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LPG as a clean cooking fuel: Adoption, use, and impact in rural India[☆]

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ABSTRACT

Liquefied petroleum gas (LPG) is by far the most popular clean cooking fuel in rural India, but how rural households use it remains poorly understood. Using the 2014–2015 ACCESS survey with over 8500 households from six energy-poor Indian states, our study reports on results from a comprehensive survey of LPG use in rural India using a holistic approach to understanding the integration of a clean cooking fuel into rural household's energy mixes. There are three principal findings: (i) fuel costs are a critical obstacle to widespread adoption, (ii) fuel stacking is the prevailing norm as few households stop using firewood when adopting LPG, and (iii) both users and non-users have highly positive views of LPG as a convenient and clean cooking fuel. These findings show that expanding LPG use offers great promise in rural India, but affordability prevents a complete transition from traditional biomass to clean cooking fuels.

1. Introduction

Liquefied petroleum gas (LPG) is, by a wide margin, the most popular clean cooking fuel in rural India. At the same time, results from the 2011 Indian Census show that only 11% of rural households use LPG as their primary cooking fuel; the rest rely on burning solid fuels—firewood, coal, and dung—to address their daily cooking and heating needs (Tripathi et al., 2015). Important policy efforts are being made to improve access and adoption of LPG in rural Indian households in hopes of addressing the massive health, economic, and social burdens of widespread solid fuel use. Cooking with solid fuels is recognized as a significant global health hazard, with women and children facing the greatest risks (Lim et al., 2013). There is now strong evidence from field studies and systematic analyses suggesting that clean fuels, as opposed to cleaner improved wood-burning stoves, are necessary to bring air pollution exposure below the World Health Organization standard over the long term (Simon et al., 2014; Pope et al., 2017; Sambandam et al., 2015). The adoption of clean fuels—like LPG, electricity, or ethanol—is a critical first step towards achieving the health benefits suggested by the burden of disease attributable to air pollution exposure resulting from solid fuel combustion for cooking. However, sustained clean fuel use that *displaces* the majority of traditional solid fuel use is paramount to realizing benefits, since even limited solid fuel combustion leads to substantial increased health risk (Johnson and Chiang, 2015).

The burdens of disease (Lim et al., 2013), socio-economic impacts (Kowsari and Zerriffi, 2011; Duflo et al., 2008), environment effects (e.g., accelerated degradation, depletion of local resources (Ghilardi et al., 2009; Masera et al., 2006)), and climate consequences (Bond et al., 2004; Jeuland and Pattanayak, 2012) from solid fuel use around the world are massive. As a result, national transitions to clean fuels can have large multi-sectoral impacts. Through numerous policy initiatives promoting LPG access (*Ujjwala*) and greater subsidies for the poor ("Give it Up"), the Indian government has sought to capitalize on the potential *golden thread* of cooking fuels, which can be linked to 10 Sustainable Development Goals.[1] A recent discussion has highlighted the relationship between clean cooking's multiple objectives (e.g., health, climate, environmental protection, local and women's empowerment), discussing in particular climate versus health benefits (Goldemberg et al., 2018), noting that achieving health goals is sometimes limited by sustainability-oriented objectives to mitigate greenhouse gas emissions. Given the limited net climate impacts from improved wood-burning, Goldemberg et al. (2018) ultimately argue that the health and social benefits of clean cooking fuels merit primary emphasis. At the same time, the ultimate goal may be electric stoves—especially high-efficiency induction stoves—powered by renewable energy, as in Ecuador (Goldemberg et al., 2018). In addition, clean fuels

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[1] 1: No poverty; 2: Zero hunger; 3: Good health and well-being; 4: Quality education; 5: Gender equality; 7: Affordable and clean energy; 8: Decent work and economic growth; 11: Sustainable cities and communities; 13: Climate action; and 15: Life on land.

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like LPG or electricity may offer greater potential climate benefits than improved cookstoves (Rosenthal et al., 2018). Given the pressing need to reduce the burden of disease from air pollution exposure, this study adopts a health-centered framework when considering decisions about household cooking transitions.

Although LPG promises tremendous benefits, researchers still have a limited understanding of its adoption and use in rural households. Prior studies have recognized the importance of factors such as affordability (Cheng and Urpelainen, 2014; Alkon et al., 2016), age of household head and primary cook (Lewis and Pattanayak, 2012), and social factors like religion, caste, and gender (Lewis and Pattanayak, 2012; Bhojvaid et al., 2014; Sehjpal et al., 2014) in determining household decision-making patterns. However, a shared limitation of all these studies is that they focus primarily on the adoption of clean cooking fuels. They do not offer a comprehensive overview of the multiple dimensions of clean cooking fuels: adoption, sustained use, and impact. While the decision to adopt a clean cooking fuel is an important first step, households must also decide how much and to what end they want to use the fuel considering its advantages, disadvantages, availability, and cost. The role that clean cooking fuels play after adoption, and after integration into daily routines, warrants more attention. This study combines detailed investigation into stable (that is, outside of an experimental context where patterns are evolving and subject to intervention removal) household fuel use patterns with a large sample size.

The purpose of this study is to offer a comprehensive assessment of LPG use in rural households of India. Findings from this study come from the 2014–2015 ACCESS survey with 8568 households from 714 villages in six north Indian states, offering a wealth of data on different dimensions of LPG adoption, use, and impact in rural India (Aklin et al., 2016). Importantly, the data presented in this study represent long-term cooking patterns and arrangements. Furthermore, a valuable contribution of this study is its holistic approach to characterizing household cooking fuel mixes. Past analyses—of ACCESS and other large-scale energy access surveys—have focused individually on stove or fuel adoption (Patnaik and Tripathi, 2017), use, or independently on cooking satisfaction (Baquié and Urpelainen, 2017). Furthering these efforts, this study triangulates findings using diverse results of household LPG adoption, fuel use patterns, and perceptions of cooking fuels. In doing so, results deeply describe the integration of LPG into household cooking mixes and move beyond the acknowledgement of fuel stacking realities to push the understanding of its motivations and the specific roles of LPG and secondary solid fuel use in household energy end uses. In doing so, this study offers guidance for clean cooking fuel policies and programs in India and also around the world.

Results can be summarized in three core messages. First, both the cost of LPG connections and the monthly cost of the fuel are crucial obstacles to widespread adoption and use. Second, fuel stacking continues to characterize cooking with LPG in rural India. Fewer than 60% of LPG users consider it their primary cooking arrangement, and even in this group households frequently use solid fuels to cook different dishes. The remaining 40%, in turn, mostly use LPG to prepare tea and snacks. In total, only 4% of LPG-owning households use the fuel exclusively. Finally, LPG is not only a very popular and much appreciated fuel among its users, but even households not using LPG consider it a superior alternative to traditional choices such as firewood and cow dung. Nonetheless, fuel stacking is the norm.

These three central patterns have two important implications for research and practice on clean cooking fuels. The first is that cost, instead of inferior performance, is the critical obstacle to widespread adoption. Access to LPG, through increased connections (where a household acquires a stove and is placed in administrative records), in rural India has been transformed in the last decade: between 2010 and 2013 alone, nearly 45 million new LPG connections were established in India—primarily to rural households—and the nation's official goal is 80% of households cooking with a clean fuel by 2019 (Jain et al., 2015). However, the cost of and access to cylinders (because of still-limited distribution routes) has until now not caught up to the LPG access promotions. As a result, actual LPG use is constrained, leading rural households to continue using potentially health-harming solid fuels.

The second implication is that even if Indian policymakers manage to solve the problems of cost and affordability, fuel stacking remains a fundamental obstacle to better social and health outcomes. India is not alone in this effort; for instance, in the past decade Indonesia transitioned 50 million households' primary cooking fuel from kerosene to LPG (Budya and Arofat, 2011) (see Quinn et al., 2018 for a discussion of 11 clean cooking fuel case studies, including Indonesia, Ghana, and Peru). There is clear demand around the world for continued and increased effort to provide access to clean cooking facilities (Daly and Walton, 2017) but this is just a first step. The long-term benefits from clean fuels, and all efforts to promote clean fuels, depend on *both* the continued use of clean fuels after adoption and the reduction of traditional cooking technologies. Improved understanding of households' established cooking patterns with clean fuels, and motivations for continued solid fuel use after clean fuel adoption, is needed to provide clean fuels that comprehensively address all household energy needs and may be used exclusively in the long term.

2. Literature review

Data analysis is motivated in three steps. First, a description of the need for cleaner cooking. Second, a discussion of the literature on the adoption and use of clean cooking fuels. Finally, a review of the Indian case.

2.1. Limitations of improved wood-burning stoves

Today, one-third of the world's population still relies on solid fuels for cooking and heating. Burning solid fuels in ineffciently in traditional stoves is the leading cause of death for children under the age of 5 and the greatest global environmental health risk. The term household air pollution serves to encompass a range of exposures to air pollution resulting from the combustion of solid fuels, including outdoor exposures near the home and the contribution of prevalent solid fuel combustion for cooking to ambient air pollution (Chafe et al., 2014; Conibear et al., 2018). Furthermore, the term incorporates other exposure sources like space heating, lighting, and non-solid fuels (e.g., kerosene). Implicit in the term household air pollution is that multiple clean energy options may be needed to lower exposure to air pollution. There has been much attention drawn towards interventions to lower air pollution exposure from cooking with solid fuels. Smith and Sagar (2014) term the two central choices *making the available clean* and *making the clean available*. Determining the best path has not been straightforward.

Until recently, most interventions have focused on the adoption and sustained use of improved wood-burning cookstoves—stoves that burn available, free-of-cost firewood efficiently. Hundreds of cookstove designs were engineered and made commercially available globally to promote improved energy efficiency or some form of smoke exhaust ventilation. The variability in cookstove designs responded to differences in cooking styles around the world and also to different approaches to improving combustion efficiency. Detailed discussion of improved cookstove design and performance is available elsewhere (Jetter et al., 2012; Kshirsagar and Vilas, 2014; Mehetre et al., 2017); briefly, there are three principal designs: (i) natural draft cookstoves, which are free-convection driven (the most popular and low-cost); (ii) forced-draft cookstoves, which rely on fans to mix fuel, air, and flame for more complete combustion (the most promising for reducing emissions and the most expensive); and (iii) chimney stoves that focus on venting emissions outside the home (popular in Central and South America). Although improved cookstoves often perform well under laboratory conditions (Jetter et al., 2012)—especially forced-draft cookstoves—or shortly after installation, they have largely failed to achievable measurable exposure improvements over long time horizons in households, including in high-profile randomized controlled trials (Mortimer et al., 2017; Tielsch et al., 2016; Romieu et al., 2009). The Cookstove and Pneumonia Study (CAPS) is one notable example. CAPS is the largest randomized intervention trial to publish results to date: the study provided two forced-ventilation improved wood-burning stoves (at the time, the highest rated in terms of reducing emissions on the market) to more than 8000 households in Malawi. Still, intention-to-treat results yielded no reduction in the incidence of under-5 pneumonia (incidence rate ratio: 1.01; 95%: 0.91–1.13, $p = 0.80$) (Mortimer et al., 2017).

Some improved wood-burning stoves have indicated potential for environmental and livelihood benefits when used consistently and properly, resulting in fuel savings, monetary and time savings, and some air pollution reductions (Rosa et al., 2014; Bensch and Peters, 2013, 2015). However, considering a focus on health, improved cookstoves have not demonstrated sufficient reductions in personal exposure to air pollution to yield long-term population health benefits. The reasons behind this central limitation of improved cookstove projects are multiple:

- *Insufficient stove emissions reductions:* Experimental and meta-analysis evidence suggests the likelihood that even the most advanced wood-burning stoves may not be efficient enough to reduce HAP sufficiently in real world contexts (Sambandam et al., 2015; Pope et al., 2017). Epidemiological evidence points towards a supra-linear dose-response relationship between HAP exposure and health outcomes (child acute lower respiratory infections, ischaemic heart disease, and chronic obstructive pulmonary disease) (Burnett et al., 2014). Such a relationship implies that risk declines more steeply at lower levels of exposure and, unfortunately, Pope et al. (2017) note that the majority of solid fuel stoves evaluated in their meta-analysis did not achieve levels close to the WHO annual standard of $35\ \mu g/m^3$. This situation may change if outdoor cooking patterns increase substantially, but further research is required to clarify and contextualize the relationship between cooking location, personal exposure to air pollution, and community-level air pollution (Langbein et al., 2017).
- *Stove stacking:* New technologies get incorporated into existing use practices. Multiple stove use is common to address multiple energy end uses. Inclusive, different stoves may be used to accomplish the same cooking task (Masera et al., 2000; Ruiz-Mercado et al., 2011; Kowsari and Zerriffi, 2011; Pine et al., 2011; Bensch and Peters, 2013). However, to bring HAP below the WHO guideline for air quality and achieve health benefits near elimination of traditional cooking practices is required (i.e., 1–3 h per week of traditional cooking is sufficient to bring a household above $35\ \mu g/m^3$) (Johnson and Chiang, 2015).
- *Improper use:* Correct use and maintenance of improved cookstoves is important to achieving sustained field performance and increasing stove lifetimes. Stove degradation and destruction is common, either because of natural wear or because of user-made adjustments to accommodate traditional cooking practices (Mortimer et al., 2017; Hanna et al., 2016). However, such modifications limit efficiency and exposure reductions. Sustained cookstove use may improve when paired with use, maintenance, and repair training (Bruce et al., 2017; Barnes et al., 2015), however until now careful study of the impact of post-acquisition services remains limited (Gould et al., 2018; Jagger and Das, 2018).
- *Failures of compatibility:* Stoves must meet the needs of households—cognizant of household, cultural, and environmental conditions—to be adopted and used consistently (Lewis and Pattanayak, 2012; Simon et al., 2014). Compatible stoves are more likely to be adopted and used (Bensch and Peters, 2015). User-centered approaches that incorporate preferences and needs must be considered throughout the intervention, from cookstove design to post-acquisition services (Hollada et al., 2017; Lambe and Atteridge, 2012). Traditional cooking practices are often highly ingrained and, as a result, promoting change is challenging. These gaps between cooking demands and intervention stoves often lead to stove stacking or stove modifications, limiting its impacts and potential benefits. In addition, many regions in the world using solid fuels have high heating demand. In these areas, heating demands are met by solid fuel combustion, which may also be used for cooking. Improved cookstoves, however, demand thermal efficiency to burn less fuel and release fewer emissions, thus reducing their ability to heat a room (Simon et al., 2014; Hollada et al., 2017; Bruce et al., 2017).
- *Community-level air pollution:* For the most part, household energy interventions have occurred in small subsets of communities. As a result, large portions of these communities and intervention household neighbors continue to cook on traditional stoves. This may result in high levels of ambient air pollution, direct leakage from neighboring households into intervention households, or exposure when visiting traditional households, all of which limit potential personal exposure reductions from the intervention (Smith et al., 2011; Bruce et al., 2017; Simon et al., 2014; Mukhopadhyay et al., 2012). Careful empirical investigation is required to disentangle the influence of traditional cooking on community-level air pollution and personal exposure in intervention communities.

2.2. Adoption and use of clean cooking fuels

Since solid fuel use and high HAP exposure affects one-third of the world's population, there are significant demands for widespread and scaleable solutions. However, given the variability of household, cultural, and environmental conditions around the world it seems unlikely that there will be a single solution. There are a number of clean cooking fuels (those that burn with very few emissions) that present alternatives to solid fuel combustion—gas (LPG, piped natural gas, biogas), electricity (coil, induction, solar), and ethanol. LPG, in particular, is promising: it can be easily liquefied under moderate pressure, facilitating simple storage and transportation in cylinders. These aspects make LPG advantageous in terms of efficient distribution in low- and middle-income countries. Indeed LPG is widely used around the world and is regularly the first clean fuel to reach rural communities making it the most poised to deliver substantial health, economic, and social benefits (Simon et al., 2014; Bruce et al., 2017).

Clean cooking fuel promotion programs must account for fuel stacking patterns and the motivations for continued solid fuel use. There has been limited study into rural households' cooking patterns with LPG; however, there are some case studies that suggest fuel stacking is prevalent (Hollada et al., 2017; Mukhopadhyay et al., 2012; Troncoso and Silva, 2017). Explaining fuel stacking practices for a popular and clean option will be an important task. Furthermore, as was the case with improved cookstove interventions, high community-level air pollution from solid fuel users may affect the HAP levels inside LPG-using households. In addition, LPG faces some barriers to widespread uptake and displacement of solid fuel combustion to lower air pollution exposure:

- *Cost:* The cost of LPG—both initial cost of the stove and connection as well as regular fuel costs—is an important barrier to adoption and continued use in households. Especially among the rural poor, where liquidity constraints are common, cost is the most important factor limiting adoption and sustained use (Puzzolo et al., 2016; Beltramo et al., 2014; Rehfuess et al., 2014; Lewis and Pattanayak, 2012). LPG cylinder “lumpiness” has been previously cited as a constraint on exclusive use, especially in comparison to other fuels that may be either collected or purchased in small quantities (Bensch and Peters, 2013).
- *Availability:* While solid fuels are often free and widely available,

acquiring LPG requires supply networks outside of the control of households. As a result, certain households may have limited access to LPG, which may contribute to infrequent use, fuel conservation, and fuel stacking practices (Puzzolo et al., 2016; Bruce et al., 2017; Simon et al., 2014). In some rural parts of low- and middle-income countries, sustainable LPG supply chains may not be available in the immediate future.

- *Heating:* In colder climates and rural contexts, space heating benefits from wood-burning stoves are appreciated and needed (Hollada et al., 2017; Baumgartner et al., 2011). This further contributes to fuel stacking practices.
- *Safety concerns:* Many households express fear about LPG stoves and tanks in their households (Hollada et al., 2017; Mukhopadhyay et al., 2012). Leaks from old valves and faulty cylinders can result in explosions. Though up to this point these incidents have been relatively rare, cylinders can be dangerous when safety features are not regularly checked (Express News Service, 2017b, 2017a; Trichy News, 2016).
- *Taste:* Households regularly remark on differences in food tastes when transitioning from wood-burning stoves to LPG (or any clean fuels) (Hollada et al., 2017; Terrado and Eitel, 2005; Mukhopadhyay et al., 2012; Lambe and Atteridge, 2012). Desire to maintain traditional food tastes may in some cases be a barrier to full adoption of LPG.

Still, gas delivers several advantages over solid fuels and is popular in both urban and rural households around the world. Principally, gas has (i) clean combustion and low emissions leading to negligible HAP and cleaner pots, pans, and walls; (ii) easily controlled and consistent flames at high, medium, and low heat facilitating multi-tasking during cooking; (iii) quick cooking start and heating; and (iv) time savings and reduced drudgery from not having to collect woodfuels (Simon et al., 2014; Smith and Dutta, 2011).

2.3. Clean cooking fuels in India

Although LPG has had a presence in India since 1950, and despite prevalent government subsidies for everyone, use has largely been limited to the middle and upper classes. In recent years, the Indian government has sought to change these use patterns through a series of targeted policies. Since 2015, the Government of India, along with three large oil companies, has begun three major programs to promote LPG to poor and rural households: (i) *Pahal* moves fuel subsidies directly to individuals' bank accounts, to reduce illicit use of subsidized LPG outside the non-household sector; (ii) *Give it Up* enables middle class households to transfer their subsidies to poor households; and (iii) *Pradhan Mantri Ujjwala Yojana* (Ujjwala) will provide free connections to 80 million poor households by 2019 (Khan, 2017). Already 10 million households have participated in "Give it Up" and 20 million households have received a free connection through *Ujjwala* (Smith, 2017). Officially, the Government of India intends to achieve 80% clean cooking fuel use by 2019, more than doubling the historical clean fuel growth rate. These political efforts are substantial and, though they did not originate from the health or environment sectors or ministries, may have substantial public health and environmental benefits. While increasing the number of LPG connections among poor households is a critical first step towards success, it is now clear that the long-term benefits of these substantial political and economic investments relies on sustained use of LPG and the reduction of solid fuel combustion. Up to this point, there has been little investigation into current LPG cooking patterns and fuel stacking practices in rural Indian households.

Programs like *Ujjwala* are rapidly changing the landscape of LPG access in rural India. Until now, access has varied dramatically between states: from Punjab where ownership was 34% to Chhattisgarh where was it was 2% in 2010 (Patra, 2015). LPG adoption has been sharply marked by a rural-urban divide as well as by economic level, with the highest use among the urban wealthy (Patra, 2015; Jain et al., 2015). *Ujjwala*, and other related programs promoting access to the poor, have led many to believe that a dramatic shift in cooking fuel is about to occur in rural Indian households. While use has historically remained low because of limitations of cost and access, LPG has been an aspirational fuel (more so than improved wood-burning cookstoves) for rural Indian households. Current cooking patterns in households already using LPG can provide guidance on the form that future incorporation of LPG into households' cooking mix will take. Up to this point, discussion of LPG in rural Indian households has been limited to data that contain only primary cooking fuel (failing to acknowledge the realities of fuel stacking) (Smith and Sagar, 2014; Tripathi et al., 2015; Patra, 2015; Kumar et al., 2016) or small sample sizes and intervention settings (Mukhopadhyay et al., 2012). These studies are important but they insufficiently describe widespread, established cooking patterns in LPG-owning households. Some qualitative studies have begun to discuss LPG cooking, noting primary use for small meals, snacks for visitors, and for making tea (Bhojvaid et al., 2014; Alam et al., 2016). Although LPG is widely preferred to solid fuels for its cleanliness, quickness, and ease of handling (Patra, 2015), in many cases, high fuel costs and access limit use. As a result, households are hesitant to cook fuel-intensive meals like vegetables or thick curries as a way to ration gas (Wang, 2014).

Affordability, availability, and awareness define the LPG situation in rural households around the world. Government programs can address all three issues, but high fuel cost often remains a major challenge for rural households even when LPG is subsidized (Jain et al., 2015; Kumar et al., 2016). Previous efforts by the research group in collaboration with the Council on Energy, Environment and Water describe broad state-by-state and overall trends of clean cooking access (Jain et al., 2015; Patnaik and Tripathi, 2017), demonstrating continued barriers to adoption. In addition, earlier analysis of the ACCESS database shows that LPG is very popular in rural Indian households, and that its use is a strong predictor of subjective satisfaction, primarily by offering smoke reduction and improved cooking speed (Baquié and Urpelainen, 2017). This study expands on these analyses to provide insights into current cooking and fuel stacking patterns. Indeed, there is demand for this type of analysis in the literature and beyond as India and other countries heavily invest in promoting LPG cooking (Kumar et al., 2016; Patnaik et al., 2017).

3. Data and methods

3.1. ACCESS survey

Our findings are based on the "Access to Clean Cooking Energy and Electricity – Survey of States" (ACCESS) survey conducted in 2014–2015 in collaboration with the Council on Energy, Environment and Water. ACCESS is the largest survey of energy access to this date. The survey was administered in 8568 households, 714 villages, and 51 districts across six energy-poor, contiguous states of India: Bihar, Jharkhand, Madhya Pradesh, Uttar Pradesh, Odisha, and West Bengal. These north Indian states are among the country's four most populous (Aklin et al., 2016). The survey was conducted in the local language, which is Hindi in all states except West Bengal (Bangla) and Odisha (Odia). The 45-min survey instrument contains information on household lighting fuels, electricity use, and cooking arrangements. This study uses data from the modules on cooking, during which questions were posed to the primary household cook. Survey sampling weights are used obtain descriptive statistics that are representative at the population level (developed by comparing our survey results to India's National Sample Survey, 2009–2010). Data were collected by MORSEL India Research and Development Private Ltd. Full text of the ACCESS survey is available in Supplementary Material. For more information about the ACCESS survey, see Aklin et al. (2016), Jain et al. (2015) and Aklin et al. (2016).

3.2. Adoption variables

Households not owning LPG were asked: "Why don't you have LPG?" Responses were coded into four options, mirroring the central factors limiting clean fuel adoption in discussed in the literature (Puzzolo et al., 2016): (i) "Is it not available or too far from your village?", (ii) "Is it too expensive to install an LPG connection?", (iii) "Is the monthly expense of LPG too expensive?", and (iv) "Do you not know how to get an LPG stove or whom to ask?" Two central barriers to LPG use are described in terms of (i) cost: the cost of LPG cylinders (small and large cylinders from the market and authorized distributors) and (ii) access: self-reported one-way distance to acquire LPG cylinders. In addition, LPG-owning households were asked the length of time (in terms of years) they have had LPG.

3.3. Use variables

Up to this point descriptions of LPG use in large samples have often been measures of LPG *access*, insinuating use from ownership. More nuanced options may distinguish between primary and secondary fuel use, allowing for indications of fuel stacking. A more careful description of LPG use—including regarding specific energy end uses—is needed to understand the role LPG has in households, and the potential benefits gained through clean fuel access programs. This study describes cooking fuel use in three parts:

- *Fuel prevalence and stacking* of solid fuels like firewood, dung, and kerosene along with LPG.
- *Self-reported LPG use* in kilograms per month is calculated by adding together self-reported small (5 kg) and large (14.2 kg) LPG cylinder purchases (both from the market and from authorized distributors) made in a year and dividing by 12 months. LPG cylinder purchases are consistent and repeated activities, so self-reported data are expected to closely reflect actual use.
- *LPG end uses* as defined by cooking important dishes: chapatis, vegetables, rice, tea/snacks, and heated milk. Commonplace enough to be present in all Indian households to some degree, these tasks are important touch stones for intuiting relevant cooking patterns when combined with fuel use groups. Discussing fuel end uses (like specific dishes) is especially useful for studying motivations for continued solid fuel use, since preference or necessity to cook certain dishes with solid fuels is often cited as a barrier to exclusive clean fuel use.

3.4. Satisfaction variables

This study characterizes subjective satisfaction and dissatisfaction with primary cooking fuel and perceptions of LPG compared to traditional cooking technologies using a variety of measures. In addition to a measure of overall satisfaction with the primary cooking fuel with a set of additional positive perceptions (binarized choosing the positive perception compared to neutral or negative when appropriate): (i) "Does the primary cooking arrangement have good quality of cooking?", (ii) "Considering the impact on health, compared to a traditional cookstove, LPG-based cooking is: better, similar, worse, or don't know?", (iii) "Considering the convenience of cooking, compared to a traditional cookstove, LPG-based cooking is: better, similar, worse, or don't know?", and (iv) "How satisfied are you with the availability of your primary cooking fuel (1: Unsatisfied, 2: Neutral, 3: Satisfied)?"

Primary cooks reporting dissatisfaction were asked to describe negative perceptions they have of their primary cooking arrangement (binarized choosing the negative perception compared to neutral or positive when appropriate): (i) produces excessive smoke, (ii) too expensive to use, (iii) too dangerous to use, (iv) too time consuming, (v) too difficult to use, (vi) unsatisfied with fuel availability, (vii) cooks less because of poor fuel availability, and (viii) believes that there is an impact on health from the cookstove used.

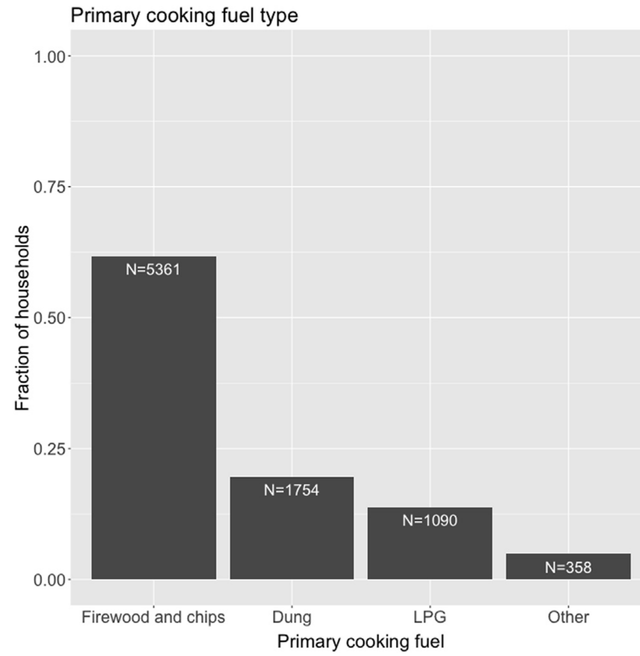

Fig. 1. Households' reported fuel use (ACCESS, 2015–2017).

LPG owners were asked a further subset of LPG-specific questions, starting again with a question on overall satisfaction with their LPG situation. Unsatisfied LPG owners were prompted to describe their rationale with four responses: (i) too expensive to consume, (ii) poor availability, (iii) too far to procure, and (iv) poor maintenance services.

4. Results

This study is organized under two broad categories: adoption and use patterns.

4.1. Adoption Patterns

The fuel choices of the households in our sample are shown in Fig. 1, and the distribution of stoves in study households is found in Supplemental Information Figure A3. Fig. 1 shows the proportion of households in the sample that use different fuels: firewood, cow dung, LPG, and agricultural residues. Of the four fuels, only LPG can be considered a clean cooking fuel—the others are traditional alternatives with lower energy densities and more impurities that contribute to air pollution. As the graph shows, only 22% of households in this rural sample own LPG. This clean cooking fuel remains relatively rare, though there is widespread variation in adoption rates across states. Supplemental Information Figure A1 shows the geographic distribution of LPG adoption in study states ($N = 6$) and districts ($N = 51$)—ranging from as low as 5% in some states to as high as 35% in others. Supplemental Information Figure A2 shows the numerical distribution of LPG adoption in study districts and then again at the village level ($N = 714$). In both cases it is clear that most regions have populations heavily reliant on solid fuels; though, LPG uptake is limited throughout, there is heterogeneity.

By far the most common reasons for non-adoption ($N = 6712$) are installation cost (0.95 of sample) and monthly cost of fuel (0.88). The median self-reported cost of LPG connection was 4700 INR; most households reported paying between 3000 and 6000 INR (0.67). For context, the median monthly expenditure in this sample was 4000 INR (mean: 5300 INR, standard deviation: 3900 INR). The unavailability of connections and fuel is also a regularly reported reason (0.72), whereas

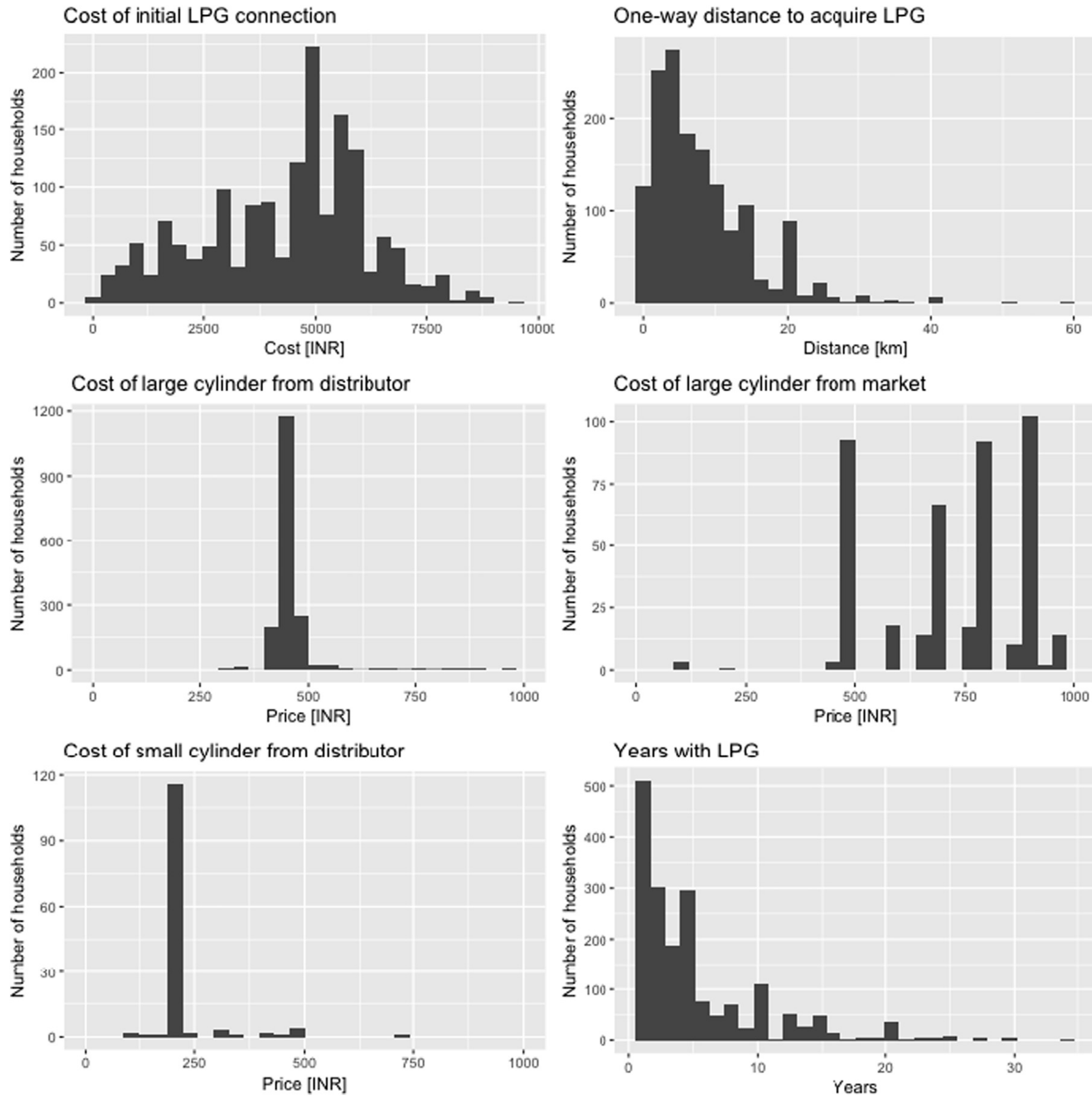

Fig. 2. Barplots showing descriptive statistics of LPG characteristics (ACCESS, 2014–2015).

lack of information about how to obtain the connection and how to use LPG is less cited (0.41). These results are consistent with the clean fuels and LPG literature discussed previously.

Fig. 2 shows the distribution of a number of key LPG variables: cost of initial LPG connection, one-way distance to acquire LPG, cost of large cylinder from authorized distributors, cost of large cylinder from the market, cost of small cylinder from the distributor, and years with LPG. 95% of all respondents report purchasing large cylinders from the distributor at a cost between 400 and 550 INR (6.18–8.50 USD). One large cylinder, then, would account for approximately 10% of the total monthly expenditure of a household. Beyond the monetary expenditure, purchasing LPG requires a significant investment in time and energy: 75% of respondents said they have to walk four km or more one way to acquire a LPG cylinder. From the results it is clear that cost and access are significant barriers to adoption, but especially to sustained LPG use. Among households that did have an LPG stove, the majority reported to have had it for more than one year (0.72), with the median length of time since connection being three years.

To summarize, LPG remains a relatively rare fuel in rural India and the most important explanation for this rarity is cost. Both the cost of a connection and the monthly cost of the fuel are important obstacles. While the *Ujjwala* program may provide free LPG connections to poor households, it does not subsidize fuel costs or provide increased access to LPG supply networks. Though, the government has offered a partial subsidy and invests in supply through other policies. Monthly fuel costs, cited here by 88% of households as a barrier to *adoption*, will remain a significant barrier to sustained use.

4.2. Use patterns

Having briefly reviewed adoption patterns for LPG, this study next examines use patterns—a much less understood aspect. Only four percent of households reported not using any solid cooking fuels (e.g., firewood, dung, agricultural residues, coal, or kerosene) ($N = 410$). Those that did were exclusive LPG users ($N = 386$) or exclusive electric stove users ($N = 24$). As presented above in Fig. 1, the prevalence of cooking with firewood and chips (0.83) and dung (0.68) was high in comparison to LPG (0.22) and electric-based cooking (0.01). The majority of households used both firewood and dung (0.58). Similarly, primary fuel use was dominated by firewood and chips (0.63) and dung (0.20), followed by LPG (0.13) (Supplemental Information Figure A4). This implies that LPG was a secondary fuel option, after a solid fuel, in

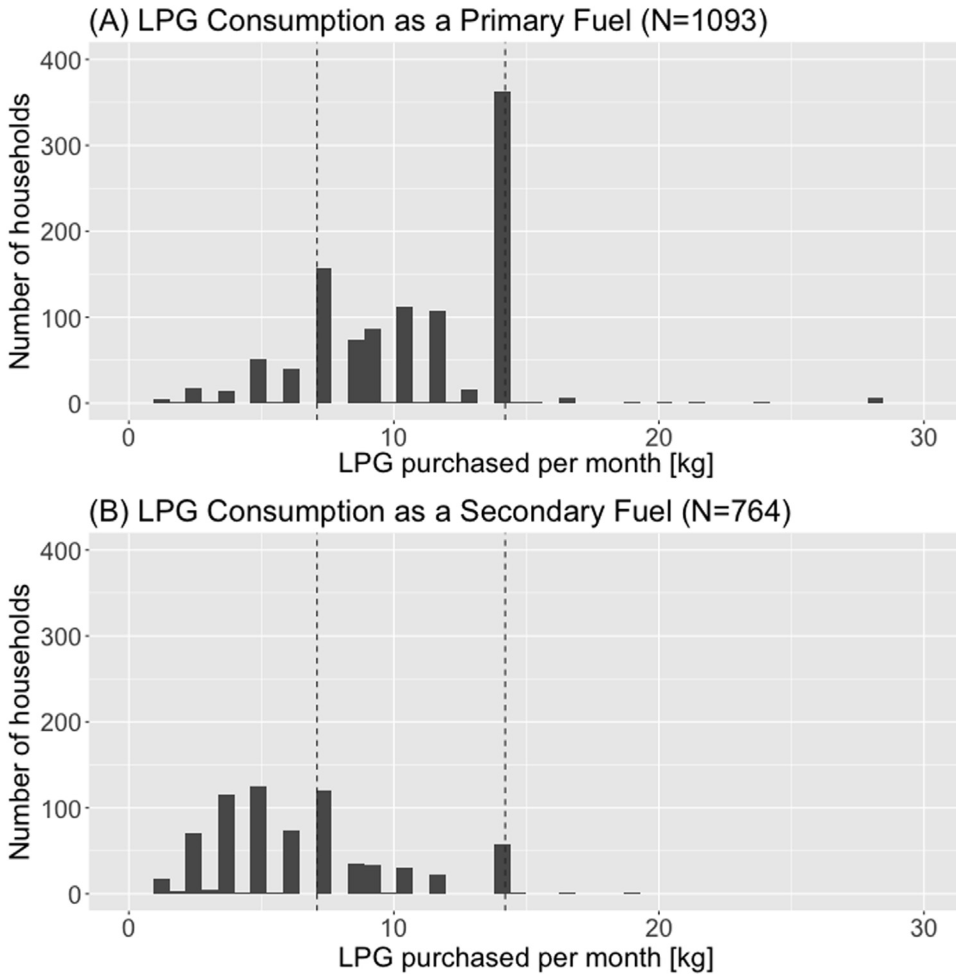

Fig. 3. Distribution of self-reported LPG purchase in kilograms among households (A) where LPG is a primary fuel compared to (B) households where LPG is a secondary fuel. Marks are made at 1 and 0.5 large 14.2 kg cylinders per month (ACCESS, 2014–2015).

41% of LPG-owning households.

The majority of households utilizing LPG as the primary cooking fuel report purchasing one 14.2 kg cylinder per month (Fig. 3). When LPG is a secondary fuel, households report purchasing a large cylinder once every two or three months, with some still using one cylinder a month. Although two sizes of LPG cylinders are offered (14.2 kg and 5 kg), the larger size accounts for the vast majority of purchases among primary LPG users (0.99) and among secondary LPG users (0.96). In addition, by total kilograms purchased, the vast majority of LPG comes from authorized distributors as compared to the market for both primary LPG users (0.97) and secondary LPG users (0.94). Relatively few households can get their gas delivered directly to their household (0.18).

Next, this study turns to the end uses of LPG in cooking. Fig. 4 shows the proportion of LPG-owning homes cooking specific dishes; impressively, more than two-thirds of homes used LPG to cook each dish. Although cooking chapatis—a staple of Indian cooking in almost every meal—on LPG has been reportedly low in other samples because of bad taste or the need for direct flame, they were cooked on LPG by 68% of LPG-owning households in this sample (Wang, 2014; Joon et al., 2009). Use of LPG for tea and snacks was also high, which follows other reported literature where small tasks are regularly cooked with LPG because they are especially facilitated by a quick lighting period and controllable flame. These patterns demonstrate that LPG can be used to cook a variety of core Indian dishes, including chapatis, vegetables, and rice, and not only little meals.

Specific dishes cooked in LPG-owning homes are further investigated by primary LPG users and households where LPG is a secondary stove in Fig. 5. Dish cooking was very high (about 0.90) for primary LPG users but much lower for secondary LPG users (about 0.40), with the exception of tea and snacks which stayed at the same proportion in both user groups (0.92). Here, the results are clear: primary LPG households cook nearly all dishes with LPG and secondary LPG households are more selective about which dishes they cook. It is important to recall that even the vast majority of primary LPG households rely on solid fuels in some capacity (only 4% are exclusive LPG users). Despite the high rate of LPG used to cook these core Indian dishes, fuel stacking suggests that solid fuels are being used either for other end points (e.g., heating, other dishes) or in parallel with LPG stoves during the same meals. Among secondary LPG households, more than half report not cooking chapatis or rice with LPG ever, relying heavily on solid fuels like firewood and dung for these dishes. Patterns of dishes cooked described remain consistent across households that have had LPG for less than 1 year and those that have had it for longer (Supplemental Information Figure A5).

This study next shows patterns of LPG use for different purposes among households with an LPG stove. Fig. 6 is a correlation plot that shows the relationship between dishes cooked with LPG. Chapatis, vegetables, and rice are well correlated (bivariate Pearson's Rs around 0.55). These three dishes are items that some households prepare consistently, perhaps because they typically go together for regular meals. The other items, however, are only weakly correlated with each other, suggesting that households use LPG to prepare them in a less systematic manner. Perhaps most importantly, tea and snacks as a

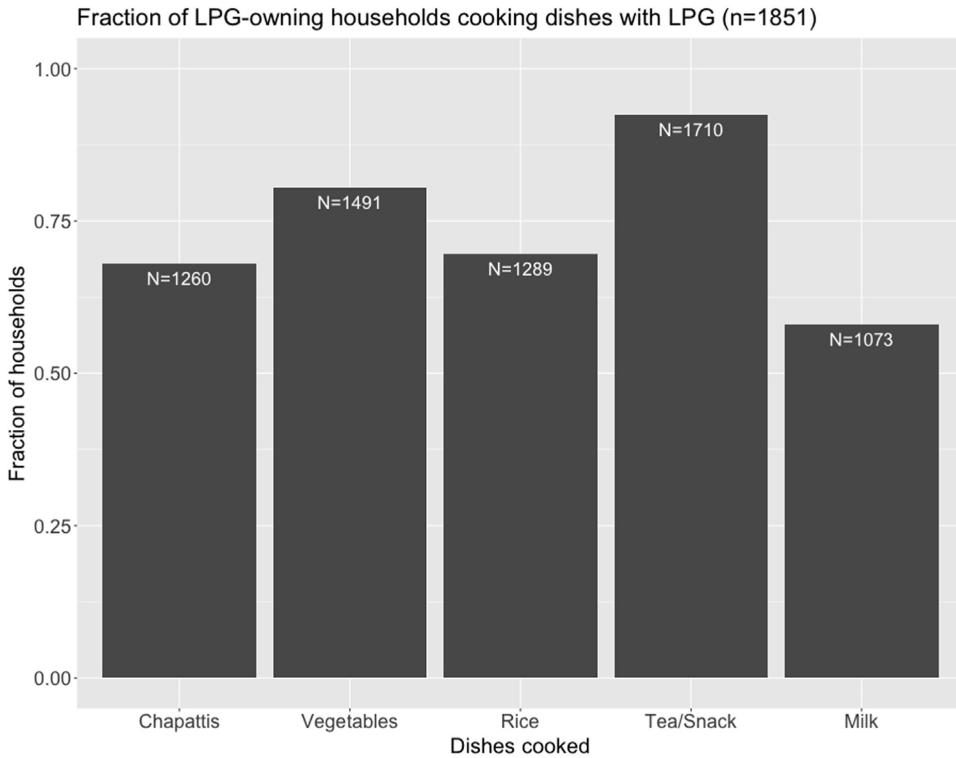

Fig. 4. Barplot showing the fraction of LPG-owning homes cooking specific dishes (ACCESS, 2014–2015).

category is not at all correlated with other dishes—almost all households choose to prepare tea and snacks with LPG, but use for other dishes is much less frequent.

Fig. 7 shows the correlations between specific LPG use to cook dishes separated by primary and secondary LPG households. In households where LPG is the primary fuel all dishes are well correlated because use is high across all dishes. In households where LPG is a secondary fuel, only chapatis, vegetables, and rice are well correlated. This correlation plot, along with the prevalence of dishes cooked, suggest a use pattern whereby secondary LPG users either cook these three dishes or largely rely on LPG only to cook tea and snacks.

Together, these results describe LPG use in rural Indian households at several levels: fuel use types (primary and secondary usage of clean and solid fuels), kilograms of LPG purchased, and LPG use for core dishes. Used in 22% of all study households, LPG was a primary fuel in only about 60% of LPG-owning households and an exclusive fuel in less than 5%. LPG is used to cook a wide variety of dishes, including chapatis. However, use patterns sharply divide between primary LPG and secondary LPG households. While more than 85% of primary LPG households report cooking each dish, the majority of secondary LPG households did not cook each dish, with the exception of tea/snacks and vegetables. Correlations between dishes cooked among secondary LPG households show a subset that do cook the set of core dishes: chapatis, vegetables, and rice. These results suggest that LPG, because it is widely used to cook all important daily dishes, has the potential for significant use in households. Limited LPG use, notable in secondary LPG households and the near absence of exclusive LPG users, suggests that there remain significant barriers to greater LPG use and motivations for continued solid fuel use. Next, this study describes reported positive and negative perceptions of each main cooking fuel and LPG to contextualize our findings of cooking fuel use patterns and investigate potential motivators for continued solid fuel use and the limitations of LPG.

4.3. Fuel perceptions

Participants' perceptions of their own main cooking fuel (firewood, dung, and LPG) are shown in Fig. 8. Households cooking primarily with LPG are much more satisfied with their main cooking arrangement than those cooking primarily with solid fuels. Inclusive, even households using firewood or dung as their primary fuel widely perceive LPG to be better for their health and more convenient for cooking. Furthermore, LPG-using households have higher reported satisfaction with their fuel availability as compared to firewood- and dung-using households. Overall dissatisfaction is very low among primary LPG households. Although these are the most relied on cooking fuels, solid fuel users noted several significant drawbacks: excessive smoke (about 0.95), too time consuming (about 0.85), too difficult (about 0.55), and that their cookstove was impacting their health (about 0.80). Primary LPG users did regularly note its high cost (0.58), a perception of danger (0.62), and that it was harming their health (0.35).

LPG owners received a second set of more specific questions related to their perceptions of the fuel. Fig. 9 shows the distribution of these LPG-specific perceptions among households using it as a primary fuel as compared to those households for whom it is a secondary option. Satisfaction is high across both user groups, though, as expected, slightly higher in primary LPG households. Dissatisfaction is significantly higher among households using LPG as a secondary fuel, though LPG is still heavily preferred over firewood for convenience and health. Cost and availability are the primary reasons cited by households dissatisfied with their LPG situation. Notably, three-quarters of secondary LPG households cite cost as a reason for dissatisfaction while cost is cited by only slightly more than half of primary LPG users. Secondary LPG households report a monthly expenditure of 5019 INR, which means that a 15 kg cylinder (at 460 INR) is nearly 10% of the household's total monthly expenditures. Perahps as a result, many secondary LPG households limit their use to make one 15 kg cylinder last two months or purchase one 5 kg each month (230 INR). Still, for primary LPG households with an average monthly expenditure of 7237 INR, a 15 kg cylinder is 6% of their monthly spending.

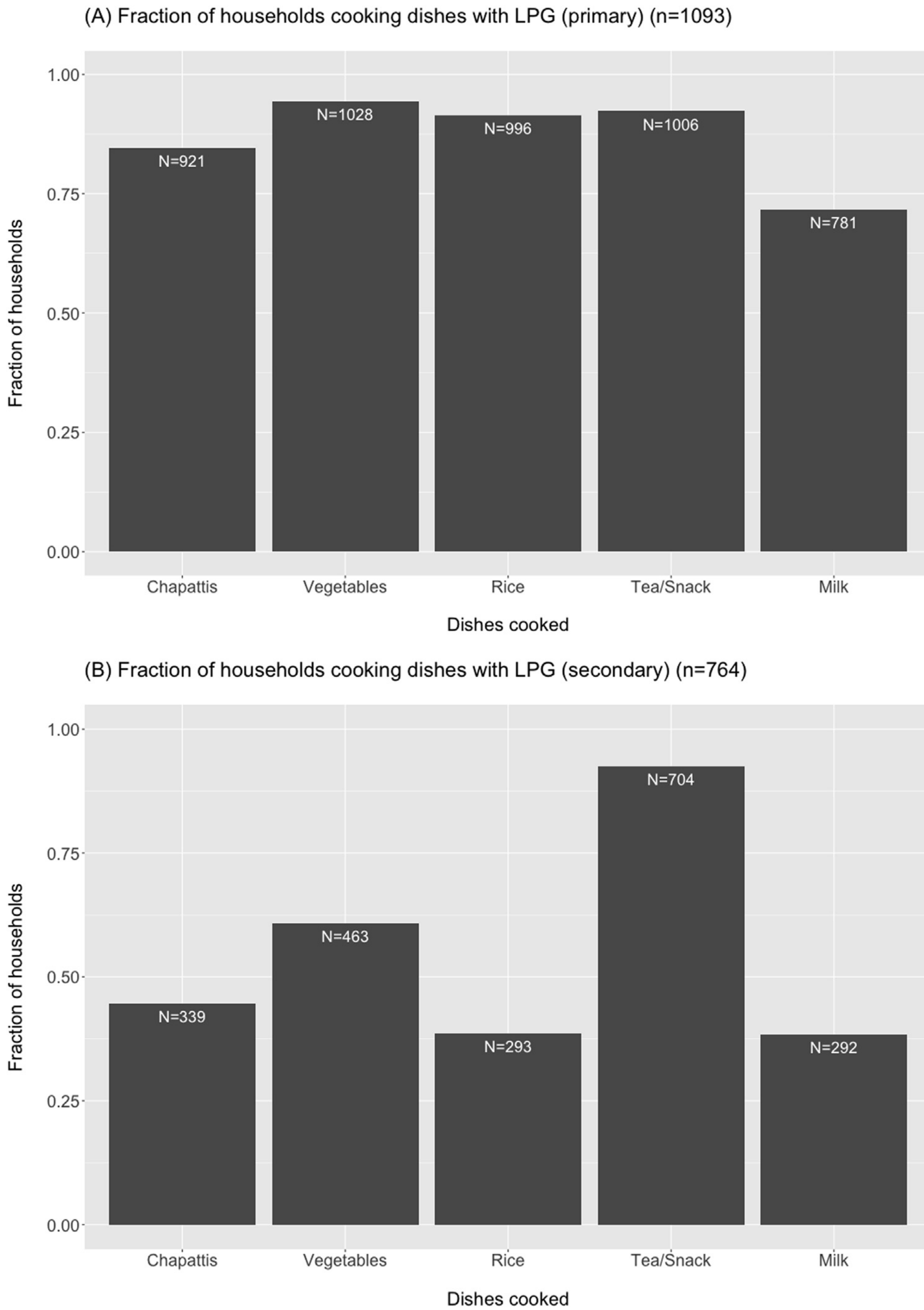

Fig. 5. Barplot showing the percent of dishes cooked in (A) households where LPG is the primary stove and also (B) homes where LPG is the secondary stove (ACCESS, 2014–2015).

Access to fuel, an issue for all LPG owners, is divided in two questions: (i) poor LPG availability is a large factor for both primary (0.82) and secondary LPG households (0.77) and, even more pervasive, (ii) travel distance required to acquire LPG is very problematic for primary (0.91) and secondary LPG (0.87) households. Travel distance required of households to acquire LPG does not vary between primary and secondary LPG households; both on average must travel 8.5 km and more than half of households must travel more than 5 km (see Supplemental Information Figure A6).

5. Conclusion

This study has described the contours of LPG adoption, use, and impact in rural India. Using data from the 2014–2015 ACCESS survey with over 8500 households from six large Indian states, this study reaches beyond counting LPG connections and offers a panoramic view of the different aspects of LPG as a clean cooking fuel. Both the cost of an LPG connection and the cost of LPG fuel are important obstacles to the adoption of this clean cooking fuel. Still, even non-LPG users tend to have overwhelmingly positive perceptions of the fuel. At the same time, and likely related to fuel costs, continued firewood use remains common among LPG-using households. Only about 60% of LPG-using households consider it their primary cooking fuel, and even they do not cook all of their food with LPG. Firewood remains a pervasive feature of the cooking realities of rural India. Solid fuel combustion for cooking—even as a secondary cooking option—is likely to lead to substantial increased risk for HAP-related diseases. Furthermore, solid fuel use in densely-populated communities can lead to high community

Fig. 6. Correlation between dishes cooked using LPG among all LPG-owning households (N = 1854) (ACCESS, 2014–2015).

ambient air pollution, limiting potential reductions in personal exposure to air pollution even in households with very low solid fuel combustion. Together, these factors suggest that the potential health benefits of India's massive clean cooking fuel transition may be limited without directly addressing the continued use of firewood as an important source of household energy.

Importantly, the results from this study are based on well-established cooking and decision-making patterns, as most households have in the sample have been cooking with LPG for several years (median = 3 years). This level of granular cooking and fuel stacking detail is rare outside of an intervention context, which rely on still-forming post-adoption cooking patterns and are subject to respondent biases. Furthermore, observed fuel use and cooking patterns do not significantly change when comparing households owning stoves for one year or less compared to those owning LPG stoves for longer.

This study makes important contributions to the understanding of clean cooking fuel transitions by triangulating core findings from diverse and distinct measures of household cooking patterns and motivations for observed patterns. The integration of clean cooking fuels into households relying on solid fuels for cooking is a process with several steps. As the first step in this process, adoption has understandably received substantial effort in the household energy community—both in terms of research and policy efforts. Sustained use has grown in importance recently and, indeed, research shows that clean cooking fuels must be elevated to a household's primary cooking fuel to obtain benefits. This study shows that this process is itself a challenge for many households, as 40% of LPG-owning study households considered a solid fuel their primary cooking fuel and use LPG only for small tasks like tea and snacks. Households for whom LPG is the primary cooking fuel are highly satisfied with their cooking arrangement; nonetheless, they continue using other fuels for their cooking, especially firewood. An additional step is needed, then, after adoption and sustained use a primary fuel: the reduction of polluting solid fuels—this third step crucial to reducing exposure to air pollution has so far been rare. This study shows that the difficult task of shifting household energy mixes away from solid fuel combustion may be the next crucial step for the Government of India to improve population health from clean energy.

These findings have two major implications for India's energy access policy. On the one hand, LPG clearly is a desirable fuel that rural households find convenient and healthy. To promote adoption, the primary challenge for the Indian central and state governments is to find ways to make LPG use more affordable. For many households, the *Ujjwala* scheme already solves the problem by providing free connections, but the cost of the LPG fuel remains an obstacle. Furthermore, clean fuel accessibility is an important constraint throughout India and much of the world. However, the Indian government and Oil Marketing Companies have made tremendous efforts to deepen LPG availability throughout the country; 5300 new distributors have been commissioned since 2014 and a reported 6400 more are still to come (Dakwale, 2018). Since the Indian state has deemed the widespread use of LPG fuel an essential social goal and a policy priority, subsidizing the use of LPG fuel for poor rural households more generously may be an important policy measure. Here, India may note lessons from countries that have employed substantial long-term LPG subsidies. LPG has had a strong presence in Brazil for more than five decades, with households transitioning from solid fuels and kerosene to LPG during the 1960s and 1970s facilitated by government subsidies (Lucon et al., 2004). Now, 98% of Brazilian households cook with LPG, and the majority have done so for three decades. At the same time, more than 60% of rural households continue to use firewood and charcoal as supplemental fuels (Instituto Brasileiro de Geografia e Estatisticas, 2011). A similar story can be told about Ecuador where LPG has been subsidized to approximately 10% of the market price since the 1970s but some evidence suggests despite 90% of the country using LPG as their primary cooking fuel there may be prevalent secondary firewood use, at least in the Andean region (Gould et al., 2018). Furthermore, the situation of Ecuador illustrates how large universal LPG subsidies may result in substantial government fiscal burdens; in response to annual government expenditures of between 300 and 700 million USD, Ecuador has begun the promotion of induction stoves to alleviate the fiscal burden of the LPG subsidy and utilize the country's growing hydroelectric capacity. In addition, there is emerging evidence of similar firewood stacking patterns occurring in LPG-adopting households in Peru (Pollard et al., 2018). The lesson here is clear: fuel stacking remains a

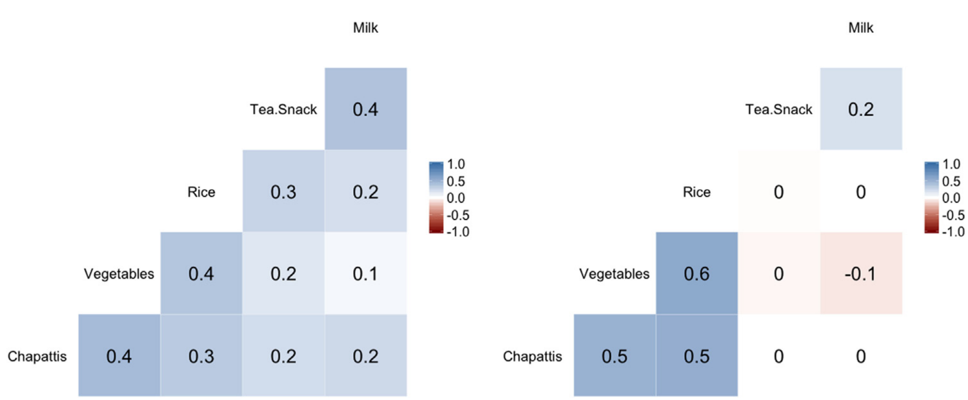

Fig. 7. Correlation between dishes cooked using LPG among households where LPG is the primary fuel *left* (N = 1093) and where LPG is the secondary fuel *right* (N = 764) (ACCESS, 2014–2015).

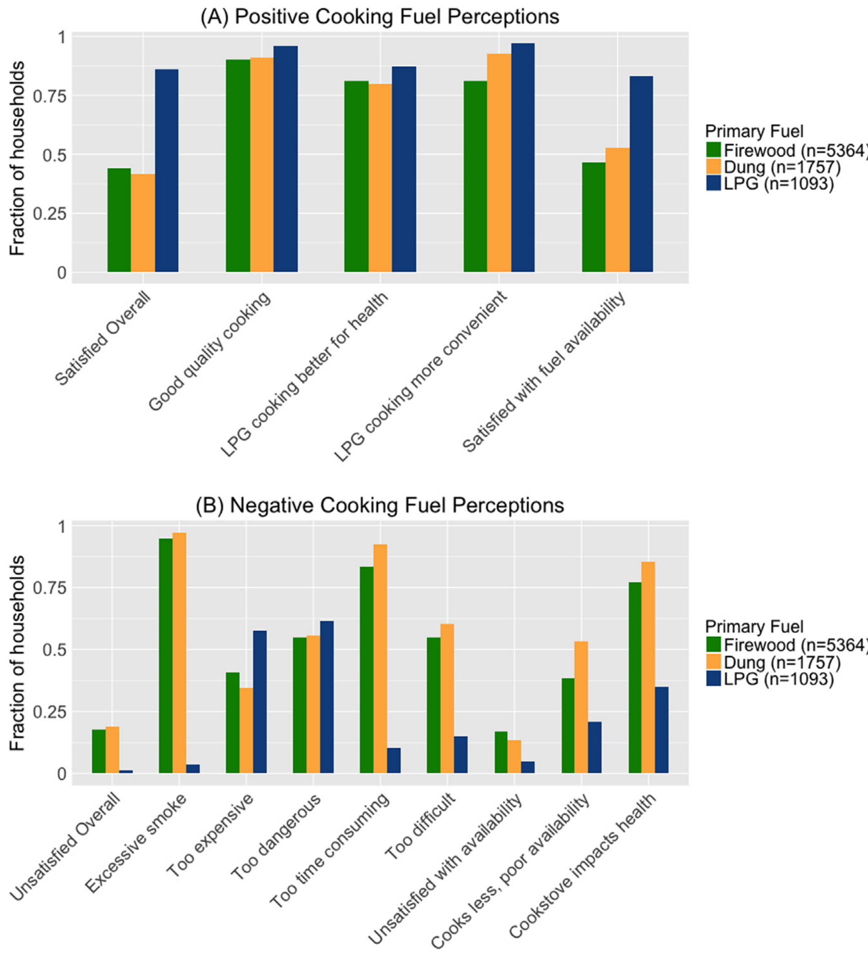

Fig. 8. Barplots showing fraction of households with specific (A) positive and (B) negative perceptions of their primary fuels (ACCESS, 2014–2015).

challenge even after LPG access is improved. Furthermore, although large cooking fuel subsidies may effectively facilitate national transitions to clean cooking fuels, continued solid fuel use is probable.

Household cooking fuel choice is a complex process circumscribed by numerous social, demographic, and environmental contexts and bound by resource constraints. There have been several studies positing conceptual frameworks for household cooking fuel decision-making (Kar and Zerriffi, 2018; Wilson and Dowlatabadi, 2007; Kowsari and Zerriffi, 2011; Van der Kroon et al., 2014); in short, mechanisms for prioritizing the multiple dimensions and determinants of fuel choices and transitions are still not evident. Nonetheless, it is increasingly clear that the multiple actors involved in household energy transitions (e.g., primary cooks, chief wage earners, other household members, community leaders) and the multiple dimensions of fuel choice (e.g., cost,

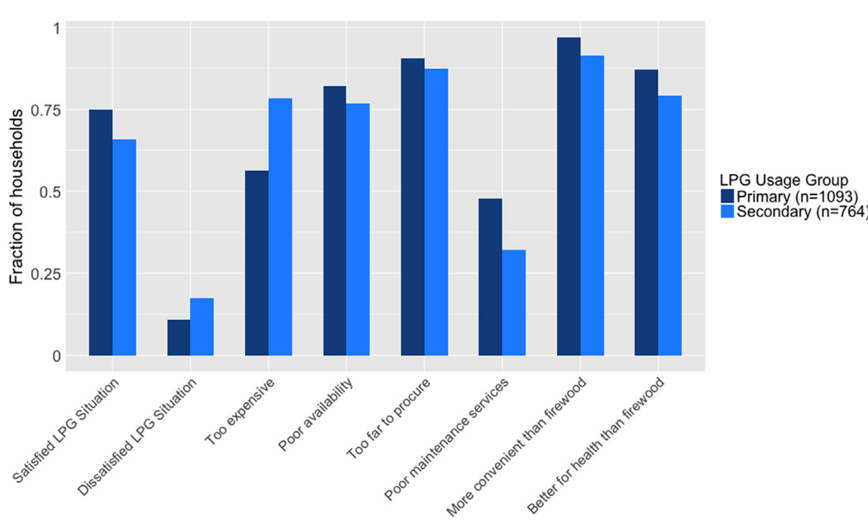

Fig. 9. Perceptions of LPG in households using LPG as a primary fuel compared to households using LPG as a secondary fuel (ACCESS, 2014–2015). Only households reporting to be disatisfied with LPG situation contribute to data of reasons for disatisfaction.

availability, ease of cooking, familiarity, taste of food, heating benefit) will have to be engaged to affect a stable, long-term, and large-scale transition from solid fuels to clean cooking fuels. This study shows that even after a popular clean cooking fuel is adopted and regularly used in a household, the benefits of solid fuels remain an important motivation for their continued use. These benefits depend on the region of focus, and merit further discussion and investigation elsewhere, but may range from space heating, the ability to cook large dishes for families or for animal feed, cost-free availability, and safe-guarding against other fuel shortages. Therefore, fuel stacking is acknowledged as the norm and a result of rational decision-making given the realities of household choices.

At the same time, the public health benefits of partial LPG use remain unclear. Current evidence emphasizes the exclusive use of clean fuels and full replacement of traditional polluting solid fuels (Sambandam et al., 2015; Pope et al., 2017). As long as households continue to stack LPG with solid fuels, the full health benefits in terms of reduced household air pollution are not obtained. Therefore, work remains to be done to understand the nature of cooking fuel decision-making beyond "primary or secondary" fuel use patterns. This study responds to this inquiry by evaluating in a detailed manner the nature of household energy transitions. While this study's discussion of specific household meals is tailored to rural north Indian households, these methods of discussing *how* cooking transitions take place in kitchens have broader applicability in other contexts (Kar and Zerriffi, 2018). A further step is use large-scale field-based measurements in LPG-adopting households of India to characterize cooking patterns and their implications for personal exposure to air pollution.

Results from this study suggest that clean cooking programs—in India and around the world—may need more holistic approaches to reducing exposure to air pollution, including explicit plans to reduce the use of solid fuels in households. Our multi-dimensional approach shows that simply promoting LPG adoption (e.g., *Ujjwala*), or even partial use, is not enough to deal with the problem of fuel stacking. As households make rational choices regarding their cooking systems the household energy community must acknowledge the difficulty of the complete replacement of solid fuels. Here the critical issue is to find technologies and policies that are appropriate to reduce the presence of solid fuels across the spectrum of energy needs. Specifically, this includes the preparation of large meals that are energy intensive and may require several simultaneous dishes cooking and addressing demand for heating—an advantage of solid fuels not easily replicated with clean cooking fuels. Potential policies include cooking fuel subsidies, improved delivery systems that provide frequent and consistent access to clean fuels like LPG, new clean energy cooking technologies and appliances tailored to specific end uses (e.g., rice cookers, hot water kettles) and geographies (e.g., efficient clean energy heaters, solar cookers), awareness campaigns, incentives for reducing solid fuel use, and other measures to promote use of LPG and reduce solid fuel consumption. In certain scenarios, efforts to reduce exposure to air pollution may rely on high-performing improved biomass-burning stoves as an interim step towards clean cooking fuels, including promising options like forced-draft and pellet-based gassifier stoves currently promoted in Rwanda and Malawi (Wathore et al., 2017; Jagger and Das, 2018).

For researchers, our findings open new avenues of study. This study leverages cross-sectional surveys to understand cooking patterns, and future research should conduct similar holistic studies in broader geographies, including other parts of India. Smart policy design may next benefit from randomized controlled trials testing potential policy or technology interventions. Customer-centric studies focusing on the user experience may also generate new insights into how rural households make decisions about clean cooking fuels. The broader point of our study is that the problem of clean cooking fuels, including LPG, is multi-dimensional. Adoption, use, and impact are all inter-related. Households adopt LPG anticipating certain use patterns as a function of fuel access and costs, and use patterns in turn shape impact. Research and practice should focus on developing a comprehensive understanding of the situations that circumscribe clean cooking fuel use and the continued presence of solid fuels in household energy mixes, and then develop policies accordingly.

Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2018.07.042. Replication data and code for this publication is available online at https://doi.org/10.7910/DVN/EVM78E (Gould and Urpelainen, 2018).

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