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Using high-frequency household surveys to describe energy use in rural North India during the COVID-19 pandemic

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COVID-19 continues to exact a substantial toll on health. While mortality and morbidity associated with the pandemic are the most obvious impacts, social and economic disruptions are becoming apparent. There is reason to believe that the COVID-19 pandemic has slowed or reversed gains in clean household energy use in rural India. Here we describe phone surveys deployed repeatedly in Jharkhand and Bihar to describe pandemic-related changes in household socio-economic conditions and energy-use patterns. Over three-quarters of households reported hardships during the pandemic, including loss of employment and an inability to search for jobs. In turn, some of these households relied more on polluting fuels. Despite nearly all households preferring gas and electricity, we observed varied behaviours related to the cost of and access to these modern energy sources. We highlight the success of India's three-free-cylinders scheme, with 90% of households aware of the programme and utilizing at least one free cylinder. These findings illustrate the utility of high-frequency energy-related questionnaires and suggest that interventions to improve clean fuel accessibility and affordability can increase the resilience of transitions to clean household energy.

The toll of COVID-19 on human health is undeniable with over 410 million cases and 5.8 million deaths globally as of 15 February 2022[1]. Furthermore, the pandemic and associated lockdowns have caused widespread economic hardship and financial difficulties, especially in low- and middle-income countries, where household savings may be small or non-existent, involvement in informal employment is widespread and social safety nets may be weak[2–4]. Changes in household energy-use patterns due to the pandemic—and reversion to unclean fuel use for cooking and heating—have been documented[5–8]. Less well described is the impact of the pandemic on household energy in countries where clean fuel use is tenuous and where biomass fuels are dominant, available and perceived as free. Understanding such shocks—such as pandemics and economic downturns, among others—can help understand the stability of household energy transitions and the ways in which clean-energy use may or may not be prioritized at the household level.

India has made remarkable progress, through large-scale government policies, towards universal electrification (the *Saubhagya* scheme, announced in 2017) and clean-cooking access (*Pradhan Mantri Ujjwala Yojana*[9] (PMUY), announced in 2016). As of 2020, more than

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95% of households are connected to grid electricity and have access to a clean-burning cooking fuel (namely liquefied petroleum gas, or LPG)[10]. While these recent advances suggest improved health through lower household air pollution[11,12] and the potential for broad social welfare benefits, they are contingent on the consistent use of clean fuels (electricity, LPG) in such a way that the use of polluting fuels (kerosene, biomass) is nearly eliminated. However, the COVID-19 pandemic has heavily impacted India, with an estimated death count of roughly 3 million (ref. [13]) and intermittent, widespread economic shutdowns. The extent to which the pandemic and related socio-economic shocks has halted or even reversed clean household energy use remains unknown.

During the pandemic, the government of India established a three-free-cylinders scheme that targeted households that received their LPG stove via PMUY. These households were eligible to receive three free LPG cylinder refills between 1 April 2020 and 30 June 2020, though the scheme was eventually extended until 30 September 2020[14]. The scheme was part of a broader effort to assist poor communities known as *Pradhan Mantri Garib Kalyan Yojana*[15] (roughly translated as prime minister's welfare scheme for the poor).

To describe the changes to household energy use associated with COVID-19 and related policy measures, we deployed two distinct and panel phone surveys. One survey was administered to 600 households in the state of Jharkhand approximately once every two months for one year, and one was administered to 200 households in the state of Bihar approximately every week for two months. Three-quarters of households surveyed reported experiencing pandemic-related changes in household economic conditions, such as loss of employment opportunities. In turn, households that reported experiencing such pandemic-related changes had higher odds of using polluting cooking fuels. While gas and electricity were nearly universally preferred, we document substantial short-term variations in the use of household fuel mixes, primarily owing to the cost and accessibility of these modern energy sources. In addition, we observed that 90% of households were aware and took advantage of the three-free-cylinders scheme, indicating that the programme potentially provided several weeks of clean cooking for many. Secondarily, we sought to assess the utility of more frequent, phone-based surveying to capture nuances in household energy use missed by standard, infrequent surveying (as during a census). Our findings point towards the usefulness of repeated phone surveys of differing frequencies to uncover how household energy-use choices change over relatively short periods of time and in response to changing socio-economic and market conditions.

Study design

Surveys were conducted by local enumerators and were designed to be relatively rapid—between 10 and 15 minutes (Jharkhand) and 5 and 10 minutes (Bihar). Our survey questions focused on household lighting and cooking, the costs and accessibility of modern fuels and the reasons that households reported using fuels as they did over the course of the pandemic. We describe findings from each survey separately.

The Jharkhand survey was administered six times between July 2020 and July 2021 to a panel of 882 rural households. We began by drawing from a statistically representative sample of 1,440 rural households previously surveyed in July–August 2019 (Methods). In each round, 600 of the 882 households were surveyed; 261 households were surveyed in all six rounds, 310 were surveyed four or five times and 107 were surveyed once (Supplementary Fig. 1). Household heads were predominately men (86%), roughly half were literate (58%) and 39% had no formal education (Supplementary Tables 2 and 3). More than half of households did not belong to the general caste, and 45% had Below Poverty Line ration cards. At baseline, 85% of households were grid electrified, and an additional 2% had access to electricity from a micro-grid or a solar home system; still, 24% used kerosene lamps as their primary lighting source. Two-thirds of participants reported mixed use (also known as stacking) of a polluting cooking fuel with LPG, and one-third reported exclusively using polluting fuels; exclusive LPG use was nearly non-existent (<1%). Between the baseline survey in 2019 and the COVID surveys described here, one-third of households without LPG had acquired it. The survey in Jharkhand additionally evaluated economic hardships encountered during the pandemic.

For the second survey, we recruited 450 households from eight districts across Bihar that were selected at random from a pool of 38,000 phone numbers registered to individuals living in the state and maintained by Morsel Research and Development Private Limited (based in Uttar Pradesh, India). Participants were primary cooks over 18 years of age who reported use of both biomass and clean fuels for cooking in the week preceding the baseline survey administered in January 2021. After completing the baseline survey, 203 participants were randomly selected and were called once per week for eight weeks. At baseline, 16% of household heads had no formal education, and two-thirds had received a secondary education or greater (Supplementary Table 4). One-quarter of participants belonged to the general caste; nearly 60% belonged to the so-called 'Other Backward Class'. Three-quarters of participants reported that LPG was their main cooking fuel. Primary cooks were almost all female (99.5%, $n = 1$ male).

In both study areas, fuel refills were obtained through an LPG cylinder-recirculation model, as is the norm in India. Households either call or visit their local LPG distributor to request a refill. When households purchased refills, they paid the full market/international price (that is, approximately 960 INR or US$12.84 for a 14.2 kg cylinder in January 2022). A subsidy was deposited in the consumer's bank account some time later. In addition to understanding energy-use behaviours during COVID-19, we sought to characterize how refill and subsidy deposit times varied during the pandemic.

Figure 1 diagrams the overall timing and design of the study, including overlap with COVID-19 case numbers, LPG cylinder refill prices and government policies addressing the pandemic (Fig. 1b–d). The first round of surveys in Jharkhand coincided with the initial pandemic wave, while the fourth and fifth rounds coincided with the 'Delta' variant wave. Lockdown orders have been in place at various points during the pandemic, at differing levels of stringency, though for the most part, individuals were instructed to limit outdoor activities and businesses were suspended except for essential services, which included the LPG-distribution system.

Pandemic socio-economic hardship and energy use in Jharkhand

Two-thirds of households in Jharkhand reported experiencing pandemic-related economic hardship, including increased prices or difficulty acquiring household goods, losses in employment or reduced job opportunities and reduced income at some point during the study period. Distinct pandemic waves were visible in the variations in reported economic hardship across the study period, peaking during survey rounds 1 (first COVID wave in India) and 4 and 5 (rise of the Delta variant) (Fig. 2a and Supplementary Table 5).

In concert with these socio-economic outcomes, households also reported increased LPG cylinder refill prices and difficulty in acquiring refills as compared with before the pandemic (Fig. 2b, Supplementary Table 6 and Supplementary Table 7). Almost all participants reported higher LPG cylinder refill prices, one-half reported increased wait times to receive their LPG cylinder subsidy and one-third reported increased difficulty acquiring a cylinder refill during round 4 as compared with before the pandemic. At baseline, one-quarter of households had LPG cylinder refills delivered to their doorstep; the remainder travelled a median distance of 5 km to pick up cylinder refills. Across rounds, between 26% and 41% of all respondents had their LPG cylinder refills delivered and most of the remainder travelled to an LPG distributor to get their refills (32% to 61%).

Three-quarters of households at baseline reported collecting firewood as opposed to purchasing. Each round, between 50% and

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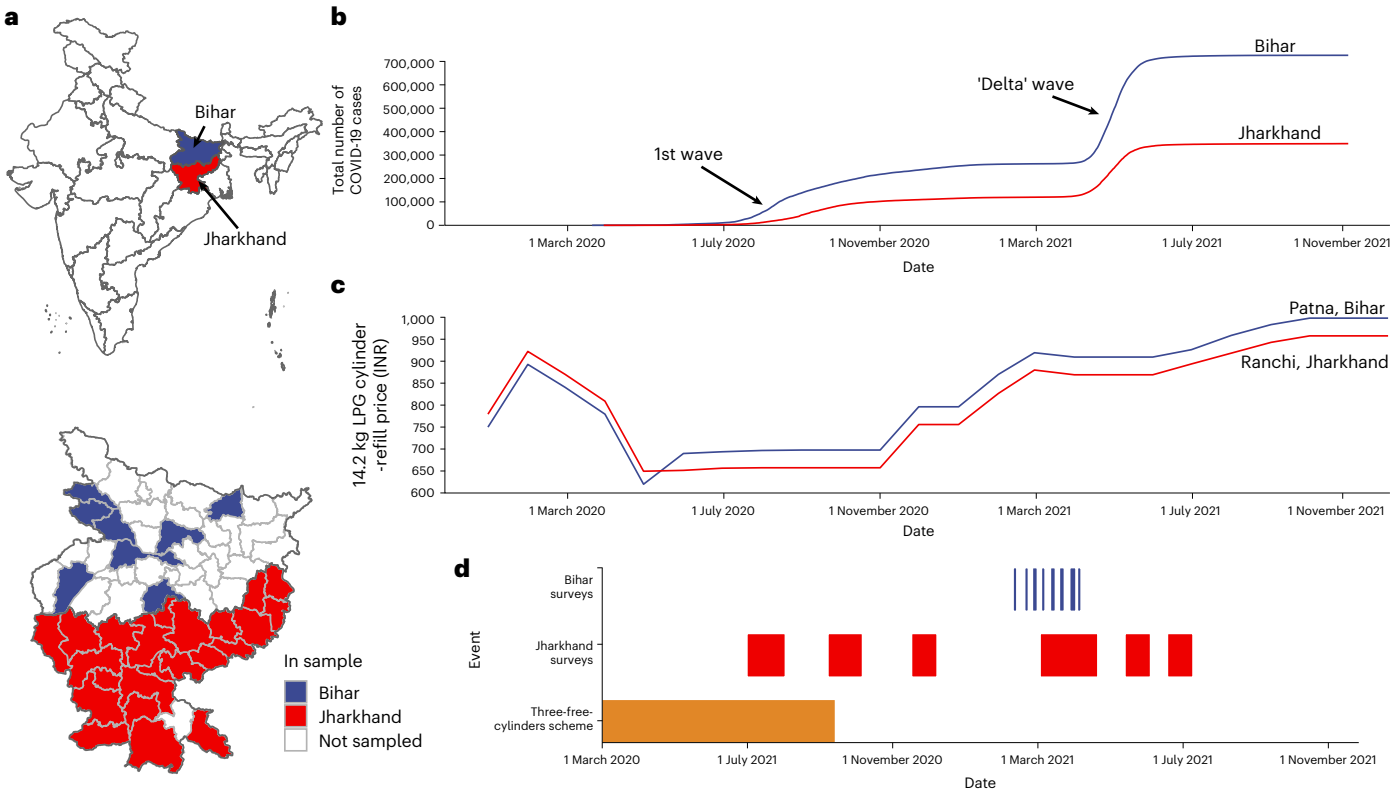

Fig. 1 | Study sites and timing of surveys in relation to COVID-19 cases, LPG cylinder refill prices and the government of India's three-free-cylinders scheme. a, Illustration of states and districts sampled. **b**, Total COVID-19 cases over time (from the Development Data Lab, https://github.com/devdatalab/covid). **c**, Prices of 14.2 kg LPG cylinder refills in the capital cities of Bihar and Jharkhand (data from https://www.goodreturns.in/lpg-price-in-patna.html and https://www.goodreturns.in/lpg-price-in-ranchi.html). **d**, The timing of the eight survey rounds in Bihar, the six rounds of Jharkhand surveys and the government of India's three-free-cylinders scheme. Specific dates for survey rounds are shown in Supplementary Table 1.

80% of households reported that their biomass-collection patterns had not changed in terms of the amount they collected per trip, the frequency of collection trips or the difficulty of collecting firewood, though some increases and decreases in all categories were reported (Supplementary Table 8).

Most households reported using similar lighting sources as before the pandemic, though there were some deviations. Grid electricity was the primary source of lighting for 74% of households at baseline in June and August 2019; still, 86% reported also using kerosene lamps. Across survey rounds, approximately 90% of households relied primarily on grid electricity for lighting. As was the case during baseline, many households also reported use of kerosene (~50%), though we note the fraction of households using kerosene decreased during later survey rounds (Supplementary Table 9 and Supplementary Fig. 2). Households reported using more than one fuel—commonly grid electricity and kerosene—to meet their lighting needs in 81% of observations (Supplementary Table 9 and Supplementary Fig. 2). Three-quarters of households reported using kerosene lamps the same amount as compared with before the pandemic and, of the remaining respondents, a roughly equal proportion reported using kerosene lamps more (11%) and less (16%) than before the pandemic (Fig. 2c). Households that had kerosene lamps but did not use them in the preceding four days reported doing so because they had no fuel (47%), they were conserving their fuel (9%) or they were unable to buy fuel (10%) (Supplementary Table 10).

There were substantial changes in household cooking fuel-use patterns throughout the pandemic. Across the entire study, a large proportion of households reported using more- or less-polluting cooking fuels at different time points during the pandemic as compared with before it (Supplementary Table 9). For example, in survey round 1, three-quarters of participants reported using polluting cooking fuels as much or less than before the pandemic, while in survey round 4, one-half of households reported that they were using polluting fuels more than before the pandemic (Fig. 2c). Correspondingly, LPG use also rose and fell throughout the study period. In round 4, more than half of households said they were using LPG less than before the pandemic, an increase from the between one-fifth and one-third reporting to do so in rounds 1 through 3 (Supplementary Table 6).

Overall, we document the increased use of polluting household energy sources and reduced clean fuel use corresponding with reported socio-economic hardships and challenges surrounding the acquisition of LPG cylinder refills (Fig. 2d). As compared with a round without reported hardship, households that reported some form of socio-economic hardship had 1.5 times the odds of using kerosene for lighting (95% confidence interval (CI): 0.8–2.6), 2.5 times the odds of primarily using a polluting cooking fuel (95% CI: 1.4–4.3) and 2.9 times the odds of any use of polluting cooking fuels (95% CI: 1.5–5.5), including fixed effects for households and survey rounds. Associations between specific domains of socio-economic hardships were similar to the overall association, and results related to polluting cooking-fuel use were robust to the inclusion of LPG cylinder refill costs (Supplementary Fig. 3).

Households took advantage of programmes to alleviate financial hardship related to fuel purchasing—and were broadly aware of these programmes. At the time of the first survey round, 74% of respondents in Jharkhand knew of the government's three-free-cylinders scheme, with most learning of it from local gas agencies or distributors (50%), their neighbours (30%) or from television advertisements (15%); nine in ten of them had already availed themselves of at least one such free

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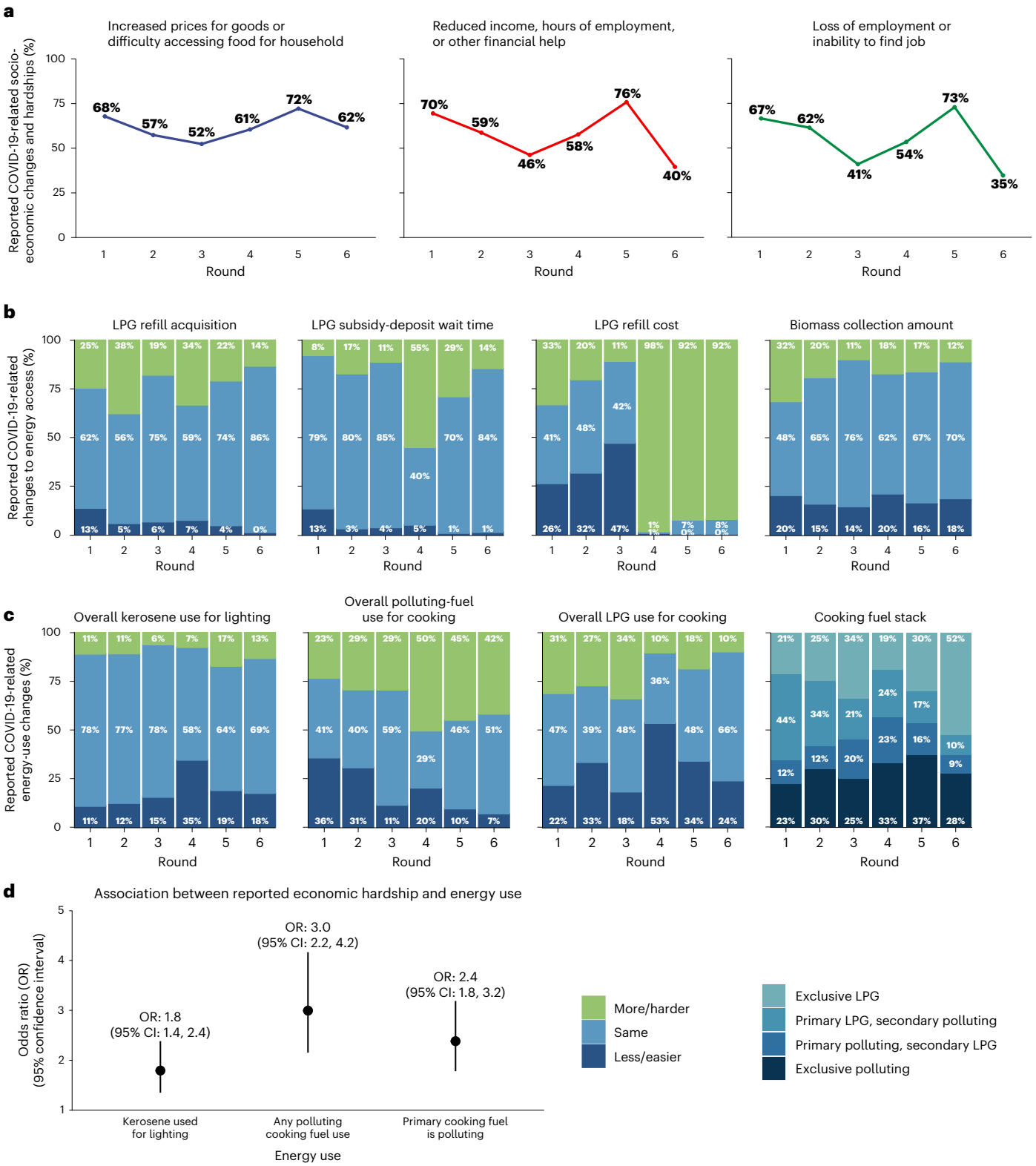

Fig. 2 | Reported COVID-19 related changes to household socio-economic conditions and energy use in Jharkhand, India. a, Round-by-round reported socio-economic changes and hardships by subgroup (Methods provide full description of variable construction). **b**, Round-by-round reported changes to household energy access. **c**, Round-by-round reported changes to household energy-use patterns. **d**, Associations between reported socio-economic hardships and key household energy-use outcomes (kerosene used for lighting, primary cooking fuel is polluting and any polluting cooking fuel used) from regressions carried out using the 'fixest' package in R that contains (1) a dummy variable for reporting to have experienced any socio-economic hardship in that round and (2) fixed effects for household and round, with standard errors clustered at the household level. The coefficient for the socio-economic hardship dummy variable was exponentiated to estimate the odds ratio and 95% confidence interval plotted in the panel. The sample sizes for these regressions were $n = 2{,}868$, $n = 2{,}761$ and $n = 2{,}499$, respectively.

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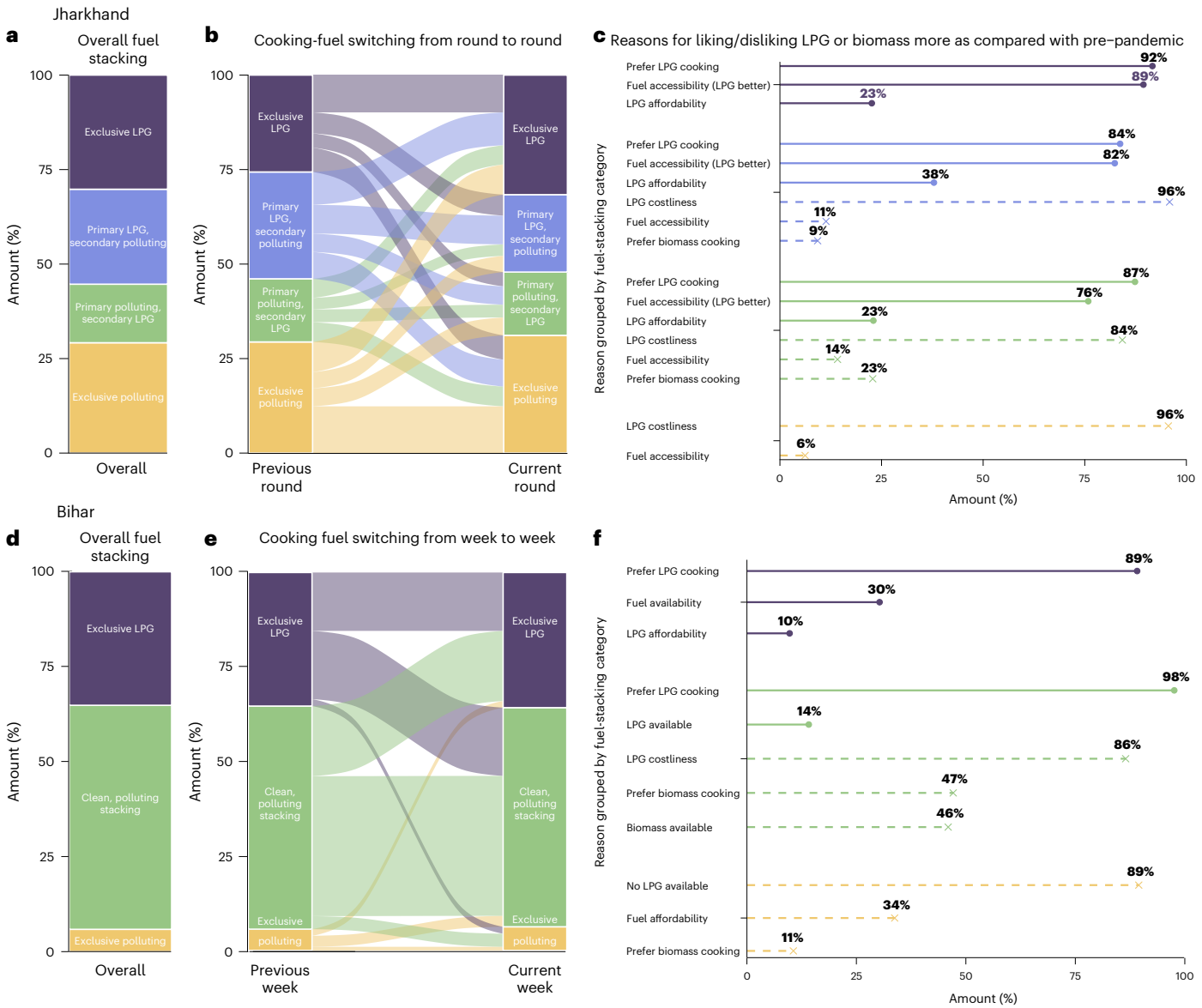

Fig. 3 | Prevalence of cooking-fuel stacking, round-to-round fuel switching and the motivations for reported fuel-stacking behaviours. a,**d**, 'Overall Fuel Stacking'—pool data from all survey rounds for the given sample and the overall distribution of reported fuel stacks for Jharkhand (**a**) and Bihar (**d**). **b**,**e**, 'Cooking fuel switching from round (week) to round (week)'—the distribution and flow of cooking-fuel stacks within households surveyed more than once for Jharkhand (**b**) and Bihar (**e**). Their 'previous' stacking category is shown on the left side, and the groups of participants that fall in the 'current' stacking category are shown to flow from the previous to the current stack categories. **c**,**f**, 'Reasons' describe the reasons that participants provided for either liking or disliking LPG or biomass more as compared with before the pandemic (Jharkhand sample; **c**) or using cooking fuels as reported (Bihar sample; **f**), grouped by the participants' reported fuel-stacking category at that time point. Reasons that are considered 'pro-LPG' or 'anti-biomass' are solid lines with filled-in dots as point estimates, and those that are 'anti-LPG' or 'pro-biomass' are dashed lines with 'x' as point estimates. Reasons were not prompted, were non-exclusive and participants could report more than one reason. Methods and Supplementary Table 15 provide more details on the survey questions that underlie the reported reasons for cooking-fuel use as reported in panels **c** and **f**.

refill. By the end of the full study period, more than 90% of respondents had been made aware of the programme and had obtained at least one free cylinder refill. Participants reported that obtaining these free refills was just as convenient as acquiring a typical refill, especially in later study rounds (Supplementary Table 11).

Week-to-week cooking-fuel stacking and switching in Bihar

Although all households in the Bihar sample reported stacking both biomass and clean fuels at baseline, exclusive LPG use in the preceding four days was reported in 35% of observations post-baseline (Fig. 3d). Exclusive biomass use was comparatively rare, occurring in 6% of observations. When both a clean and polluting biomass fuel were used, LPG was the primary fuel 83% of the time (Fig. 3d). Households switched their fuel-stacking category from one week to the next half the time, and nearly all (99%) households switched their fuel-stacking category at some point during the study period (Fig. 3e).

Regardless of fuel-stacking category, households reported cooking for a similar number of hours each day—an average of 3.5 hours (standard deviation, 1.0 hour)—and carrying out roughly the same tasks in the preceding four days (Supplementary Table 12). On average, participants reported using LPG more frequently than biomass, but

use of either occurred for an overall similar number of hours (~2 hours) each day. Participants almost always reported cooking rice, lentils, vegetables, roti and tea/snacks in the preceding four days (including when LPG was used exclusively). Fuel-stacking participants often reported using both LPG and biomass to cook all main dishes, though tea and snacks were often cooked only with LPG, and preparation of meat and fish, though uncommon, was frequently only with biomass (Supplementary Fig. 4).

Non-cooking tasks were rare in the study sample: heating water for bathing was reported in only around 5% of participant-week observations, cooking fodder for animals in 13% and space heating in 7% (Supplementary Fig. 4). Participants reported carrying out non-cooking tasks somewhat more often when also reporting that they used a biomass fuel at all (Supplementary Fig. 4). Non-cooking tasks were most frequently carried out using biomass fuels, though instances of LPG being used for heating bath water were observed (Supplementary Fig. 4).

Motivations for fuel stacking in Jharkhand and Bihar

Having characterized household energy-use patterns and the extent of cooking-fuel stacking and switching (visualized for Jharkhand in Fig. 3a,b), we now turn towards describing the motivations for these behaviours. In Jharkhand, we asked participants questions about their preferences related to all cooking fuels as compared with before the pandemic; these are displayed in Fig. 3c. Most participants reported that they liked cooking with LPG more during the pandemic as compared with before because it is easy, convenient, fast and clean (Supplementary Table 6). Participants also reported liking LPG because cylinder refills were more accessible than before the pandemic (Supplementary Table 6).

Participants that reported liking LPG less than before the pandemic overwhelmingly said this was due to the high costs of LPG cylinder refills, leading to reliance on biomass. Participants that had not used LPG in the preceding four days said they did not have sufficient gas and/or that they were conserving it in 96% of instances and almost never reported that it was for lack of interest in using LPG (1%), for fear of using it (1%) or because their stove was broken (1%) (Supplementary Table 10).

In Bihar, participants were asked more directly why they used cooking fuels in the way that they did (Fig. 3f). For example, participants that used only LPG were asked why they did not use biomass. In this case, roughly 90% said it was because they preferred cooking with LPG, with another 30% adding that they had sufficient LPG to do so (Supplementary Table 13). When LPG was stacked with biomass, participants provided the same reasons for using LPG and not only biomass—that is, they preferred cooking with LPG and that they had sufficient LPG to do so (Supplementary Table 14). In comparison, they also said that they used biomass and not only LPG because LPG is too costly to use exclusively. Half of participants added that biomass is preferred for some tasks because they require too much LPG to complete or because LPG is not powerful enough for these tasks. Some participants also stated that biomass is preferred regardless of circumstance (28%) and that their cooking was outside, so biomass is preferred (25%). Nine in ten exclusive biomass users reported not using LPG because there was none available (Supplementary Table 14). Additionally, one-third of exclusive biomass users reported that LPG was expensive, so they did not use it.

Discussion

We expand on previous studies[6–8,16] detailing the pandemic's impact on household financial conditions and market access by providing more granular evidence that there were changes in the use of polluting fuels for lighting, cooking and heating in rural Jharkhand and Bihar, India. Most households surveyed in Jharkhand reported experiencing some socio-economic hardships, peaking during the initial pandemic wave in July 2020 and then again following the rise of the Delta variant beginning in May 2021. We observed that households in Jharkhand reporting socio-economic hardships used kerosene lamps for lighting and polluting fuels for cooking more frequently in that same week, probably exposing themselves to health-harming levels of air pollution[17,18].

Our findings show that when there was sufficient LPG to use, households did so because it is easy, clean and fast. Notably, while nearly all households reported generally stacking LPG with polluting biomass fuels, in about one-third of observations across both samples, participants reported only cooking with LPG in the preceding several days. In total, 71% and 93% of households in Bihar and Jharkhand, respectively, reported exclusive LPG use at some point during the time period. Combined with the high proportion of primary LPG users at baseline, these results suggest that exclusive LPG use for several days on end is not uncommon. Nevertheless, most households used biomass to complement LPG because of the costliness of gas-cylinder refills and because biomass is preferred for some cooking tasks. We reinforce the importance of addressing the cost and accessibility concerns that surround LPG cylinder refills in rural India, which consistently appear as major barriers to full displacement of biomass in household fuel mixes and dull the benefits of clean cooking[19–23].

Knowledge and use of the government of India's three-free-LPG-cylinder-refills scheme among our study population is noteworthy. Nearly all participants in our study sample were aware of the programme and availed themselves of at least one free refill over the study period, reporting that the process overall was no different than their typical refills. This level of awareness is in contrast with findings from an assessment of pro-poor packages deployed by the government of India in response to COVID-19; that survey found that communication and distribution of the benefit were limitations of the programme[15]. Nevertheless, for our rural participants, this policy provided much needed relief as LPG cylinder refill prices were unstable and elevated for much of the pandemic. Considering that the average PMUY beneficiary in Bihar and Jharkhand respectively averaged 4.7 and 3.5 14.2 kg LPG cylinder refills between April 2020 and March 2021[24], the scheme could imply a near doubling of consumption for a household and potential saving of substantial expenditures[25]. As of 30 November 2020, the Indian government reported that 141 million free LPG cylinder refills were provided to 75 million PMUY beneficiaries[26], totalling roughly 82 billion INR (US$1.1 billion) in benefits[27].

Both the uptake of this policy and our findings of its reach and utilization by rural households indicate the seeming necessity of subsidies to drive continued LPG use. Policies to reform energy subsidies in India and beyond should target those with the greatest need rather than aiming to eliminate subsidies entirely. This is especially true in contexts where clean-energy transitions are relatively new and, as shown in this study, potentially fragile. Recent consumer LPG subsidy reform in India—removing the subsidy for all consumers, save PMUY beneficiaries—indicates acknowledgement of the need to make sure the subsidy reaches those who would benefit most from it. Targeting helps ensure efficient allocation of resources and should enable subsidies to scale such that LPG cylinder refills are affordable. As of July 2022, 14.2 kg LPG cylinder refill costs exceeded 1,000 INR in India (78% higher than prices in June 2020) with subsidies of roughly 200 INR per cylinder—implying a subsidized cost of 800 INR per 14.2 kg LPG cylinder refill[28].

In Bihar, our findings regarding the frequency of observed cooking-fuel stacks (notably the frequency of exclusive LPG use week to week) should be contextualized within the unique conditions of data collection having occurred in the middle of the pandemic. Given what we find in our Jharkhand survey rounds—that households reported socio-economic hardship, reduced access to LPG cylinder refills, higher LPG cylinder refill costs and increased biomass use—our observations in Bihar may not be representative of cooking-fuel-stacking patterns outside of pandemic-related conditions. Still, we highlight the utility

of surveys even when there is no baseline for comparison; put another way, we observe dynamic energy use—both relative to a baseline, as seen in Jharkhand, but also during the pandemic, as seen in Bihar—that would be poorly captured with a single survey or even panel surveys spaced by several months.

This study makes several contributions to the literature describing the consequences of the COVID-19 pandemic and our understanding of cooking-fuel-use patterns through its timeliness and use of repeated surveys, albeit of differing frequencies. Some of these findings and methodological innovations may have relevance beyond the pandemic. Unlike most household energy studies, we leverage repeat, phone-based survey tools to gain a more nuanced understanding of household energy-use patterns among a cohort of rural households. These types of survey enable understanding of how unexpected shocks—such as COVID-19—may alter fuel costs and energy use over time, and if continued, document how households recover and persist after such events. Given the relative efficiency with which they can be deployed, and the potential value of the information, we are optimistic about their utility in other Indian states and more broadly in other low- and middle-income countries around the world, both during exceptional periods, such as the pandemic, and during more stable periods to characterize 'typical' variability in energy-use patterns. Typical practice—of surveying households once or twice during a study, or once or twice a year for some period of time—probably do not capture the true heterogeneity in household energy use.

This study also has several limitations that should be considered, including its limited geographic size, scope and the convenience-based difference in survey timings between states. We note that we exploited the final weakness—the difference in frequency and duration of surveying between states—to evaluate the feasibility of these approaches at differing levels of intensity. Given the usefulness of the information obtained, we suggest expanding revised versions of these surveys to additional households and to other states in India. We suggest future evaluations of what frequency of survey optimizes between limited resources and information gain.

During analysis and review of survey responses, we identified a few questions that would benefit from revision (Supplementary Note 1). Like most surveys, our instrument was imperfect and there is some chance of misunderstanding in translation. We translated and back-translated our instruments to minimize this probability. In the Jharkhand survey, we noted that our sample was somewhat irregular from round to round, with a sample of 600 in each round and a total of 882 households participating across the full study period.

Given our reliance on mobile phones for survey administration, it is important to consider the prevalence and distribution of mobile phone ownership in India. As of the 2015–2016 National Family Health Survey, household-level mobile phone ownership was 87% and 96% in rural and urban India, respectively[29]. While it is likely that household-level mobile phone ownership has increased in the last five years, women and marginalized individuals may still be underrepresented. Recent estimates suggest that mobile phone penetration across India is 84% (ref. [30]), though the 2019–2021 National Family Health Survey reported that 54% of women have a mobile phone they use themselves[31].

We acknowledge that our sample may not represent typical biomass-using households in that the sample here may be somewhat higher income (as assessed by the fraction of households below the poverty line). Our specific findings are also probably not generalizable outside of the districts and states within which this work was performed, though we think the methodological innovation of repeat telephone surveying probably would yield similar types of insight in other settings.

Due to the circumstances created by COVID-19, and to keep both field staff and householders safe, we did not verify any of the responses by in-person visits to households. Future work could pair this type of repeat surveying with field visits or sensor-based measurement of stove use to validate responses, especially on fuel- and stove-use questions. We acknowledge the limitations of surveys alone for assessing some of these parameters. Finally, and most saliently, we note that the pandemic has broadly disrupted mobility, work and health—profoundly impacting daily life. Our relatively simple survey probably was unable to capture the extent and magnitude of this disruption.

The COVID-19 pandemic has revealed the precarity of recent gains towards clean-energy use for rural and poor populations. Given the importance of universal access to clean energy for health and economic well-being and the high degree to which recent adopters want to use clean energy, addressing the affordability and accessibility factors that constrain clean-energy use is a high priority to build resilience for those most vulnerable.

Methods

Jharkhand survey setting, design and implementation

Setting. Jharkhand is in the eastern part of India and is rich in natural resources. It has a total population of 32 million, with 76% living in rural areas[32]. In addition, about 26% of Jharkhand's population is characterized as tribal; the state is home to 32 officially recognized tribes, including larger groups such as the Ho, Santhal, Oraon and Munda[32]. According to a multi-dimensional poverty index based on the 2015–2016 National Family Health Survey (NFHS-4), 42% of the Jharkhand population is considered multi-dimensional poor[33]. More than 60% of the Scheduled Tribe and Schedule Caste population live below the poverty line. Further, as per 2011 census data, the average literacy rate in rural areas of Jharkhand was estimated at 61% (73% for men and 27% for women)[32]; the NFHS-5 reports that 75% of men and 52% of women were literate in 2019–2020[31]. According to the NFHS-5, 94% of households in Jharkhand have electricity and 32% cook primarily with a clean-cooking fuel (71% of urban households, 20% rural).

Baseline survey. The full details of the baseline survey sampling are available elsewhere[34]. Briefly, between July 2019 and August 2019, a statewide survey of rural households in Jharkhand was conducted to understand household energy access and use and workers' employment. Six rural villages were randomly selected in each of the 24 districts of Jharkhand, with larger villages being more likely to have been selected. Ten households were surveyed at random in each village. The baseline study sample is thus representative of rural areas of Jharkhand.

At baseline, 87% of the respondents had some kind of electricity access, with the vast majority of those (97%) relying on a grid electricity connection and the remainder (3%) using a micro-grid or solar home system. However, only 82% of tribal households had electricity at home. Only 36% of grid electricity users were satisfied with the quality of their electricity service. That is unsurprising, given that the median supply of electricity in rural areas was only 9 hours per day.

The survey showed that only 53% of rural households had an LPG connection (for tribal households, this number was only 40%). Among all rural households, a vast majority (83%) reported fuel stacking, with firewood, cow dung and coal being the primary solid fuels used. Indeed, 71% of the rural population reported firewood as their primary cooking fuel, while only 17% said LPG is their primary cooking fuel. Three-quarters of LPG users reported being satisfied with their cooking fuel, but nine in ten reported concerns about the high cost of refills.

Government of India's energy-access policies have played a major role in improving energy access. Among electrified households, 33% had received a connection under Prime Minister Narendra Modi's *Saubhagya* scheme for free or heavily subsidized electricity connections. Among LPG users, as many as 76% were connected through the *Ujjwala* scheme.

Survey design and implementation. The telephonic survey was designed in collaboration between researchers in the United States and in India. The initial draft was written in English by United States-based

researchers and then reviewed by Indian researchers at the Initiative for Sustainable Energy Policy and field staff at Morsel Research and Development Private Limited (Morsel), the survey company used to deploy finalized surveys to participants. Translation was done by Morsel. After multiple rounds of pre-testing and piloting with subjects from the baseline survey, the final version was programmed for administration using SurveyCTO (Version 16).

The survey was administered by field researchers using telephonic communication from their own homes. The survey team called subjects from the baseline survey in random order, requested permission to conduct the survey and confirmed their willingness to participate in the future rounds. The rounds were administered evenly over time, though the Delta wave in early 2021 caused a temporary pause.

The baseline and repeated surveys are available in Supplementary Note 2. Data were processed using R version 4.1.2.

Study sample characteristics. The baseline characteristics of the study sample differed somewhat as compared with the original baseline sample (Supplementary Table 2). Surveyed participants were younger, more educated and more commonly belonged to the general caste as compared with those in the baseline that were not surveyed in the current study. The distribution of ration cards was similar across surveyed and non-surveyed households. Surveyed households had an average of 440 INR more in monthly expenditures than non-surveyed households (4,769 versus 4,325; $P = 0.01$). Surveyed participants were connected to the electrical grid at a higher rate than those that were not surveyed and had been connected for longer. Similarly, more surveyed participants used LPG than non-surveyed participants. Although the study sample differed somewhat from round to round, there were no meaningful differences in sample-level baseline characteristics across rounds (Supplementary Table 3).

Defining socio-economic hardship. As shown in Supplementary Table 5, we asked participants about several specific socio-economic hardships. These were collapsed into three overarching categories as shown in Fig. 1a and further collapsed into a single category for the regression approach shown in Fig. 1d and discussed below. The category 'Increased price for goods or difficulty accessing food for household' indicates that a participant reported (1) increased difficulty accessing food for the household or (2) increased prices for necessary goods. 'Reduced income, hours of employment, or other financial help' indicates (1) reduced income from any form of economic activity or (2) reduced hours of employment, reduced days of waged employment, reduced cash from any other sources such as family members outside the household or government cash transfer programmes. 'Loss of employment or inability to find job' indicates (1) loss of salaried employment or (2) loss of hourly waged employment or loss of daily waged employment and (3) unable to look for employment, such as going to a town for seasonal labour.

Reported motivations for observed stacking. Participants were asked if they liked cooking with LPG more, less or the same as compared with before the pandemic and then, if they responded that they liked LPG either more or less, to provide specific reasons for their response. Reasons were grouped into either 'pro-LPG/anti-biomass' or 'pro-biomass/anti-LPG' and then into sub-themes. The 'pro-LPG/anti-biomass' sub-themes were: (1) prefer LPG cooking (for example, we value faster cooking with LPG more now during lockdown); (2) fuel accessibility (for example, LPG is more accessible now) and (3) LPG affordability (for example, LPG is cheaper now). The 'pro-biomass/anti-LPG' sub-themes were: (1) LPG costliness (for example, LPG is more expensive now); (2) fuel accessibility (for example, LPG is less accessible now); and (3) prefers biomass cooking (for example, household prefers taste of food cooked over biomass now). Supplementary Table 15 provides the specific reasons that comprise each sub-theme.

Regression models. We estimated associations between reported socio-economic hardship and three binary household energy-use outcomes: (1) kerosene used for lighting, (2) any polluting cooking-fuel use and (3) primary reliance on a polluting cooking fuel. The independent variable of interest was a dummy variable for reporting to have experienced any socio-economic hardship in that round. These quasi-binomial logistic regressions included fixed effects for round and household, with standard errors clustered at the household. In alternative specifications, we carried out separate regressions for each domain of socio-economic hardship (Supplementary Fig. 3). Models were carried out using 'fixest' package in R.

Bihar survey setting, design and implementation

Setting. Bihar is in the eastern part of India and is one of India's largest and poorest states. It has a total population of roughly 128 million, with almost 90% living in rural areas according to the 2011 Census[32]. On the basis of the 2015–2016 National Family Health Survey (NFHS-4), 52% of the Bihar population is considered multi-dimensional poor[33]. Per the 2019–2020 NFHS-5, 96% of rural Bihar households had access to electricity, 46% had access to an improved sanitation facility (for example, flush toilet, ventilated improved pit or pit latrine not shared with another household) and 30% primarily used a clean-cooking fuel[31]. Additionally, according to the same survey, 52% of rural women and 75% of rural men were literate[31]. In Bihar, 79% of urban households and 30% rural households cook primarily with a clean fuel.

Survey design and implementation. Our findings are based on longitudinal data from high-frequency phone surveys conducted in Bihar, India, during the period January to April 2021. We partnered with Morsel Research and Development to carry out this work, as in the Jharkhand study. We designed a 20-minute baseline survey and a 5- to 10-minute high-frequency survey. Enumerators were trained by a member of the authorship team in the purpose of the study and design of the questions. Both surveys were then piloted twice by those trained enumerators and members of the authorship team to ensure that questions were being administered and understood appropriately and that all common responses were coded as options. Pilot data were reviewed for consistency and accuracy.

From Morsel's maintained phone database of 38,000 registered phone numbers of individuals living in Bihar, we randomly recruited 450 households from eight districts to receive the baseline survey and potentially participate in the study. Study districts (Golpaganj, Nawada, Patna, Rohtas, Samastipur, Saran, Siwan and Supaul) were selected to achieve geographic coverage of Bihar. Morsel's phone database has been used for numerous electrification and energy surveys in Bihar. Participants were always greater than 18 years of age, were primary cooks and lived in a household that used both a biomass fuel and a clean-cooking fuel for cooking in the preceding week before the baseline survey (administered in January 2021).

Participants in the study were first administered a baseline survey in January 2021. This survey covered basic socio-economic, demographic and patterns related to cooking-fuel access and use. After completing the baseline survey, 203 participants were randomly selected and were called once per week for eight weeks and asked how much they cooked in the previous four days on average, which fuels they used in the preceding four days, which household energy tasks they carried out in the previous four days and which fuels were used to meet these tasks.

All participants received the baseline survey and eight follow-up surveys within one week of each other. Four participants did not participate in the Week 7 follow-up survey; otherwise, all participants successfully received the baseline and responded to all eight weekly surveys. The baseline and repeated surveys are available in Supplementary Note 2.

Participants were compensated in phone credit each time they were surveyed (50 rupees directly deposited as phone credit for the baseline survey and 20 rupees for every survey thereafter).

Data were processed using R version 4.1.2.

Study sample baseline characteristics. Supplementary Table 3 shows baseline study characteristics. Nearly all participants were female (N = 202, >99%), married (N = 198, 98%), and they were an average age of 35 years (standard deviation 11 years). Two-thirds of household heads—typically the participant's spouse or a parent-in-law—had received a secondary school education or greater, with an additional 18% receiving a primary school education and 16% no formal education. The study sample was predominately Hindu (79%), with the remainder Muslim. One-quarter of participants reported belonging to the general caste; nearly 60% belonged to the so-called Other Backward Class and 15% belonged to the scheduled caste. The primary source of income for one-third of the households was from day labour, for another third it was agriculture on their own land and for a smaller portion a salaried job (12%) or their own business (9%). In a typical month, households reported spending a median of 8,000 rupees (US$107) on household needs (interquartile range: 6,000–10,000 rupees). Most participants reported carrying out only household (86%) work, and only 7% reported to have a wage-earning occupation.

Reported motivations for observed stacking. We asked participants questions specific to their self-reported cooking-fuel stack to identify the reasons that participants used each cooking fuel as they had reported. For example, a household that stacked both LPG and a polluting fuel was asked both why they used LPG and not only biomass for all their needs and why they used biomass and not only LPG for all their needs. Participants could provide more than one response to each question and were asked to identify the most important reason. While each question had tailored responses, these responses were generally either 'pro-LPG/anti-biomass' or 'pro-biomass/anti-LPG' and were grouped into sub-themes. The 'pro-LPG/anti-biomass' sub-themes were: (1) prefer LPG cooking (for example, preference for using LPG because of speed); (2) LPG affordability (for example, we have enough LPG and can afford to use it all the time) and (3) fuel availability (for example, did not have any biomass to use). The 'pro-biomass/anti-LPG' sub-themes were: (1) LPG costliness (for example, conserving LPG because it is expensive); (2) prefer biomass cooking (for example, did not use LPG much because biomass is preferred for most tasks); (3) biomass is available (for example, had available biomass, so wanted to use it) and (4) no LPG available (for example, not much LPG in cylinder so wanted to save it). Supplementary Table 15 provides the specific reasons that comprise each sub-theme.

Ethical considerations

Question types and approximate duration of the survey and study were communicated to participants. All participants provided oral consent in both studies and could withdraw consent at any time. The Jharkhand study was approved by the Johns Hopkins University Institutional Review Board, reviewed and granted an exemption by the Emory University Institutional Review Board (STUDY00001045) and the Institutional Review Board of Morsel Research and Development. The Bihar study was approved by the Johns Hopkins University Institutional Review Board and the Institutional Review Board of Morsel Research and Development.

Reporting summary

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

Data availability

Data that underlie this study are available at https://doi.org/10.7910/DVN/8KQN5Y.

Code availability

Code that underlie this study are available at https://doi.org/10.7910/DVN/8KQN5Y.

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Author contributions

C.F.G.: conceptualization, funding acquisition, methodology, analysis and writing–original draft. A.P.: conceptualization, funding acquisition, methodology, analysis, project administration and writing–original draft. S.S.: investigation, data curation and writing–review and editing. V.N.: investigation, data curation and writing–review and editing. L.M.T.: conceptualization, funding acquisition, methodology, writing–review and editing. J.U.: conceptualization, funding acquisition, methodology, project administration and writing–original draft.

Competing interests

The authors declare no competing interests.

Additional information

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☐	☒	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Survey data collection used SurveyCTO Version 16.
Data analysis	R programming language version 4.1.2 was used for data analysis. The 'fixest' package was used for regression analysis.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

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All collected data and code that underlie this study are available at https://doi.org/10.7910/DVN/8KQN5Y. For more details about the Morsel phone database, please contact care@morselindia.org care to Bhartendu Trivedi.

Field-specific reporting

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Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	The data used in this study were collected via telephone surveys, which were in large part closed-response or had enumerators classify responses into categories. Data analyzed were quantitative. Participants were surveyed several times and the data are analyzed both cross-sectionally within each round and longitudinally to examine fuel switching, trends, and to make inferences about the association between reported pandemic-related hardships and household energy choices.
Research sample	Jharkhand: Participants were greater than 18 years of age and lived in rural Jharkhand. About half were from the general caste, 80% benefitted from some ration card, two-thirds could read and write in their native language, and the average age was 38 years. Further descriptive statistics are available in Table S2. The sample was drawn from a representative sample of rural Jharkhand households (see below), but the current study sample did deviate overall from the previous baseline sample. Bihar: Participants lived in rural Bihar. Participants were always greater than 18 years of age, were primary cooks, and lived in a household that used both a biomass fuel and a clean cooking fuel for cooking in the preceding week prior to the baseline survey (administered in January 2021). Nearly all participants were women. Neither samples can be considered fully representative of their study areas. The rationale for our Jharkhand sample was to leverage the existing randomly-sampled sample. The rationale for the Bihar sample was that it was based on funding priorities for IGC-India.
Sampling strategy	Jharkhand: We draw from a previously-established sample. The baseline sample was established between July 2019 and August 2019 via state-wide survey of rural households in Jharkhand that was conducted to understand household energy access and use, and workers' employment. Six rural villages were randomly selected in each of the 24 districts of Jharkhand, with larger villages being more likely to have been selected. Ten households were surveyed at random in each village. The baseline study sample is thus representative of rural areas of Jharkhand. From this sample of 1440 rural households, we sampled 882 total. Bihar sample: From Morsel's phone base of 38,000 registered phone numbers of individuals living in Bihar, we randomly recruited 450 households from eight districts across the state to receive the baseline survey and potentially participate in the study (Golpaganj, Nawada, Patna, Rohtas, Samastipur, Saran, Siwan, and Supaul). Participants were always greater than 18 years of age, were primary cooks, and lived in a household that used both a biomass fuel and a clean cooking fuel for cooking in the preceding week prior to the baseline survey (administered in January 2021). Power calculations were not performed due to the exploratory nature of the study. In both cases, sample sizes were chosen based on budgetary constraints with the aim of achieving maximum sample size in each survey round while also achieving our desired frequency and duration of the study period (i.e., six surveys across 1 year in Jharkhand and eight sequential weekly surveys in Bihar).
Data collection	Jharkhand: The telephonic survey was designed in collaboration between researchers in the United States and in India. The initial draft was written in English by U.S.-based researchers and then reviewed by Indian collaborators and field staff. The translation was done by the survey company, Morsel Research and Development Private Limited (Morsel) (Uttar Pradesh, India). After multiple rounds of pre-testing and piloting with subjects from the baseline survey, the final version was programmed for administration using SurveyCTO (Version 16). The survey was administered by field researchers using telephonic communication in Hindi from their own homes. The survey team called subjects from the baseline survey in random order, requested permission to conduct the survey, and confirmed their willingness to participate in the future rounds. Bihar sample: We designed a 20-min baseline survey and a 5- to 10-min high-frequency survey. Enumerators called the mobile phone of participants and recorded responses using SurveyCTO. Survey instruments are available in the appendix in English and Hindi. There was no blinding involved in this study.
Timing	Table S1 fully outlines the timing of survey rounds. Jharkhand Start End Round 1 2020-07-23 2020-08-22 Round 2 2020-09-24 2020-10-21 Round 3 2020-11-28 2020-12-18 Round 4 2021-03-08 2021-04-22 Round 5 2021-05-13 2021-06-02

Round 6 2021-06-15 2021-07-05

Bihar

Start End
Round 1 2021-02-15 2021-02-18
Round 2 2021-02-24 2021-02-27
Round 3 2021-03-02 2021-03-06
Round 4 2021-03-09 2021-03-12
Round 5 2021-03-16 2021-03-20
Round 6 2021-03-23 2021-03-27
Round 7 2021-03-31 2021-04-05
Round 8 2021-04-06 2021-04-09

Data exclusions

No data were excluded. No exclusion criteria were established a priori.

Non-participation

Jharkhand: We do not have information at this time about non-response rate with respect to reaching the original sample. However, the most common reported reason by enumerators was that the phone numbers previously provided were no longer functional. This is a common issue in rural India. 107 of the 882 households were only surveyed once, though whether they were only surveyed once due to declining to participate or an inability to reach them is unknown.

Bihar: We recruited 450 households and then randomly selected 203 participants. We do not have a known declined response rate. Of the 203 households, only four participants did not participate in the week 7 follow up for unknown reasons. All other participants received the baseline and responded to all eight weekly surveys.

Randomization

No randomization occurred. We do not use covariates because those available to us are time-invariant and we use panel fixed effects models to show associations between pandemic related hardships and household energy outcomes.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☐	☒ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics

See above

Recruitment

All participants had mobile phones. All participants in the Bihar sample used both a polluting and clean cooking fuel. Thus, the sample could be on average somewhat wealthier and more connected than the average rural household in these states, though as of the time of data collection mobile phone ownership and LPG ownership are increasingly common even in rural areas. Additionally, in both surveys, it is possible that respondents with multiple observations in the study may be different from those with fewer responses. It is not self-evident how these factors would affect our results at this point. It is plausible that if our sample were wealthier than the average that they may be better insulated from the impacts of the pandemic on their household economics and be more likely to continue using clean energy. In this scenario, our estimates of the prevalence of pandemic-related socioeconomic household changes and their associations with more polluting household fuel use would be underestimates.

Ethics oversight

Participants provided oral consent in both studies. The Jharkhand study was approved by the Johns Hopkins University Institutional Review Board, reviewed and granted an exemption by the Emory University Institutional Review Board (STUDY00001045), and the Institutional Review Board of Morsel Research and Development. The Bihar study was approved by the Johns Hopkins University Institutional Review Board and the Institutional Review Board of Morsel Research and Development. Participants in the Bihar sample were compensated in phone credit each time they were surveyed (50 rupees directly deposited as phone credit for the baseline survey and 20 rupees for every survey thereafter).

Note that full information on the approval of the study protocol must also be provided in the manuscript.