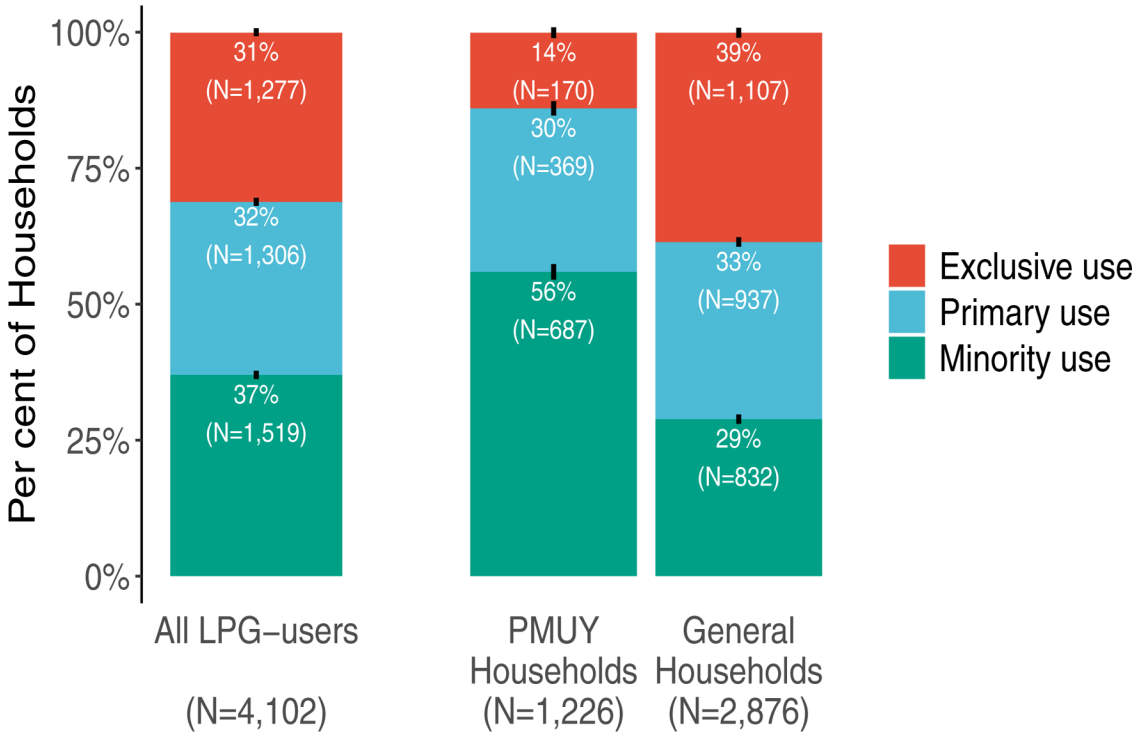

Fig. 1 |. Distribution of LPG-use categories among LPG households in 2018.

Percentages refer to the fraction of households in each LPG-use category in wave 2 (2018). Sample sizes are included in parentheses. Black lines indicate standard errors. Using a two-sample test of proportions (which uses the *t*-statistic), we find that the difference between the proportions of exclusive users of LPG among PMUY households and general customers is statistically significant.

Fig. 2 |. Household-level shifts in fuel stacking from 2015 to 2018 in the panel subset.
The nodes on the left of the alluvial diagram refer to LPG-use category status in wave 1, and those on the right of the chart refer to category status in wave 2. Sample sizes in each category in each wave are indicated below the labels. The links flowing from the left nodes to the right nodes indicate upward, lateral and downward movement of households in each LPG-use category from wave 1 to wave 2. We discuss specific patterns of downward movement in the Methods.

Table 1 |

Explaining LPG use in wave 2 (cross-section model)

	Odds of primary use as opposed to minority use				Odds of exclusive use as opposed to primary use			
LPG-use category: dependent variable	**OR (s.e.m.)**	***P* > *z***	**95% CI**		**OR (s.e.m.)**	***P* > *z***	**95% CI**	
Whether household is a PMUY beneficiary	0.641 (0.066)	<0.001***	0.523	0.784	0.564 (0.068)	<0.001***	0.446	0.714
Percentage of households in a village using LPG as their primary cooking fuel	1.043 (0.002)	<0.001***	1.039	1.048	1.027 (0.002)	<0.001***	1.023	1.031
Weekly expenditure on biomass (wave 1) (ln + 1)	1.012 (0.016)	0.467	0.981	1.044	0.982 (0.017)	0.270	0.950	1.015
Whether firewood is collected multiple times a week (wave 1)	0.895 (0.085)	0.245	0.743	1.079	0.788 (0.081)	0.021**	0.643	0.965
Whether women are involved in the household decision-making	1.135 (0.099)	0.149	0.956	1.348	0.873 (0.082)	0.146	0.727	1.048
Number of years that the household has had LPG (ln)	1.260 (0.088)	0.001***	1.099	1.445	1.226 (0.089)	0.005***	1.064	1.412
One-way distance to procure LPG cylinders (km)	1.010 (0.007)	0.155	0.996	1.023	1.000 (0.008)	0.984	0.985	1.015
Whether the household owns cattle	0.447 (0.039)	<0.001***	0.377	0.530	0.423 (0.036)	<0.001***	0.358	0.499
Whether the household owns land	0.838 (0.084)	0.079*	0.687	1.021	0.835 (0.086)	0.080*	0.683	1.022
Economic status index	1.147 (0.030)	<0.001***	1.089	1.208	1.171 (0.030)	<0.001***	1.113	1.232
Household size (ln + 1)	0.604 (0.067)	<0.001***	0.487	0.750	0.484 (0.053)	<0.001***	0.390	0.600
Education of the household head (by category; base category is 12th standard and above)								
No education	0.742 (0.086)	0.010**	0.592	0.931	0.742 (0.090)	0.014**	0.585	0.941
Up to 5th standard	0.919 (0.103)	0.449	0.737	1.145	0.755 (0.086)	0.013**	0.602	0.941
Between 5th and 10th standard	1.019 (0.127)	0.882	0.797	1.302	1.005 (0.121)	0.959	0.785	1.259
Caste of the household head (by category; base category is OBCs and general caste together)								
Scheduled caste	0.984 (0.099)	0.877	0.808	1.200	0.948 (0.104)	0.568	0.757	1.165
Scheduled tribe	0.936 (0.165)	0.707	0.662	1.323	0.964 (0.184)	0.810	0.658	1.388
Primary source of income of the household (by category; base category is salaried occupation)								
Agriculture on own land or leased land	0.595 (0.094)	0.001***	0.437	0.810	0.619 (0.086)	<0.001***	0.469	0.806
Casual agricultural or daily-wage labour	0.496 (0.082)	<0.001***	0.358	0.686	0.610 (0.092)	0.001***	0.449	0.809
Own business	0.850 (0.159)	0.385	0.588	1.227	0.905 (0.144)	0.500	0.658	1.226
Others	0.989 (0.296)	0.971	0.551	1.777	0.920 (0.246)	0.729	0.540	1.538
Number of households (n)	4,102							
State fixed effects	Yes							

	Odds of primary use as opposed to minority use			Odds of exclusive use as opposed to primary use		
LPG-use category: dependent variable	**OR (s.e.m.)**	***P*** **> z**	**95% CI**	**OR (s.e.m.)**	***P*** **> z**	**95% CI**
log-likelihood	−3,603.996					
Probability > χ^2	<0.0010					
Pseudo R^2	0.1981					

Results from the cross-section generalized-ordered logistic regression model are shown here. The response variable is the LPG-use category in wave 2. The model explains determinants of households being primary users of LPG (compared to minority users), and of being exclusive users of LPG (compared to primary users) in wave 2. There are 4,102 households, all of which were surveyed in both waves, and were using LPG in wave 2. Standard errors of the mean (s.e.m.) are in parentheses after the OR values.

*** $P < 0.01$,

** $P < 0.05$,

* $P < 0.10$.

Table 2 |

Explaining household-level change in LPG use between wave 1 and wave 2

Dependent variable: LPG-use category	**OR (s.e.m.)**	***P*** **>** ***z***	**95% CI**	
Percentage of households in a village using LPG as their primary cooking fuel	1.046 (0.003)	<0.001***	1.041	1.052
Women are involved in the household decision-making	0.784 (0.086)	0.027**	0.633	0.972
Number of years that the household has had LPG (ln + 1)	1.161 (0.066)	0.008***	1.040	1.297
One-way distance to procure LPG cylinders (km)	1.000 (0.008)	0.970	0.985	1.015
Household owns cattle	0.275 (0.031)	<0.001***	0.221	0.344
Household owns land	1.070 (0.148)	0.623	0.816	1.403
Economic status index	1.204 (0.032)	<0.001***	1.143	1.269
Household size (ln + 1)	0.510 (0.065)	<0.001***	0.398	0.655
Primary source of income of the household				
Agriculture on own land or leased land	0.662 (0.093)	0.003***	0.502	0.872
Casual agricultural or daily-wage labour	0.643 (0.100)	0.005***	0.474	0.872
Salaried occupation	1.192 (0.190)	0.271	0.872	1.629
Number of observations	2,821			
Number of households	1,411			
State fixed effects	Yes			
log-likelihood	−2,515.184			
Wald χ^2	577.569			
Probability > χ^2	<0.0010			

The table shows results from the panel-ordered logistic regression model. The response variable is the LPG-use category in both waves of survey. The model explains household-level determinants of the movement to higher LPG-use categories from wave 1 to wave 2. It includes 1,411 households, all which used LPG in both waves. The s.e.m. are in parentheses after the OR values.

*** $P < 0.01$,

** $P < 0.05$,

* $P < 0.10$.