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Jointly modeling the adoption and use of clean cooking fuels in rural India

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Abstract

Solid fuel combustion is a major cause of household air pollution, a leading environmental health risk factor globally. In India, over 750 million people continue to rely on firewood and other solid fuels for daily cooking. We explore the drivers of adoption and use of liquefied petroleum gas (LPG), India's dominant clean cooking fuel. We document strides in LPG ownership using a panel dataset of over 8,500 rural households from six Indian states surveyed in 2015 and 2018 (ACCESS), partially due to India's flagship clean cooking policy *Pradhan Mantri Ujjwala Yojana* (PMUY). We further demonstrate that the drivers of initial LPG adoption also apply to use. While fuel stacking—using solid fuels and LPG jointly—is pervasive, improved rural incomes and education result in the increased use of clean cooking fuels. After adoption, general LPG customers are predicted to consume on average 93 kilograms of LPG yearly (95% confidence interval (CI): 91–95 kg/year). However, PMUY beneficiaries are predicted to consume 27 kilograms of LPG (95% CI: 24–30 kg/year) less on average than general customers each year, even after controlling for socio-economic differences and years of using LPG. Our findings suggest that additional strategies to accelerate the transition to exclusive LPG use among the 80 million households acquiring LPG through PMUY should aim to improve affordability and increase awareness to realize the full benefits of the Government of India's investments in cleaner cooking.

Widespread solid fuel combustion to meet daily household cooking and heating needs has profound global impacts on health [1], climate [2], and the environment [3]. Roughly 2.8 billion people worldwide rely on inefficiently burning solid fuels like wood, dung, charcoal, or agricultural residues to meet their daily household energy needs [4], resulting in high levels of household air pollution (HAP). Clean cooking is an essential part of Sustainable Development Goal (SDG) 7: ensuring access to affordable, reliable, sustainable, and modern energy for all (SDG 7.1.2 specifically identifies increasing clean fuel use) [5]. Furthermore, expanding clean cooking is a promising strategy for achieving other SDGs [6–8], such as reducing the under-5 mortality rate (SDG 3.2.1), reducing mortality associated with household and ambient air pollution (SDG 3.9.1), empowering women and girls (SDG 5), combating climate change (SDG 13), and sustainably managing forests and halting land degradation (SDG 15). Previous analyses show that India, where about 750 million people rely on solid fuels each day [9], will particularly benefit from the expansion of clean cooking fuels to address equity, health, and climate challenges [7, 8, 10, 11]. Yet, the adoption and sustained use of clean cooking fuels remains limited across India and much of the world's resource-poor rural communities.

India is in the midst of a nationwide transition to cleaner cooking with liquefied petroleum gas (LPG). More than 75 million Indian households have acquired an LPG stove since 2015 [12]. While LPG is a popular cooking fuel in rural India [13], lessons from around the world show that households adopting a clean cooking fuel

commonly continue to use their traditional stoves and fuels—a practice termed fuel stacking—rather than fully replace their previous cooking practices [14]. Partial transitions to clean cooking are unlikely to lower air pollution levels enough to significantly reduce health risk [15]. Still, non-health co-benefits are likely to be obtained as clean cooking fuels displace solid fuels in households [16]. Therefore, understanding the determinants of clean cooking fuel adoption and use can inform measures that can accelerate the transition toward near-exclusive clean fuel use so Indian households can reap the full rewards of clean cooking.

Previous studies and reviews have pointed to the roles of individual (perceptions, preferences, behavior), household (demographics, socio-economic status), local environmental (climate), and contextual (fuel prices and availability, policies, cultural practices) characteristics in determining the adoption and use of clean cooking fuels [17–22]. Historically, study of cooking fuel choice has rarely featured longitudinal data and has had limited capacity to capture within-household transitions. Panel designs enable the study of both the transition from exclusive solid fuel use to clean fuel adoption and the transition from limited to near-exclusive clean fuel use.

Our work builds on a few recent studies. A study leveraging a cohort from three provinces in China with data collected from 1995 to 2016 showed that the determinants of clean fuel adoption and the determinants of the suspension of solid fuel use differ to some extent [23]. Higher household incomes, younger household heads, and smaller household sizes were associated with clean fuel adoption, whereas younger age and being widowed were associated with solid fuel cessation. Younger age, greater education, and poor self-reported health status were associated with earlier solid fuel cessation. Recent studies in Tanzania [24] and Ethiopia [25] used three rounds of panel survey data to assess the socio-economic determinants of fuel stacking behavior, finding that household expenditures, education, and fuel prices are associated with fuel choice. However, while both studies included multiple survey waves they did not model within-household fuel switching. These studies emphasize the need to model both the adoption of clean cooking fuels and use after adoption alongside the cessation of solid fuel use to identify policies that benefit health, the economy, and the environment.

In addition, a recently-published companion study to our own assessed the determinants of fuel stacking among LPG-owning rural Indian households cross-sectionally in 2018 ($N = 4{,}102$ households) and then modeled within-household shifts in primary and secondary cooking fuel use from 2015 to 2018 among households that owned LPG in both years ($N = 1{,}411$ households) [26]. In this study, households acquiring LPG through Pradhan Mantri Ujjwala Yojana (PMUY) had lower odds of using LPG as their exclusive or primary cooking fuel as compared to general consumers. The number of years a household had LPG and household wealth were associated with an increased role for LPG in the household. These are important findings related to PMUY and we build on this study in three principal ways. First, whereas Mani *et al* [26] consider primary and secondary fuel use categorically, we model LPG consumption in kilograms. As a result, we estimate LPG consumption for all categorical covariates and flexible dose-response relationships for continuous covariates. Second, we leverage the full panel of households (LPG-owning and non-owning in 2015 and 2018) ($N = 17{,}640$ observations) to model fuel use in both waves rather than shifts in fuel stacking only among households that owned LPG in both years. In doing so, we offer a direct assessment of the factors that influence both adoption and the subsequent use of LPG. Finally, we discuss primary cooks' self-reported satisfaction related to LPG and reasons for satisfaction or dissatisfaction, dishes cooked with LPG, and access to LPG cylinder refills as explanations for observed results on LPG consumption.

This study jointly addresses two principal questions: (1) What factors are linked to a household's probability of adopting LPG in rural India? and (2) What factors predict overall LPG use (in kilograms) if a household does adopt LPG?

We use a comprehensive energy access survey administered in more than eight thousand rural households across six energy-poor Indian states in 2014-2015 and then again in 2018. We find that the extent of LPG use has increased substantially since 2015, but that the majority of households continue to use solid fuels for at least some of their cooking. Still, exclusive clean cooking fuel use has increased from less than 5% to nearly 17% in just three years. We leverage our panel data structure to jointly model LPG adoption and use in a two-stage hurdle model. We find that the same determinants of LPG adoption—expenditures and education—also explain LPG consumption. Still, we find that PMUY beneficiaries are predicted to consume about 30% less LPG than general customers after accounting for baseline socio-economic and demographic differences across households and the years of experience using LPG. In an exploratory analysis, we offer some preliminary evidence that, overall, general customers have better access to LPG cylinder refills than PMUY beneficiaries, primarily due to a relatively greater share LPG owners in remote villages being PMUY beneficiaries. These findings provide insights for future energy policies that seek to facilitate widespread use of clean cooking fuels to reduce the environmental impacts and public health burden of solid fuel use.

Transitions to clean cooking fuels in india

LPG has historically been too expensive or unreliably accessible for use in most rural households in India and around the world [20, 27]. In response, the Government of India and the country's largest Oil Marketing Companies (OMCs) have implemented a series of state and national policies to increase clean cooking among the country's poorest households over the last ten years.

The ambitious Pradhan Mantri Ujjwala Yojana (PMUY) was launched in 2016 and had a goal of providing LPG to 80 million below-poverty-line households by 2020 (increased from its original goal of 50 million) [28]. PMUY leads India's national LPG program and has received substantial international attention. However, the Government of India has been facilitating the use of LPG since the late 2000s by improving accessibility and lowering costs. The Rajiv Gandhi Grameen LPG Vitrak scheme was launched in 2009 to increase LPG distribution in remote areas by increasing LPG coverage and providing below-poverty-line families a one-time grant for new LPG connections. In 2015, the Direct Benefit Transfer for LPG, or PAHAL, developed a system to directly deposit the difference between the market and subsidized cost of cylinder refills into participants' bank accounts, facilitating a flexible and more efficient subsidy transfer system [29]. Rural LPG distribution was once again enhanced by increasing the reliability of cylinder refill supply and implementing direct home refill deliveries in 2016. That same year, the 'Give it Up' program enrolled more than 10 million LPG consumers to voluntarily discontinue their subsidy and transfer it to below-poverty-line households [29].

Through PMUY, the Government of India provides assistance of 1,600 Indian Rupees (INR) (about 25 USD) to establish each household LPG connection by subsidizing the LPG cylinder deposit and regulator and installation charges. In India, an LPG connection refers to the ability to purchase LPG cylinder refills from the national market. While the installation charges and cylinder deposit are subsidized through PMUY, households must purchase a double-burner LPG stove (1,000 INR) and their first LPG cylinder (500 INR), with optional loan assistance. Along with increasing the number of LPG consumers, PMUY has further expanded the coverage of LPG distributors in rural India. The Government of India estimates that about 80 million new LPG connections have been established since 2016 [30].

Despite great advances in LPG stove ownership across the nation (seen in Figure 1), relatively little is known about the extent to which LPG is displacing the use of solid fuels for cooking. Data on new LPG connections—a marker of the ability to use LPG stoves—are regularly updated; however, information detailing LPG cylinder refills consumed by PMUY beneficiaries remain limited [31, 32]. Based on available aggregate data, an estimated one-quarter of households purchase five or more cylinder refills yearly but approximately 20% do not return for a single refill in their first year of LPG ownership [12, 33, 34]. In total, among PMUY beneficiaries enrolled for one year or more as of December 2018, an estimated half obtained three or fewer LPG cylinder refills in a year [12]. In a study of one rural district in Karnataka using LPG refill sales data from 2017-2018, researchers found that only 7% of PMUY beneficiaries purchased four or more cylinders in their first year with LPG, suggesting that the vast majority use LPG as a secondary option [35]. Though general customers (non-PMUY) in this district appear to use LPG more, only about one half appear to use LPG as their primary cooking fuel and and even fewer exclusively [35].

Research design

We use the Access to Clean Cooking Energy and Electricity—Survey of States (ACCESS) with 17,640 observations over two waves collected in 2015 and 2018. Data were collected using household surveys in rural villages across the six northern Indian states of Bihar, Jharkhand, Madhya Pradesh, Odisha, Uttar Pradesh, and West Bengal. Retention was 86% between the first and second waves. Survey design and data collection are described in greater detail in the Methods.

We apply a two-stage double-hurdle model to jointly assess a household's choice to adopt LPG and how much LPG is then used after adoption using the full data sample. The two-stage double-hurdle model has two main benefits. First, the model enables an assessment of the differing influences of covariates on determining LPG adoption and then use after adoption. Second, the two-stage double-hurdle model can include additional covariates for the second (use) stage of the model that would otherwise be perfectly correlated with LPG adoption, like status as a PMUY beneficiary and years of experience cooking with LPG. We present results from the double-hurdle model as the average-adjusted predicted probability of LPG adoption and then the amount of LPG consumed in kilograms (kg) each month. Average-adjusted predicted probabilities are those where all other covariates are held at their averages.

We fully elaborate on covariate selection and the statistical approach in the Methods. Briefly, we select covariates for the determinants of cooking fuel choice from the literature, capturing demographic, socio-economic, and contextual dimensions of fuel choice. In our first of two main specifications, we include a

parsimonious set of common household and individual characteristics collected in ACCESS, including monthly household expenditures, the education of the household head, household caste, gender of the decision-maker, status as a PMUY beneficiary (consumption stage only), and years of cooking with LPG (consumption stage only). We use state fixed effects to control for any residual confounding due to spatial heterogeneity—like different levels of fuel accessibility—in this first specification.

Still, it is possible that there are important differences at the village level that may affect cooking fuel choice. In particular, fuel accessibility can be an important determinant of household cooking fuel choices in rural India in a few ways: frequency of availability, consistency of availability, and the distance required to travel to acquire the fuel [21, 27]. Each of these aspects of accessibility can present a barrier to both LPG adoption and use after adoption. For instance, if a fuel is difficult to acquire, then the motivation to adopt is weaker and, after adoption, exclusive use may not be feasible. In addition, households may supplement LPG with another fuel—often a solid fuel with lower access costs—if the availability of cylinder refills is inconsistent to protect against potential fuel shortages [36]. To establish robustness of our main results to these additional factors, we specify a model where, in addition to the original covariates, we include village-level covariates: village size and distance of that village to the nearest town as proxies for the robustness of LPG cylinder supply, the average one-way distance traveled by LPG owners in the village to acquire cylinder refills, and surrounding forest cover as a proxy for biomass availability. We note that LPG fuel costs are largely homogeneous across the study sample due to state-run pricing so we do not include the cost of an LPG cylinder refill.

Finally, we undertake two exploratory analyses. First, we analyze primary cooks' self-reported satisfaction with their household cooking situation, satisfaction with LPG, reasons for not being satisfied or not satisfied with LPG, and items cooked with LPG. Second, we characterize the accessibility of LPG cylinder refills in terms of proportion of households reporting to receive refills delivered to their doorstep and, among those without doorstep delivery, the self-reported one-way distance required to receive refilled cylinders.
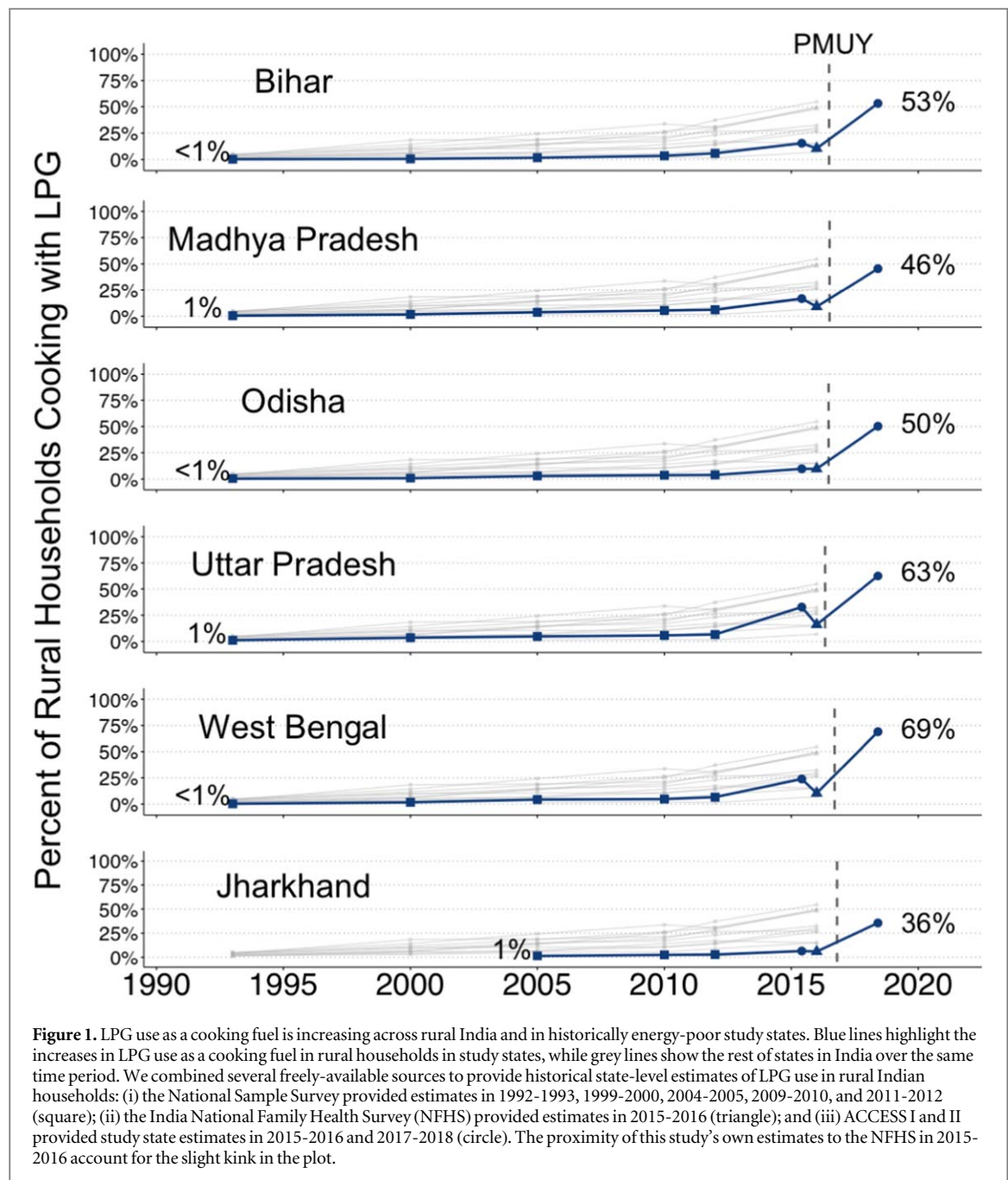
Results

LPG adoption and use increased in the study sample between 2015 and 2018. The proportion of households without LPG fell from 75% (2015) to 45% (2018) (*SI Appendix*, figure A1 available online at stacks.iop.org/ERC/2/085004/mmedia). In 2018, 17% of study households used LPG exclusively, up from just 5% in 2015. And yet, even in 2018, the majority of study households (83%) continued to rely on solid fuels (primarily firewood) to meet at least some of their cooking needs. The increased penetration of LPG into study households has coincided with increases in exclusive LPG use, but has also led to increased fuel stacking of LPG and solid fuels (from 17% to 38% of study households reporting to use both fuels). In 2018, exclusive LPG users in the study sample consumed on average 10.2 kg (standard deviation (sd): 3.9) as compared to 8.2 kg (sd: 4.1) and 4.2 kg (sd: 3.2) among primary LPG users that had a secondary solid fuel and primary solid fuel users with secondary LPG use, respectively (figure 2).

Jointly modeling LPG adoption and use

We found similarity between the predictors of LPG adoption and use. Households with greater wealth, more educated household heads, and those that belong to the general caste category had higher predicted probability of adopting LPG and subsequently consuming more LPG per month than their peers (figures 3 and 4; *SI Appendix*, table A5).
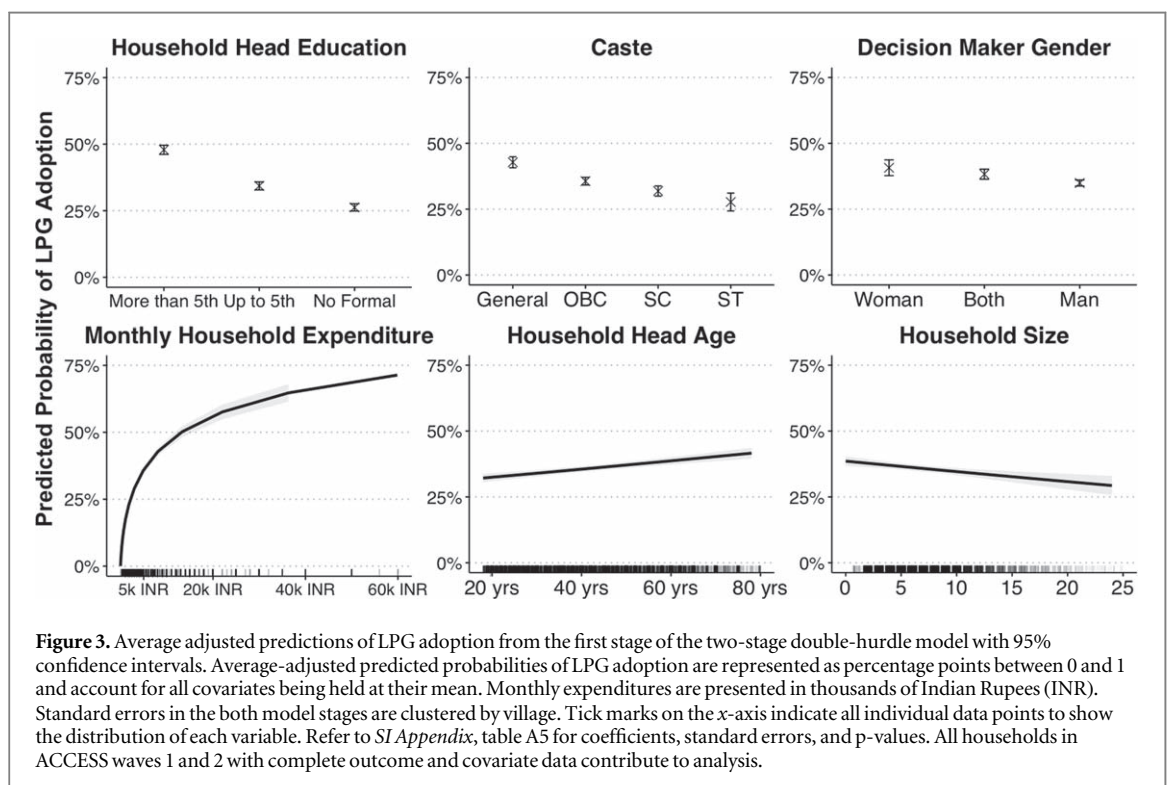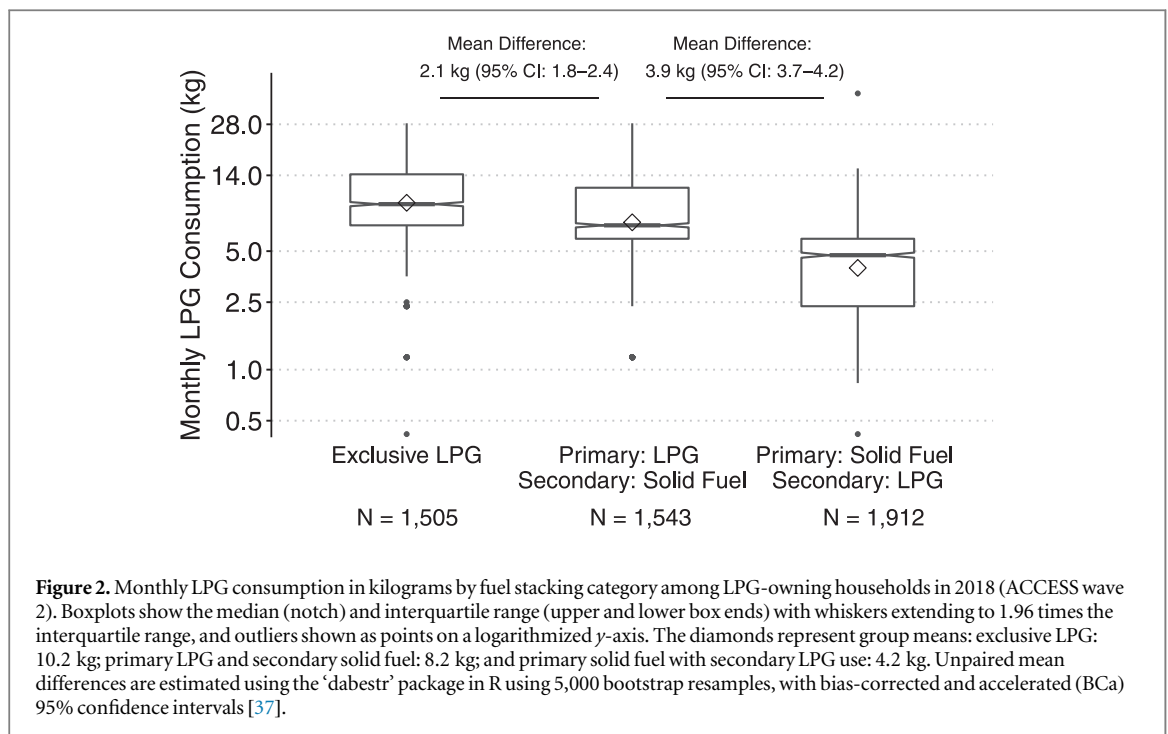
The average-adjusted predicted probability of LPG adoption when the household head had attained an education more than 5th Standard was 47.9 percentage points (95% CI: 46.1-49.6 percentage points), a full 13.6-21.6 percentage points higher than households where the household head had attained a primary level education or no formal education (figure 3). After adoption, households with a household head attaining an education more than 5th Standard were predicted to consume—holding all other covariates at their means including household size—7.6 kg of LPG per month (95% CI: 7.4-7.8 kg) (figure 4). In comparison, households were predicted to consume between 0.3 and 0.9 kg per month less when the household head had achieved a primary education or had no formal education, respectively. Over the course of a full year, then, when the household head had attained more than a 5th Standard education were predicted to consume between one-half to two-thirds of a large 14.2 kg cylinder of LPG more than their counterparts.

Trends were similar for caste. Households belonging to the general caste had an average-adjusted predicted probability of owning LPG 7.2-15.1 percentage points higher than households belonging to the scheduled caste, scheduled tribe (indigenous communities), or other backward class (an official term for other communities that are recognized as historically disadvantaged). Then, a household in the general category was predicted to consume about one-half to two-thirds of a large 14.2 kg cylinder of LPG more than their counterparts after adoption.

Figure 1. LPG use as a cooking fuel is increasing across rural India and in historically energy-poor study states. Blue lines highlight the increases in LPG use as a cooking fuel in rural households in study states, while grey lines show the rest of states in India over the same time period. We combined several freely-available sources to provide historical state-level estimates of LPG use in rural Indian households: (i) the National Sample Survey provided estimates in 1992-1993, 1999-2000, 2004-2005, 2009-2010, and 2011-2012 (square); (ii) the India National Family Health Survey (NFHS) provided estimates in 2015-2016 (triangle); and (iii) ACCESS I and II provided study state estimates in 2015-2016 and 2017-2018 (circle). The proximity of this study's own estimates to the NFHS in 2015-2016 account for the slight kink in the plot.
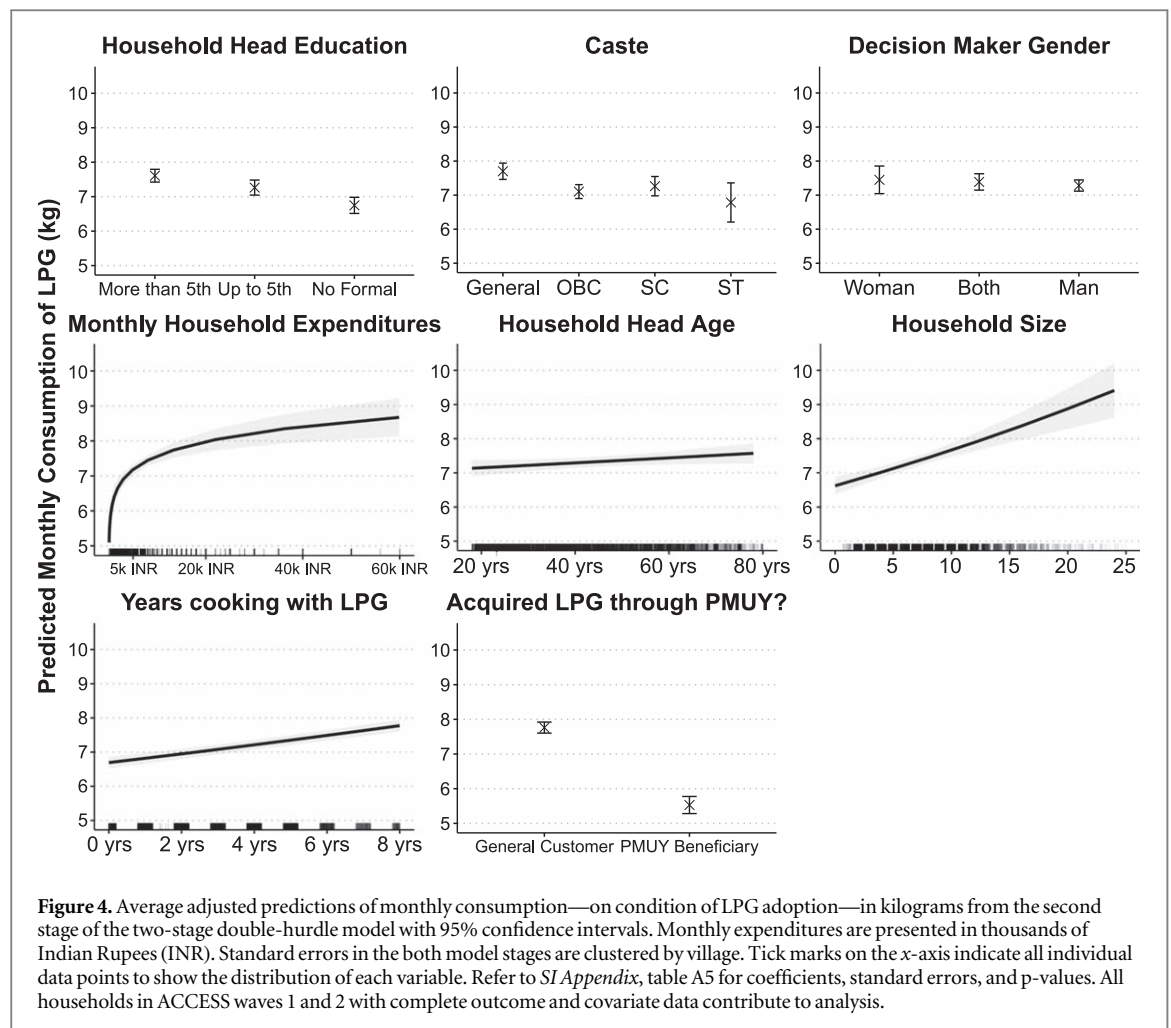
The relationships between increases in monthly expenditures and LPG adoption and use was highly non-linear for expenditures below 10,000 INR per month (approximately 85% of households reported spending fewer than 10,000 INR per month), increasing rapidly at low expenditures and leveling off at higher expenditures. Each month, households at the 75th percentile (7,000 INR per month) of monthly expenditures were predicted to consume about 0.6 kg of LPG more (about 7 kg per year more) than those at the 25th percentile (3,000 INR per month). In addition, while larger households had a lower predicted probability of adopting LPG, once adopted, larger households were predicted to consume more LPG than smaller households.

Perhaps most notably, however, we found that PMUY beneficiaries consumed significantly less LPG after adoption than their general customer counterparts. PMUY beneficiaries had an average-adjusted predicted probability of consuming 5.5 kg of LPG per month (95% CI: 5.3-5.8 kg). In comparison, general customers were predicted to consume 7.7 kg per month (95% CI: 7.6-7.9 kg). Accounting for all baseline differences—including education, caste, monthly expenditures, household size, and years of owning LPG—PMUY beneficiaries were predicted to consume 2.2 kg of LPG per month less than a household that acquired LPG independent of PMUY. In terms of 14.2 kg cylinder refills, PMUY beneficiaries were predicted to consume 4.7 cylinders and general customers 6.6 cylinders on average each year, controlling for baseline socio-economic and demographic differences.

Figure 2. Monthly LPG consumption in kilograms by fuel stacking category among LPG-owning households in 2018 (ACCESS wave 2). Boxplots show the median (notch) and interquartile range (upper and lower box ends) with whiskers extending to 1.96 times the interquartile range, and outliers shown as points on a logarithmized *y*-axis. The diamonds represent group means: exclusive LPG: 10.2 kg; primary LPG and secondary solid fuel: 8.2 kg; and primary solid fuel with secondary LPG use: 4.2 kg. Unpaired mean differences are estimated using the 'dabestr' package in R using 5,000 bootstrap resamples, with bias-corrected and accelerated (BCa) 95% confidence intervals [37].

Figure 3. Average adjusted predictions of LPG adoption from the first stage of the two-stage double-hurdle model with 95% confidence intervals. Average-adjusted predicted probabilities of LPG adoption are represented as percentage points between 0 and 1 and account for all covariates being held at their mean. Monthly expenditures are presented in thousands of Indian Rupees (INR). Standard errors in the both model stages are clustered by village. Tick marks on the *x*-axis indicate all individual data points to show the distribution of each variable. Refer to *SI Appendix*, table A5 for coefficients, standard errors, and p-values. All households in ACCESS waves 1 and 2 with complete outcome and covariate data contribute to analysis.

We also found that households were predicted to consume more LPG the longer that they had their LPG stove. After the first year of ownership, households were predicted to consume 6.8 kg of LPG per month (95% CI: 6.7–7.0 kg). Holding all else constant, households with three more years of experience using LPG were predicted to consume 5 kg per year more than one in its first year of LPG ownership.

We find that our results are robust to the inclusion of village-level covariates; the coefficients for the two-stage double-hurdle model did not substantively change after the inclusion of village-level covariates (*SI*, table A6 and figures A3). Furthermore, our results are robust to the removal of potential outlier observations of LPG consumption (e.g., consumption too low for a self-reported exclusive user) (see *Supporting Information* for details and results).

Figure 4. Average adjusted predictions of monthly consumption—on condition of LPG adoption—in kilograms from the second stage of the two-stage double-hurdle model with 95% confidence intervals. Monthly expenditures are presented in thousands of Indian Rupees (INR). Standard errors in the both model stages are clustered by village. Tick marks on the *x*-axis indicate all individual data points to show the distribution of each variable. Refer to *SI Appendix*, table A5 for coefficients, standard errors, and p-values. All households in ACCESS waves 1 and 2 with complete outcome and covariate data contribute to analysis.

Self-reported perceptions and preferences and LPG use

Overall monthly LPG consumption was positively associated with primary cooks' self-reported satisfaction with the household's LPG situation in both survey waves, and among general customers and PMUY beneficiaries (*SI Appendix,* figure A4; table A9). PMUY beneficiaries and general customers reported reasons for being satisfied with LPG at similar rates (e.g., cooking is free from smoke, LPG is convenient to use, saves cooking time, good quality of cooking) (*SI Appendix,* figure A5). In comparison to general customers, however, primary cooks in PMUY households were somewhat less satisfied with their household LPG situation, largely driven by differences in satisfaction among households consuming less than 5 kg LPG per month (less than 4-5 LPG cylinder refills per year) where 48% of PMUY beneficiaries were satisfied as compared to 62% of general customers.

While overall satisfaction differed, PMUY beneficiaries and general customers reported reasons for dissatisfaction similarly. Nearly all PMUY households and general customers reported that LPG was too expensive to consume (95%), with the distance required to collect LPG cylinder refills (70%) and LPG availability (50%) being reported somewhat less frequently as reasons for dissatisfaction (figure A6).

LPG-owning households not using LPG as their primary cooking fuel in 2018 were asked why it was not their primary option. High cylinder refill costs were again the most commonly cited explanation among both general customers and PMUY beneficiaries (95%); the easy availability of free biomass (70%) and preference for cooking certain items with the chulha (50%) were also commonly reported (*SI Appendix,* figure A7). LPG cylinder availability (25%) and not liking the taste of food cooked on LPG (25%) were not commonly cited as reasons for LPG not being the primary cooking option.

Our findings related to specific dishes cooked with LPG support those previously reported in a study of the 2014-2015 ACCESS data [13]. Households regularly using LPG cook all types of dishes with it, but households with sparing LPG use choose dishes preferentially, opting to use the fuel for less energy intensive meals like boiling water and preparing tea and snacks (*SI Appendix,* figure A8). In this respect, PMUY beneficiaries and general customers reported using LPG similarly.

Access to LPG cylinder refills: Improvements and remaining gaps

In 2014-2015, 18% of households reported having LPG cylinder refills delivered to their doorstep and in 2018 this figure rose to 39%. Among households with LPG in both waves, 27% received LPG cylinder refills delivered to their doorstep in 2018 that did not in 2014-2015 (*SI Appendix,* figure A9). Households not having LPG cylinder refills delivered to their doorstep have to travel to receive refilled cylinders. Among this group of non-doorstep-delivery households in 2014-2015 and 2018, the average one-way distance required to travel fell from 8.4 (SD: 6.4) km to 6.3 (5.7) km (95% CI for difference: 1.6-2.5 km) between survey waves (*SI Appendix,* figure A10).

Still, in 2018, fewer PMUY beneficiaries than general customers had LPG cylinder refills delivered to their doorstep (32% versus 42%). Among those that did not have deliveries, PMUY beneficiaries had to travel on average 0.9 km farther (95% CI: 0.4-1.4 km) to receive refilled cylinders (7.3 km versus 6.5 km) (*SI Appendix,* figure A11). However, the differences in cylinder refill delivery and travel distance disappear when comparing households living in the same village (*SI Appendix,* tables A10, A11). In addition, we observe that PMUY beneficiaries comprise a larger proportion of LPG-owning households in more remote study villages where relatively few study households reported to have LPG (*SI Appendix,* figures A12, A13).

Discussion

In this study, we have explored India's nascent and ambitious transition away from solid fuels and toward LPG as a clean cooking fuel. Indicative of the successes of the Government of India's PMUY scheme in increasing access to LPG, we note significant increases in the extent of LPG ownership across six north Indian states between 2014-2015 and 2018. Using two panels of data collected in rural households, we found that drivers of LPG adoption and use were similar. Most importantly, both household expenditure (a proxy for income) and education had large positive impacts on both adoption and use. While the traditional 'energy ladder' model [38] fails to capture the logic of fuel stacking, our results show that in rural north India the transition from solid fuels to LPG is nonetheless quasi-linear in nature. Variation in fuel consumption, then, is driven by the same factors that explain variation in the adoption of clean cooking fuels in the first place.

One of the major challenges of the Government of India's efforts—and other programs—to mitigate the negative environmental, economic, and health burdens of solid fuel use has been encouraging clean fuel use after adoption. Our results suggest that LPG is popular and the same factors that drive LPG adoption also encourage use. While rural income and education are broad challenges that reach well beyond household energy, their importance does highlight the importance of interventions aimed at improving clean fuel affordability and increasing awareness of the benefits of their use. These findings support the need for clean cooking policies to be complemented by broader initiatives to improve education and economic development. Furthermore, such policies can be designed to facilitate the synergistic relationships between education, economy, and clean cooking to holistically address multiple Sustainable Development Goals.

The Government of India's PMUY scheme is a logical step forward to begin a national transition to cleaner cooking. However, we found that PMUY beneficiaries in our sample consumed nearly two large cylinders of LPG less than general customers each year, even after accounting for education, monthly expenditures, caste, household size, gender of the decision-maker, age of the household head, and years with LPG. While we found that households using LPG for longer do consume the fuel more, these increases were modest and would not be expected to yield full displacement of solid fuel use even after five years. These findings contribute to growing evidence that PMUY beneficiaries consume less LPG than general customers [12, 26, 33, 39, 40], and advance previous studies by noting that the consumption gap persists after controlling for several socio-economic and demographic covariates. However, there remains little published work directly evaluating differences in consumption between PMUY beneficiaries and general customers.

We examined self-reported satisfaction with LPG and reasons for satisfaction or dissatisfaction among PMUY beneficiaries and general customers. PMUY beneficiaries and general customers reported similar reasons for not being satisfied with their LPG cooking situation, with the cost of LPG cylinder refills being by far the most reported as both a reason for dissatisfaction and also as a barrier to using LPG to meet more of their cooking needs. While the taste of food is frequently mentioned as a potential explanation for continued firewood use, primary cooks in this study rarely reported that not liking food cooked on LPG as a motivation for not using LPG for more of their cooking needs.

We observed that access to cylinder refills improved between 2014-2015 and 2018 for households owning LPG in both survey waves. About one-quarter of such households reported getting refills delivered to their doorstep in the second wave that did not in the first. Among those with no doorstep delivery in either year, the one-way distance required to get a cylinder refill was reduced by about two kilometers. Still, there remains an apparent gap in LPG cylinder refill access between PMUY beneficiaries and general customers. Fewer PMUY beneficiaries have cylinders delivered to their doorstep than general customers and PMUY beneficiaries have to

travel further to get refills when comparing among households without doorstep delivery. However, this gap in the accessibility of LPG cylinder refills—both in terms of doorstep delivery and travel distance—largely disappears when comparing PMUY beneficiaries and general customers within the same village. We find support for the hypothesis that PMUY has increased LPG penetration into remote villages where there was previously little to no LPG ownership. Given that poor access to LPG cylinder refills was commonly cited by primary cooks as an explanation for not using LPG as their main cooking option, improving the accessibility of LPG cylinder refills in villages recently receiving LPG connections via PMUY could encourage increased LPG consumption.

We contribute to growing evidence that additional actions are needed to accelerate the transition toward exclusive clean cooking fuel use. Recent studies have explored several strategies to encourage the use of clean cooking fuels in rural India, including: lower fuel costs or free fuel [41], improved fuel accessibility [41, 42], providing a second LPG cylinder to reduce gaps in fuel [41], and health messaging as a part of a package of a clean cooking intervention accounting for other supply-side issues [41]. Taken together, these studies and a recent review [43] show that efforts to address cost and liquidity constraints associated with regular clean fuel consumption and supply-side issues associated with LPG cylinder refills can accelerate the displacement of solid fuels by clean fuels for cooking.

To address refill cost considerations, the Government of India may additionally consider more targeted subsidies to poorer households and PMUY beneficiaries that currently have low cylinder refill rates. Indeed, the Government of India is actively considering subsidizing cheaper and smaller 5 kg LPG cylinders (the typical size is 14.2 kg) to increase LPG consumption. Our findings related to the accessibility of LPG cylinders suggest that increasing the number of local distributors to reduce distance to acquire a refill may yield greater LPG consumption in remote rural areas. With respect to addressing awareness, future programs may include education on the benefits of clean cooking and capacity training on the use and safe handling of LPG stoves and cylinders to increase use.

This study has a few limitations and suggests future areas of research worth considering. To minimize recall bias in our self-reported outcomes, we have conducted substantial survey piloting and ensured consistency in administration of surveys across households. We expect that recall bias may be minimized due to the relative regularity of LPG cylinder refill orders and that any additional bias will be non-differential across the study population. Nonetheless, we find that our results are robust to the exclusion of potential outliers in LPG consumption. Next, modeling solid fuel consumption is beyond the scope of our analysis. Future studies may consider conducting regular and precise measurements of fuel consumption weights collected over long time periods to enable modeling of the trade-off of increases in LPG consumption and corresponding reductions of solid fuels. In addition, we opted for parsimonious models in our analyses due to computational demands but is possible that there are omitted variables that may further explain household transitions (e.g., individual preferences).

Furthermore, the focus of this study is largely on household- and individual-level determinants of LPG adoption and use and our inclusion of village-level variables was primarily designed as a robustness check. Still, given the potential importance of village-level characteristics as determinants of household-level fuel use patterns observed elsewhere [23, 36, 44], direct evaluation of village- or even regional-level determinants of fuel choice in rural India is warranted. Furthermore, we noted differences in the accessibility of LPG cylinder refills among PMUY beneficiaries and general customers. Fully explaining these same differences is beyond the scope of this study and future quantitative and qualitative studies are needed to further understand this accessibility gap, and other differences in LPG consumption between PMUY beneficiary and general customers. Finally, while a major strength of our study is its panel structure coinciding with important policy changes in rural India, major energy transitions likely take decades to fully unfold as observed elsewhere [23, 45]. Therefore, we are inherently unable to capture the full extent of rural India's energy transition.

Conclusions

Our study confirms that the expansion of LPG into rural India owing to PMUY and other government programs over the last four years is worthy of praise. We surveyed 8,000 rural Indian households in 2014-2015, prior to PMUY facilitating LPG connections in our study communities, and then again in 2018 after PMUY had provided connections in the area. We expand on existing studies of clean cooking transitions by leveraging the panel structure of our data to gain insights into the determinants of LPG adoption and the role of LPG in a household after adoption. We further evaluate the factors that have contributed to the increased use of LPG among study households, providing specific estimates of monthly LPG use in kilograms. Future efforts will need to respond to local contexts, the multiple constraints of poor and rural households, and preferences for household energy technologies—including non-cooking end uses like heating. Such integrated policies and

programs may be needed to yield the full potential environmental, social, and health benefits of PMUY's efforts expanding clean cooking. Still, combinations of awareness campaigning and measures to enhance the affordability and accessibility of clean cooking fuels can help hundreds of millions in rural India lead healthier and more productive lives.

Methods

Two-wave representative survey of energy access in north India

We use the Access to Clean Cooking Energy and Electricity—Survey of States (ACCESS), a two-wave panel dataset [46]. Briefly, the sampling frame included 714 villages across 51 districts within the north Indian states of Bihar, Jharkhand, Madhya Pradesh, Odisha, Uttar Pradesh, and West Bengal. These north Indian states were selected because they have historically been energy-poor; furthermore, they combine to account for 500 million individuals or almost 40% of the country's population. In 2015, sampling was done using a three-stage probability-proportional-to-size (PPS) survey design. Previously, the ACCESS study team has shown that the sampling design has yielded a representative sample as compared to the 2010 National Sample Survey [47]. Nonetheless, sampling weights are used throughout to account for variations in district household populations. We describe the sampling design and survey implementation further in the Supplementary Information.

A household energy access and use survey was administered to 8,563 households in the first wave of the survey collected between November 2014 and May 2015 and 9,072 households in the second wave collected between April 2018 and September 2018. If the household head in a household surveyed in 2015 was unavailable, enumerators interviewed any other willing adult in the household. If no adult was available or willing to participate then the household was replaced with the fifth household walking to the right of the original household. In total, the attrition rate between waves was 14% (*SI Appendix*, table A1) and was accounted for with the aforementioned replacement sampling. In the second wave, additional households were sampled in three new districts of Odisha to balance sample sizes across study states.

In total, the ACCESS dataset includes household energy data from 17,640 households across both waves. While the general survey was directed to the household head or other willing adult, primary cooks were interviewed and/or present for the cooking modules used in the present study.

Dependent variables

We use a two-stage double-hurdle model to simulate adoption and use. The first-stage outcome variable is LPG ownership (0 = No LPG and 1 = Owns LPG). The second-stage outcome variable is a continuous variable for the amount of consumption of LPG among adopters or those who participate in the market. We specify LPG consumption in kilograms per month, computed from self-reported LPG cylinder refills purchased in the past year multiplied by 14.2 kg (the typical cylinder size in India) and divided by 12 months. *SI Appendix* figure A2 shows the distribution of LPG consumption among study participants in kilograms per year.

Independent and control variables

We identified covariates for inclusion in our models from previous studies of the determinants of clean cooking fuel adoption and use, drawing in particular on several reviews [19, 21, 22]. Given the computational demands of the two-stage double-hurdle model, we aimed to achieve a parsimonious model that adequately accounts for potential omitted variable bias. Here, we briefly explain our choices for covariates. *SI Appendix* tables A2 and A3 summarize the distributions of independent variables in 2015 and in 2018, respectively.

Monthly expenditure is a common explanatory variable in studies of clean cooking adoption and use [19]. Broadly, monthly expenditures are applied in this context as estimates of household material well-being, a common and effective practice in circumstances where measured incomes may be rare or unreliable [47, 48]. Increased wealth and well-being are positively associated with increased clean cooking fuel adoption and use [22]. In addition, there have been several studies specifically linking expenditures to clean cooking fuel adoption and use (including LPG) [49–52].

Household size may play a role in cooking fuel choice through different avenues. For instance, larger households may demand more cooking in terms of frequency and quantity, therefore necessitating multiple cookstoves, more cooking, or more efficient cooking depending on other priorities. In addition, households with more adults are likely to have different levels of income and expenditure, which could directly affect LPG adoption and use. However, household size has had different directions of association in empirical studies. Some have shown that larger households are more likely to cook with solid fuels [53, 54], while others have shown that larger households are more likely to use a clean cooking fuel [51, 55]. Elsewhere there has been no statistically significant association [56]. Additionally, Heltberg (2004) [50] find that larger households are more likely to stack multiple fuels, but household size does not necessarily explain the exclusive use of any fuel.

Education of the head of household is emphasized in studies of the determinants of cleaner cooking [19] as well as in the broader environmental health intervention literature [57]. Education may serve as an indicator of awareness of clean cooking, knowledge of the burdens of traditional cooking practices, ability to obtain alternative fuels, greater household wealth, greater opportunity cost for solid fuel collection, or a different willingness to pay for alternative fuels. Previously, increased education has been associated with clean cooking fuel adoption and use [58, 59] as well as reduced use of solid fuels [60]. In this study, we specify education of the household head as a categorical variable: (1) no formal schooling (the baseline), (2) up to 5th standard, and (3) greater than 5th standard.

Government-scheduled caste or tribe has been shown to be associated with lower overall socio-economic outcomes in India due to long-standing marginalization and social exclusion [61]. Studies of cooking fuel choice in India often included caste, finding a negative association with cleaner cooking [22, 49, 62, 63]. We specify caste in four categories: (1) general category (the baseline), (2) scheduled caste, (3) scheduled tribe (indigenous communities), or (4) other backward class (an official term for other historically disadvantaged groups).

Women's participation in decision-making and gender, generally, is a debated aspect of household cooking fuel choice. Given that women generally bear primary cooking responsibilities, their involvement in decision-making may explain fuel choice based on specific cooking fuel preferences, such as lack of smoke, speed, ability to cook more of food, ability to cook all types of food, and familiarity. A growing body of literature supports a positive association between women-headed households and the use of clean cooking fuels [50, 63–65]. However, few directly model women's involvement in decision-making [62]. In this study, participants were asked, 'Who in your household makes decisions on the purchase of durable goods?' Responses were categorized as (1) man, (2) woman, or (3) both man and woman. Using data from the first wave of ACCESS, we establish a robust positive association between women decision-makers and LPG adoption [66].

Religion can serve as an indicator of class welfare that can be linked to fuel choice. In rural India, followers of Hindu religions are the dominant majority, while Buddhists, Muslims, and Christians are often minorities that may exhibit lower overall socio-economic outcomes because of their marginalized position in society [67]. Identifying as Muslim, in particular, has been shown as a significant indicator of social inequality [49]. Previous studies of cooking fuel choice in India have included religion [22, 62, 68]. Here, the baseline category is a combination of religions other than Hindu.

Age of the household head may affect cooking fuel choice, and is commonly included in empirical studies of cooking fuel choice. However, there have been contradictory results to date [19, 22], with some studies showing that households with older households heads are more likely to use solid fuels [55], clean cooking fuels [51, 52, 59], or even no association [60, 62].

PMUY beneficiaries have been shown to consume less LPG than general customers in previous studies [26, 35], and in government databases on cylinder refills [12]. Understanding LPG consumption patterns after adoption through PMUY is one of the policy's most pressing questions, and a key to yielding the full benefits of LPG adoption for tens of millions of Indian households.

Years of LPG experience may affect consumption or use of LPG and other cooking fuels in the household for a variety of reasons. For example, households that have used LPG longer may have increased familiarity and ability with the cooking style. In addition, it is possible that cooking with LPG for longer has yielded shifts in attitudes and preferences towards LPG cooking or traditional cooking styles. Years of cooking with LPG has been positively associated with LPG consumption elsewhere [26, 58, 69, 70].

In an additional analysis we include four unique village-level covariates. Together, these covariates serve as proxies for LPG fuel accessibility. It is relevant to note that there is little variation in LPG cylinder costs across this region of India because prices are set by state-run oil companies and only revised on a monthly basis, as well as robust cylinder subsidies. Descriptive statistics for all village-level covariates can be found in *SI Appendix* table A4.

Number of households in the village accounts for the robustness of LPG cylinder supply. Households living in urban communities consistently use more clean cooking fuels and less solid fuels for cooking than their rural counterparts. Improved socio-economic development often accompanies the growth in community sizes, which leads to improved infrastructure and increased reliability of clean fuel supply [53]. We calculate village size using data from the 2011 National Census (for all villages except those in West Bengal) and 2001 National Census (for villages in West Bengal). In the ACCESS project we estimated the number of households in a village by speaking to a village leader. However, 232 villages had missing data, which would lead to 5,313 dropped households. We utilized Census data to avoid losing this quantity of data. Given the across-village nature of our analysis, we expect that the proportional differences between villages is more important than employing more current data.

Distance to the nearest town is a proxy for LPG cylinder supply. Previously, distance to the nearest town has been used to predict solar electrification in India [71]. We follow methods previously established by study collaborators ([71]) and use 2011 National Census data to estimate the straight line distance (in kilometers) from

village centers to the nearest statutory town, or an urban area with a municipal corporation or equivalent governing body.

Average one-way distance traveled to acquire an LPG cylinder refill is a direct self-reported measure of the burden of LPG cylinder acquisition. LPG-owning respondents were asked 'What is the one-way distance in kilometers your family typically travels to get LPG?' We averaged all responses within a village to estimate the covariate. Long travel distances may be a limiting factor in transitions away from reliance on solid fuels to clean cooking fuels [72].

Forest cover is used here as an indicator for biomass availability. Previous studies have pointed to biomass availability as a driver of cooking fuel choice [64, 73, 74]. Using freely-available information from The Socio-Economic High-resolution Rural-Urban Geographic Dataset on India (SHRUG v1.2) [75], we identify forest cover in 2014 from the vegetation Continuous Fields 250 meter resolution data for each study village. These data provide annual tree cover in the form of each pixel under forest cover based on multiple MODIS images and additional higher-resolution satellites as used previously [76]. For our variable of interest, we define average forest cover for each study village as total forest cover in the provided village polygons (based on the 2011 Census) divided by the total number of pixels comprising each polygon. Therefore, average forest cover provides us with a percentage of the total area associated with each village labeled as forest.

Statistical Approach

We jointly model the determinants of LPG adoption and the predicted amount of LPG consumption using a two-stage double-hurdle model. This model, originally formulated by Cragg (1971) [77], assumes a decision to consume a good is made in two stages. First, participants decide to participate (here, to adopt LPG). Second, consumers decide their optimal consumption (here, how much LPG to use per month in kilograms) [78]. It is plausible that the determinants of the decision to participate and the determinants of consumption are different and, therefore, a two-stage double-hurdle model is ideal for jointly modeling LPG adoption and use. Furthermore, the two-stage double-hurdle model enables the inclusion of covariates for only the second stage (consumption) that would otherwise be perfectly correlated with LPG adoption, e.g., status as a PMUY beneficiary, years of LPG ownership.

We use the 'churdle' command in Stata and define that the outcome variable is truncated at 0. We then calculate average-adjusted probabilities for participation (LPG adoption) in stage one and average-adjusted predicted LPG consumption (LPG use) in stage two using 'margins' command.

The double-hurdle model estimates four equations in two distinct stages. The first equation estimates the decision to adopt LPG in a binary logit model. This step is the 'hurdle' that households need to overcome to use LPG. Then, the second equation models the expected amount of consumption for those who participate in the LPG market. This model uses a truncated Poisson model to estimate LPG consumption in kilograms. Third, the standard deviation of the error term in the first equation is estimated. The fourth equation then estimates covariance between the error terms of the first two equations for the decision to adopt LPG and then how much LPG is consumed.

A double-hurdle model may be more ideal than tobit models when dealing with corner solutions (individuals with no option to participate in the LPG market or who refuse to participate no matter the circumstances) [78]. When the decision to adopt a technology is distinct from the decision to use it, as is the case here, a double-hurdle model offers an appealing alternative to isolate the expected probability of the amount of consumption among those who have chosen to participate in the market.

Acknowledgments

Ethical Considerations

The study protocol was reviewed and approved by the Institutional Review Boards of Johns Hopkins University and Columbia University. Informed consent was obtained from all study households.

Code and Data Availability

Data used in this study are freely available online [79, 80]. Code used in this study is available at https://doi.org/10.7910/DVN/QY5R7R [81].

Author Contributions

JU conceptualized the study and led the work. CFG, XH, JR, AS, and JU contributed to the design of the study. XH led the statistical analysis with contributions from CFG, JR, AS, and JU. CFG led the writing of the manuscript and design of figures, with contributions from XH, JR, AS, and JU. All authors discussed the results and commented on the manuscript.

Competing Interests

The authors declare no competing interests.

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References

[1] Stanaway J D *et al* 2018 Global, regional, and national comparative risk assessment of 84 behavioural, environmental and occupational, and metabolic risks or clusters of risks for 195 countries and territories, 1990–2017: a systematic analysis for the Global Burden of Disease study 2017 *The Lancet* **392** 1923–94
[2] Bond T, Venkataraman C and Masera O 2004 Global atmospheric impacts of residential fuels *Energy for Sustainable Development* **8** 20–32
[3] Bailis R, Drigo R, Ghilardi A and Masera O 2015 The carbon footprint of traditional woodfuels *Nat. Clim. Change* **5** 266–72
[4] Bonjour S *et al* 2013 Solid fuel use for household cooking: Country and regional estimates for 1980-2010 *Environ. Health Perspect.* **121** 784
[5] United Nations Statistics Division 2019 E-handbook on sustainable development goal indicators URL https://unstats.un.org/wiki/display/SDGeHandbook/Home United Nations Statistics Wiki
[6] Nerini F F *et al* 2017 Mapping synergies and trade-offs between energy and the sustainable development goals *Nature Energy* **3** 10–5
[7] McCollum D L *et al* 2018 Connecting the sustainable development goals by their energy inter-linkages *Environ. Res. Lett.* **13** 033006
[8] Rosenthal J, Quinn A, Grieshop A P, Pillarisetti A and Glass R I 2018 Clean cooking and the SDGs: Integrated analytical approaches to guide energy interventions for health and environment goals *Energy for Sustainable Development* **42** 152–9
[9] Balakrishnan K *et al* 2019 The impact of air pollution on deaths, disease burden, and life expectancy across the states of India: The Global Burden of Disease study 2017 *The Lancet Planetary Health* **3** e26–39
[10] Chowdhury S *et al* 2019 Indian annual ambient air quality standard is achievable by completely mitigating emissions from household sources *Proc. of the National Academy of Sciences* **116** 10711–6
[11] Lacey F G, Henze D K, Lee C J, van Donkelaar A and Martin R V 2017 Transient climate and ambient health impacts due to national solid fuel cookstove emissions *Proc. of the National Academy of Sciences* **114** 1269–74
[12] Comptroller and Auditor General of India 2019 *Report of the Comptroller and Auditor General of India on Pradhan Mantri Ujjwala Yojana* Audit Report, No. 14 https://cag.gov.in/sites/default/files/audit_report_files/Report_No_14_of_2019_Performance_Audit_of_Pradhan_Mantri_Ujjwala_Yojana_Ministry_of_Petroleum_and_Natural_Gas.pdf
[13] Gould C F and Urpelainen J 2018 LPG as a clean cooking fuel: Adoption, use, and impact in rural India *Energy Policy* **122** 395–408
[14] Shankar A V *et al* 2020 Everybody stacks: Lessons from household energy case studies to inform design principles for clean energy transitions *Energy Policy* **141** 111468
[15] Johnson M A and Chiang R A 2015 Quantitative guidance for stove usage and performance to achieve health and environmental targets *Environ. Health Perspect.* **123** 820–6
[16] Jeuland M, Soo J-S T and Shindell D 2018 The need for policies to reduce the costs of cleaner cooking in low income settings: implications from systematic analysis of costs and benefits *Energy Policy* **121** 275–85
[17] Joon V, Chandra A and Bhattacharya M 2009 Household energy consumption pattern and socio-cultural dimensions associated with it: a case study of rural Haryana, India *Biomass Bioenergy* **33** 1509–12
[18] Ravindra K, Kaur-Sidhu M, Mor S and John S 2019 Trend in household energy consumption pattern in india: A case study on the influence of socio-cultural factors for the chioce of clean fuel use *J. Clean. Prod.* **213** 1024–34
[19] Muller C and Yan H 2018 Household fuel use in developing countries: review of theory and evidence *Energy Econ.* **70** 429–39
[20] Quinn A K *et al* 2018 An analysis of efforts to scale up clean household energy for cooking around the world *Energy for Sustainable Development* **46** 1–10
[21] Puzzolo E, Pope D, Stanistreet D, Rehfuess E A and Bruce N G 2016 Clean fuels for resource-poor settings: A systematic review of barriers and enablers to adoption and sustained use *Environ. Res.* **146** 218–34
[22] Lewis J J and Pattanayak S K 2012 Who adopts improved fuels and cookstoves? A systematic review *Environ. Health Perspect.* **120** 637–45
[23] Carter E *et al* 2019 Household transitions to clean energy in a multiprovincial cohort study in China *Nature Sustainability* **3** 42–50

[24] Choumert-Nkolo J, Motel P C and Roux L L 2019 Stacking up the ladder: a panel data analysis of Tanzanian household energy choices *World Development* **115** 222–35

[25] Alem Y, Beyene A D, Köhlin G and Mekonnen A 2016 Modeling household cooking fuel choice: A panel multinomial logit approach *Energy Econ.* **59** 129–37

[26] Mani S, Tripathi S, Jain A and Gould C F 2020 The drivers of sustained use of liquefied petroleum gas in rural India *Nature Energy* **5** 450–7

[27] Kumar P, Rao R K and Reddy N H 2016 Sustained uptake of LPG as cleaner cooking fuel in rural India: Role of affordability, accessibility, and awareness *World Development Perspectives* **4** 33–7

[28] Ministry of Petroleum and Natural Gas 2018 Pradhan Mantri Ujjwala Yojana - Revised guidelines URL http://petroleum.nic.in/sites/default/files/revujscheme.pdf

[29] Jain A, Agrawal S and Ganesan K 2018 Lessons from the world's largest subsidy benefit transfer scheme *The Politics of Fossil Fuel Subsidies and Their Reform* ed H V Asselt and J Skovgaard (Cambridge: Cambridge University Press) 212–28

[30] Ministry of Petroleum and Natural Gas 2019 Petroleum Planning and Analysis Cell Monthly Data on LPG MarketingLPG profile as on October 1, 2019 https://ppac.gov.in/WriteReadData/Reports/201911220459272617502WebVersionLPGProfile1.10.2019.pdf

[31] Dabadge A, Sreenivas A and Josey A 2018 What has the Pradhan Mantri Ujjwala Yojana achieved so far? *Economic and Political Weekly* **53** 69–75

[32] Ministry of Petroleum and Natural Gas 2019 State-wise PMUY connections released URL http://pmujjwalayojana.com/released-connections.html Pradhan Mantri Ujjwala Yojana Official Website

[33] Kar A, Singh D, Pachauri S, Bailis R and Zerriffi H 2019 Ujjwala at 6 crores: Impact on cooking energy transition and climate change *The Ujjwala Saga—Unending Happiness & Health* (New Delhi, India: Ministry of Petroleum and Natural Gas, Government of India) 16–21 http://pure.iiasa.ac.at/id/eprint/15741/

[34] Ujjwala scheme: 82% of Ujjwala families return for LPG refill (2019). URL https://timesofindia.indiatimes.com/india/82-of-ujjwala-families-return-for-lpg-refill/articleshow/68327624.cms

[35] Kar A, Pachauri S, Bailis R and Zerriffi H 2019 Using sales data to assess cooking gas adoption and the impact of India's Ujjwala programme in rural Karnataka *Nature Energy* **4** 806–14

[36] Gould C F *et al* 2020 Household fuel mixes in peri-urban and rural Ecuador: explaining the context of LPG, patterns of continued firewood use, and the challenges of induction cooking *Energy Policy* **136** 111053

[37] Ho J, Tumkaya T, Aryal S, Choi H and Claridge-Chang A 2019 Moving beyond p values: data analysis with estimation graphics *Nat. Methods* **16** 565–6

[38] Leach G 1992 The energy transition *Energy Policy* **20** 116–23

[39] Gupta A *et al* 2020 Persistence of solid fuel use in rural North India *Economic & Political Weekly* **55** 55–62 https://epw.in/journal/2020/3/special-articles/persistence-solid-fuel-use-rural-north-india.html

[40] Swain S S and Mishra P 2020 Determinants of adoption of cleaner cooking energy: experience of the pradhan mantri ujjwala yojana in rural Odisha, India *J. Clean. Prod.* **248** 119223

[41] Pillarisetti A *et al* 2019 Promoting LPG usage during pregnancy: a pilot study in rural Maharashtra, India *Environ. Int.* **127** 540–9

[42] Pattanayak S K *et al* 2019 Experimental evidence on promotion of electric and improved biomass cookstoves *Proc. of the National Academy of Sciences*201808827

[43] Puzzolo E *et al* 2019 Supply considerations for scaling up clean cooking fuels for household energy in low- and middle-income countries *GeoHealth* **3** 370–90

[44] Shupler M *et al* 2019 Household, community, sub-national and country-level predictors of primary cooking fuel switching in nine countries from the PURE study *Environ. Res. Lett.* **14** 085006

[45] Cheng C and Urpelainen J 2014 Fuel stacking in india: changes in the cooking and lighting mix, 1987–2010 *Energy* **76** 306–17

[46] Mani S *et al* 2018 *Access to clean cooking energy and electricity: Survey of states in India 2018* Council on Energy, Environment and Water; Initiative for Sustainable Energy Policy; National University of Singapore https://www.ceew.in/publications/access-clean-cooking-energy-and-electricity

[47] Aklin M, Cheng C, Urpelainen J, Ganesan K and Jain A 2016 Factors affecting household satisfaction with electricity supply in rural India *Nature Energy* **1** 16170

[48] Klasen S 2000 Measuring poverty and deprivation in South Africa *Review of Income and Wealth* **46** 33–58

[49] Saxena V and Bhattacharya P 2018 Inequalities in LPG and electricity consumption in India: the role of caste, tribe, and religion *Energy for Sustainable Development* **42** 44–53

[50] Heltberg R 2004 Fuel switching: Evidence from eight developing countries *Energy Econ.* **26** 869–87

[51] Gupta G and Köhlin G 2006 Preferences for domestic fuel: analysis with socio-economic factors and rankings in Kolkata, India *Ecol. Econ.* **57** 107–21

[52] Farsi M, Filippini M and Pachauri S 2007 Fuel choices in urban Indian households *Environment and Development Economics* **12** 757–74

[53] Rao M N and Reddy B S 2007 Variations in energy use by Indian households: An analysis of micro level data *Energy* **32** 143–53

[54] Pandey V L and Chaubal A 2011 Comprehending household cooking energy choice in rural India *Biomass Bioenergy* **35** 4724–31

[55] Baiyegunhi L and Hassan M 2014 Rural household fuel energy transition: Evidence from Giwa LGA Kaduna State, Nigeria *Energy for Sustainable Development* **20** 30–5

[56] Chen L, Heerink N and van den Berg M 2006 Energy consumption in rural China: a household model for three villages in Jiangxi Province *Ecol. Econ.* **58** 407–20

[57] Dreibelbis R *et al* 2013 The integrated behavioural model for water, sanitation, and hygiene: a systematic review of behavioural models and a framework for designing and evaluating behaviour change interventions in infrastructure-restricted settings *BMC Public Health* **13** 1015

[58] Dalaba M *et al* 2018 Liquified petroleum gas (LPG) supply and demand for cooking in northern Ghana *EcoHealth* **15** 716–28

[59] Wolf J, Mäusezahl D, Verastegui H and Hartinger S M 2017 Adoption of clean cookstoves after improved solid fuel stove programme exposure: A cross-sectional study in three Peruvian Andean regions *International Journal of Environmental Research and Public Health* **14** 745

[60] Abebaw D 2008 Household determinants of fuelwood choice in urban Ethiopia: a case study of Jimma Town *The Journal of Developing Areas* **41** 117–26

[61] Desai S and Dubey A 2012 Caste in XXI century India: competing narratives *Economic and Political Weekly* **46** 40

[62] Menghwani V *et al* 2019 Determinants of cookstoves and fuel choice among rural households in India *EcoHealth* **16** 21–60

[63] Kumar P, Dhand A, Tabak R, Brownson R and Yadama G 2017 Adoption and sustained use of cleaner cooking fuels in rural India: A case control study protocol to understand household, network, and organizational drivers *Archives of Public Health* **75** 70

[64] Behera B, Rahut D B, Jeetendra A and Ali A 2015 Household collection and use of biomass energy sources in south Asia *Energy* **85** 468–80

[65] Rahut D B, Das S, Groote H D and Behera B 2014 Determinants of household energy use in Bhutan *Energy* **69** 661–72

[66] Gould C F and Urpelainen J 2019 The gendered nature of liquefied petroleum gas stove adoption and use in rural India *The Journal of Development Studies* **56** 1–21

[67] Borooah V K and Iyer S 2005 Vidya, veda, and varna: the influence of religion and caste on education in rural India *Journal of Development Studies* **41** 1369–404

[68] Bhojvaid V *et al* 2014 How do people in rural India perceive improved stoves and clean fuel? Evidence from Uttar Pradesh and Uttarakhand *International Journal of Environmental Research and Public Health* **11** 1341–58

[69] Sharma A, Parikh J and Singh C 2019 Transition to LPG for cooking: a case study from two states of india *Energy for Sustainable Development* **51** 63–72

[70] Dickinson K L *et al* 2019 Adoption of improved biomass stoves and stove/fuel stacking in the REACCTING intervention study in northern ghana *Energy Policy* **130** 361–74

[71] Aklin M, Cheng C and Urpelainen J 2018 Geography, community, household: Adoption of distributed solar power across India *Energy for Sustainable Development* **42** 54–63

[72] Hou B-D *et al* 2017 Cooking fuel choice in rural China: Results from microdata *J. Clean. Prod.* **142** 538–47

[73] Jagger P and Kittner N 2017 Deforestation and biomass fuel dynamics in uganda *Biomass Bioenergy* **105** 1–9

[74] Jagger P and Shively G 2014 Land use change, fuel use and respiratory health in uganda *Energy Policy* **67** 713–26

[75] Asher S, Matsuura R, Lunt T and Novosad P 2019 The socioeconomic high-resolution rural-urban geographic dataset on india (shrug) URL https://shrug-assets.s3.amazonaws.com/static/main/assets/other/almn-shrug.pdf International Growth Centre Working Paper C-89414-INC-1

[76] Asher S, Garg T and Novosad P 2018 The ecological impact of transportation infrastructure URL https://openknowledge.worldbank.org/handle/10986/29980 World Bank Policy Research Working Paper; No. 8507

[77] Cragg J G 1971 Some statistical models for limited dependent variables with application to the demand for durable goods *Econometrica* **39** 829–44

[78] García B 2013 Implementation of a double-hurdle model *The Stata Journal* **13** 776–94

[79] Mani S *et al* 2019 Access to clean cooking energy and electricity: Survey of states in India 2018 (ACCESS 2018) URL https://doi.org/10.7910/DVN/AHFINM Harvard Dataverse

[80] Aklin M *et al* 2016 Access to clean cooking energy and electricity: Survey of states in India 2015 (ACCESS 2015) URL https://doi.org/10.7910/DVN/0NV9LF Harvard Dataverse

[81] Gould C F, Hou X *et al* 2020 Replication Data for: Jointly modeling the adoption and use of clean cooking fuels in rural India, Harvard Dataverse https://doi.org/10.7910/DVN/QY5R7R