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Experimental evidence on promotion of electric and improved biomass cookstoves

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Improved cookstoves (ICS) can deliver "triple wins" by improving household health, local environments, and global climate. Yet their potential is in doubt because of low and slow diffusion, likely because of constraints imposed by differences in culture, geography, institutions, and missing markets. We offer insights about this challenge based on a multiyear, multiphase study with nearly 1,000 households in the Indian Himalayas. In phase I, we combined desk reviews, simulations, and focus groups to diagnose barriers to ICS adoption. In phase II, we implemented a set of pilots to simulate a mature market and designed an intervention that upgraded the supply chain (combining marketing and home delivery), provided rebates and financing to lower income and liquidity constraints, and allowed households a choice among ICS. In phase III, we used findings from these pilots to implement a field experiment to rigorously test whether this combination of upgraded supply and demand promotion stimulates adoption. The experiment showed that, compared with zero purchase in control villages, over half of intervention households bought an ICS, although demand was highly price-sensitive. Demand was at least twice as high for electric stoves relative to biomass ICS. Even among households that received a negligible price discount, the upgraded supply chain alone induced a 28 percentage-point increase in ICS ownership. Although the bundled intervention is resource-intensive, the full costs are lower than the social benefits of ICS promotion. Our findings suggest that market analysis, robust supply chains, and price discounts are critical for ICS diffusion.

improved cookstoves | technology adoption | Indian Himalayas | supply chain | price subsidies

Improved cookstoves (ICS) can make households healthier, improve local environments, and reduce pollutants that cause climate change (1–5).* Yet, despite evidence on their efficacy, widespread diffusion has proven challenging (7, 8). In recent years, field experiments more rigorously attribute low demand to income and liquidity constraints, social networks and peer effects, and households' undervaluation of health risks (8–10). Collectively, the limited research so far suggests that a complex combination of factors interact with local contexts (such as tastes and preferences) to limit adoption (11). It also partially explains why demand for—and impacts of—ICS technologies in certain settings can be high (12–15), while efforts documented elsewhere are disappointing (8, 16). Unfortunately, much of this evidence is idiosyncratic and patchy, and rarely derived from projects and policies implemented by firms and governments (17). Critically, it also ignores supply-side aspects such as product characteristics, supply chains, and the enabling environment (18).

We respond to this knowledge gap (of lack of adoption studies that jointly consider supply and demand promotion) by conducting a multiyear, multiphase study in the Indian Himalayas. Phase I started with a series of diagnostic steps (spanning 18 mo) to uncover the nature of low ICS adoption. In phase II, we implemented a set of pilots to simulate a mature market and designed an intervention that would reduce both supply and demand constraints. Finally, in phase III, we experimentally tested a package of interventions, spanning an additional 18 mo, in a sample of ∼1,000 households living in nearly 100 rural Himalayan communities. Our principal hypothesis, derived from insights gleaned from the diagnosis and design phases, was that ICS demand would be highly sensitive to a multipronged intervention combining (*i*) a well-developed technology supply ecosystem (characterized by delivery, demonstration, promotion, and financing) with (*ii*) demand-stimulating subsidies. Additionally, our second hypothesis was that the well-developed supply chain alone would lead to considerable ICS adoption; that is, one of the treatment arms of our randomized

Significance

Three billion people rely on traditional stoves and solid fuels. These energy use patterns exacerbate the global climate crisis (via increased carbon emissions) and forest degradation/deforestation (via daily fuelwood collection), and expose billions to toxic air pollution generated by dirty fuels. Widespread adoption of improved cookstoves (which use cleaner fuels or burn solid fuels more efficiently) may ease this "triple burden," but recent research casts doubt on their potential, given low and slow diffusion. We challenge this pessimism based on a multiyear, three-phase field study comprising diagnosis, design, and experimental testing involving 1,000 rural Indian households. We show that demand for these improved energy technologies is high when supply chains are robust, technologies match local needs, and income and liquidity constraints are relaxed.

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*We include electric, liquefied petroleum gas (LPG), and biogas stoves in our definition of ICS, going beyond only biomass-burning alternatives in line with recent calls to view modern cooking technologies in this way (6).

controlled trial (RCT) mimics the typical practices of a local supplier—combining delivery, retail, marketing, sales, and finance. This multiphase applied research plan—first diagnosing why adoption is low, then designing treatments to overcome practical hurdles, and only then field testing hypotheses experimentally—exemplifies "use-inspired basic research" necessary to address sustainability challenges (19).

Our approach is grounded in existing theories of household choice, which postulate that households will adopt environmental technologies (*i*) if they know and value expected benefits (20) and (*ii*) if suppliers have incentives to minimize costs of marketing, retailing, financing, and delivering (21). Various aspects of these theories have been tested over the last decade in rural India by our team with regard to clean water (22, 23), safe sanitation (24), and ICS (4, 25). Finally, our approach also drew on emerging evidence from the ICS literature (26, 27), especially recent calls for research that embraces multiple implementation challenges (28).

Study Design

Given this background, we designed a multiphase study involving diagnosis, design, and experimental tests in the Indian Himalayas. These are briefly summarized next.

Phase I: Diagnosis. A series of preparatory tasks preceded the actual experiment, starting with background research in three main areas: (*i*) systematic analysis of ICS adoption (17), (*ii*) cross-country analysis of ICS sales, and (*iii*) cost-benefit simulations for assessing the net benefits of changes in cooking technologies (2). The first two activities provided insight on demand- and supply-side barriers, respectively, and highlighted the dearth of experiments on common strategies for promoting behavior change in cooking. The third revealed how the economic case for ICS was contextual, thereby pointing to the need for careful field preparation before testing for potential impacts.

The desk research was followed first by a set of focus groups with over 100 households in 11 rural Indian communities (both near and far from our final sites in Uttarakhand) to better understand knowledge and perceptions of different stoves and fuels, traditional cooking practices, and preferences for improved stove features (7, 29).

Next, we designed and tested a household survey instrument, which was based on findings both from the focus groups and from many years of work in India on other household environmental health issues. These instruments included discrete choice experiments, which allowed us to better understand preferences for alternative ICS features (7). The baseline surveys in 2012 also allowed us to more generally understand preintervention characteristics of the target population.

Phase II: Design. Based on lessons from these diagnostic preparations, we conducted a series of eight small-scale pilots in three different rural settings (30). The pilots addressed various intervention components related to information/demonstrations, stove technology and choice, installment finance, rebates or subsidies, and institutional partnerships. The wide range in sales achieved across pilots demonstrated the challenges facing promoters of these technologies, but also helped crystallize three main lessons that informed the design of our main experiment. First, ICS (of any kind) were largely unavailable in our setting, except for liquefied petroleum gas (LPG) stoves, which were nonetheless often in short supply. Electric coil stoves could be found in markets in larger cities but were absent in local markets in our study communities. Electric induction stoves were similarly absent; where available, households were not interested because of the prohibitive costs of replacing all cookware for induction-appropriate options. Second, unsurprisingly, liquidity was a major barrier to adoption, and financing payment in installments or price discounts seemed to increase purchase. Third, households expressed widely varying demands for different ICS features, and giving them choice among distinct stove types improved adoption.

These activities highlighted the need to (*i*) establish a functional ICS supply chain with products that matched household preferences; (*ii*) ease income, liquidity, and information constraints; and (*iii*) respond to heterogeneous household tastes for ICS attributes such as price, smoke emissions, and fuel needs through multiple choices (e.g., biomass and electric ICS). Therefore, we designed an experimental supply-and-promotion intervention that combined (*i*) in-house delivery of suitable ICS; (*ii*) demonstration, financing, and rebates; and (*iii*) the ability to choose an electric and/or biomass ICS (Table 1).

Phase III: Test (with Randomized Intervention). We tested a two-level experimental intervention to target the primary barriers we identified: limited supply of ICS, lack of choice, lack of information, and income/liquidity constraints. The first level entailed acquiring and transporting ICS (electric and improved natural draft biomass) from urban wholesalers, developing storage and maintenance systems, training sales personnel for home delivery and for marketing (including information, communication, and cooking demonstrations), and providing installment finance spread over three payments provided every 2 wk. The second level provided one of three price discounts (rebates), the magnitude of which was revealed to the household before the purchase decision. This rebate was different from a traditional subsidy in that it was delivered only at the time of the third installment visit if a household had visibly used the new ICS (as confirmed by sales team members). Households were allowed to purchase up to one improved biomass and one electric stove at their randomly assigned rebate level. Further, our intervention distributed an informational pamphlet to households, conducted household demonstrations on proper cookstove use, and provided the option to pay on an installment-based payment plan (with 2% interest charged on the second and third payments).

The supply intervention (level 1) was randomized at the hamlet level among 97 hamlets located in two districts of Uttarakhand in the Indian Himalayan Region. Within the 70 treated hamlets, rebate offers (level 2) were further randomized across sample households (*SI Appendix*, Fig. S1).

Results

Our results reveal high demand for ICS among study households. Over 50% of the households targeted by the intervention purchased at least one of the two intervention stoves (*SI Appendix*, Table S1). Larger rebates, meanwhile, increased purchase rates (Fig. 1), rising from 28% for the negligible rebate ("High price"), to 55% at the medium rebate (about 20% of retail price) level, and 74% at the highest (33% of retail price) level. This observed

Table 1. Features of stove supply-and-promotion experiment

Experimental element	Level of random assignment
1. Acquire, transport, and deliver ICS (electric and improved natural draft biomass) from urban center	Community level
2. Provide information and conduct stove demonstration	Community level
3. Offer finance to pay in three installments	Community level
4. Announce rebate at sale and deliver after verifying stove use during visit to collect third installment	Household level

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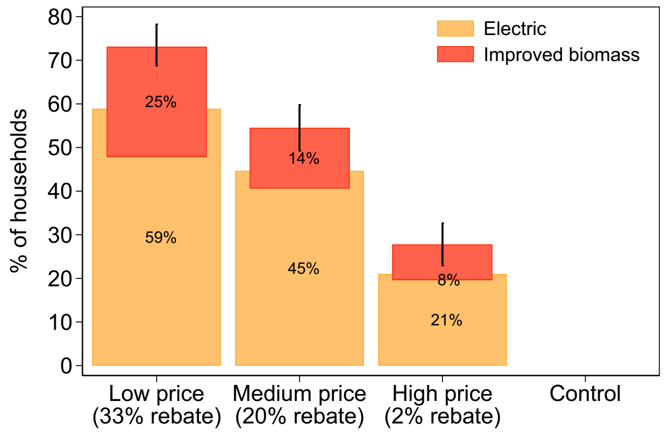

Fig. 1. Stove purchase by rebate group. Proportion of targeted households that purchased an intervention ICS, disaggregated by randomly allocated rebate (rebates were assigned to households before the purchase decision). Error bars indicate 90% confidence intervals. The ICS costs ranged from approximately 1,000 to 1,400 in Indian Rupees (INR) (USD 16 to 23), depending on stove type. See *SI Appendix*, Tables S3 and S4 for additional details.

rebate sensitivity is consistent with other studies that point to the positive effects of financial rewards in the form of climate- or use-credits on demand for ICS (4). Further, while roughly two-thirds of targeted households availed of the installment finance option to pay (over three payments provided every 2 wk), all were able to pay in full. Thus, compared with some of the early work on willingness to pay for ICS, we document varied but high demand for ICS.

We note two key results beyond the average treatment effect. First, households overwhelmingly preferred the electric stove over the biomass ICS: Approximately 40% bought an electric stove, while 15% bought a biomass stove (*SI Appendix*, Tables S1 and S2), suggesting high desirability for nonbiomass improved alternatives in this setting. Relatedly, every rupee of the rebate was approximately twice as effective in increasing ownership of electric stoves compared with the improved biomass stove (*SI Appendix*, Table S3). As revealed by postintervention surveys, the overwhelming majority of respondents indicated that they liked electric stoves because of the following attributes: (*i*) lack of smoke, (*ii*) speed of cooking, (*iii*) portability of the stove, and (*iv*) attractiveness of the stove (*SI Appendix*, Table S5), similar to our phases I and II findings on preferences for ICS. Second, we observe strong supply chain and promotion effects. That is, if we compare outcomes for the "High price" treatment arm and the control arm, we see that the combination of supply and promotion without a meaningful price subsidy induced 28% of households to purchase intervention stoves. Further, there was no increase in LPG ownership during our study period in the control arm relative to the treatment arm, likely because they were not actively promoted. In contrast, 15% of all treatment households purchased the biomass ICS, despite it being less popular than the electric ICS and LPG (*SI Appendix*, Tables S1 and S2).

In addition, we document four sets of supplementary outcomes. Postintervention surveys showed that treatment households (*i*) were more aware of clean stoves (by over 6 percentage points or 9%, although preintervention awareness in this population was already high); (*ii*) used approximately two fewer kilograms of solid fuel per day, a 15% reduction; (*iii*) spent 10 fewer minutes per day collecting fuel (or more than one fewer hour per week, a 9% reduction); and (*iv*) were more likely to report using clean fuels in the past 24 h (by 26 percentage points, double the reported rate in the control group) (Fig. 2 *A*–*D*; additional tests in *SI Appendix*, Table S1). Further, while traditional-stove ownership remained largely unchanged (exhibiting only a 2 percentage-point decrease), treatment households reduced traditional stove use by over 40 min/d (nearly 15%) (Fig. 2*E*). Postintervention surveys suggest that respondents are sensitive to the cost, convenience, and the taste of food prepared on traditional stoves (*SI Appendix*, Fig. S4), consistent with other studies that have found stove stacking (26). Moreover, through their effect on acquisition of new technologies, larger rebates successfully induced greater use of ICS and clean fuels, and decreased weighed solid-fuel use (*SI Appendix*, Table S4).[†]

We further investigated whether this ICS ownership persisted over time. In the postintervention first-round follow-up (∼3 mo after the intervention), most households that had purchased intervention stoves still owned them (Fig. 3), and nearly 70% of owners reported using them in the week before the survey (*SI Appendix*, Fig. S2). Because past work has typically only examined impacts on immediate use, we implemented a second shorter survey to examine ownership and use ∼15 mo after the intervention. Even at this stage, ownership rates of intervention stoves remained largely unchanged (Fig. 3). However, use rates had declined by about 10 percentage points (*SI Appendix*, Fig. S2). This could be partly due to maintenance and service infrastructure; at the time of this second survey, about 15% of the adopters reported that their stoves needed repair, suggesting that stove malfunction and lack of maintenance and servicing partly explain the decline in use, as observed previously in the Indian context (16).

Discussion

Despite their promise for delivering health and environmental benefits, adoption and use of ICS remain disappointingly low. Unfortunately, rigorous field-based evaluations of both demand- and supply-side constraints for ICS adoption are rare, which, in turn, hampers the design and implementation of effective policies. Rarer still are multiyear, multiphase studies that combine extensive preparatory work to diagnose barriers to adoption and generate hypotheses with careful design and experimental testing. Our multiphase study offers the following perspectives on the challenge of crafting policies that would be effective for reducing cooking-related harms. First, households face multiple constraints and have varying preferences for improved cooking technology, reflecting differences in culture, geography, institutions, and markets. Phases I and II of our multiphase research approach provide an example of how careful fieldwork and product testing can help uncover potential levers for promoting ICS (7, 29, 30). Our findings also suggest that implementers cannot focus on "silver bullet" stoves and fuels; at a minimum, they should study their local context and offer options so that households can choose those most suited to meeting their needs.

Second, while phase III (the experimental intervention) of our study showed that the intervention bundle (subsidy plus finance, retail, and marketing) was very effective in promoting adoption and use, the impact of the nonsubsidy supply chain aspects alone was also strong (as demonstrated by the comparison of the control and "High price" arms in Fig. 1). That there was no increase in LPG or electric stove ownership in the control arm relative to the treatment arm, whereas 15% of all treatment households purchased the less popular biomass ICS, demonstrates both (*i*) that demand for ICS can be met by the right combination of provision, information, and incentives and (*ii*) that widespread ICS ownership is constrained by supply challenges. Despite global attention to the problem of traditional cooking, ICS are

[†] Additional details on robustness of self-reported use data are presented in *SI Appendix*, *Appendix S1*.

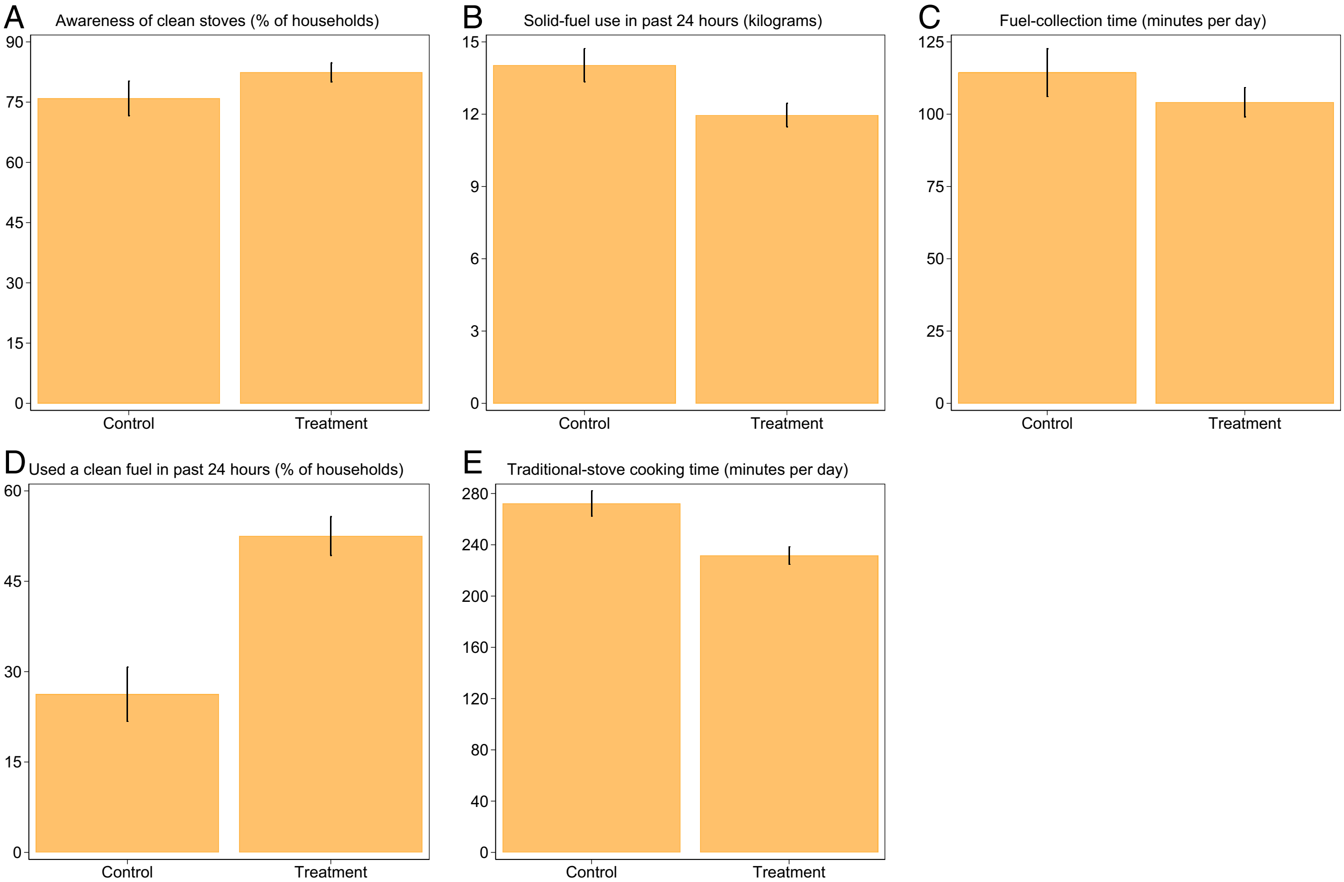

Fig. 2. Mean household-level awareness of clean stoves (*A*), solid-fuel use (*B*), fuel collection time (*C*), clean-fuel use (*D*), and time spent cooking on traditional stoves (*E*) by treatment group. Means derived from first-round follow-up surveys conducted ∼3 mo after intervention. Error bars indicate 90% confidence intervals. See *SI Appendix*, Table S1 for additional details.

simply not available where they are most needed, and demand in our setting could only be stimulated once a supply chain was established. That said, the supply chain improvement only targeted initial purchase; sustained use requires greater attention to the enabling environment (finance, marketing, regulation, maintenance, and customer service)—for electricity and LPG alike (31).

Third, households clearly preferred the electric stove over the biomass ICS, reflecting our early findings from the field suggesting that households strongly prefer stove attributes that LPG and electric stoves possess relative to biomass ICS (32, 33), and this tracks well with stated preferences for stove attributes revealed by our phase I (diagnosis) work. While electric stoves are unlikely to be viable in settings where electricity is unavailable or

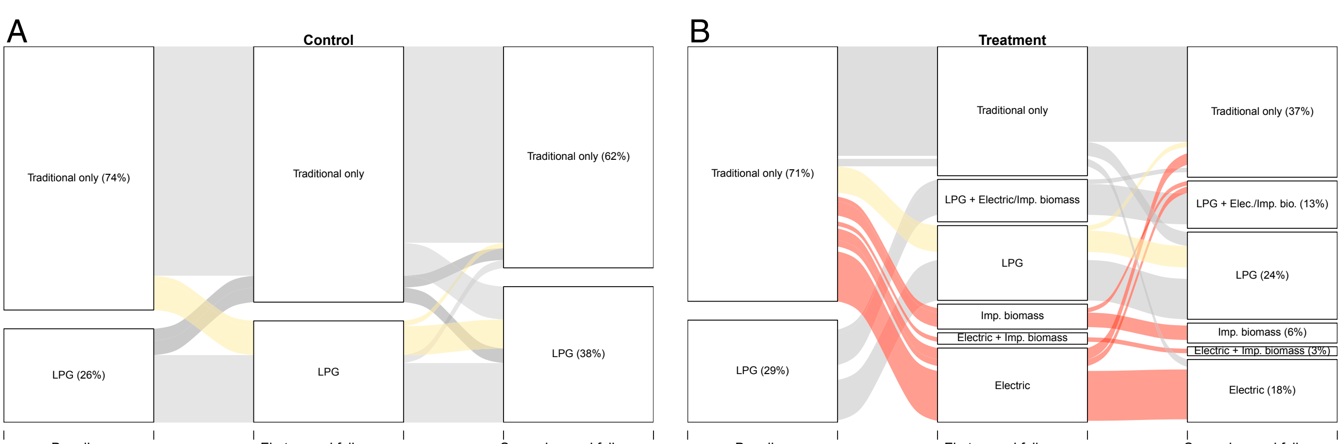

Fig. 3. Stove ownership over time by treatment group: control (*A*) and treatment (*B*). Baseline surveys occurred in summer 2012. Intervention occurred in summer 2013. First-round follow-up surveys occurred 3 mo after the intervention. Second-round follow-up occurred ∼15 mo after the intervention.

unreliable, rural electrification rates have increased rapidly from 68 to 78% globally between 2005 and 2015 (34). In India, this increase has been even more striking, growing from 57 to 83% over the same period. This growth has been accompanied by calls for research on electric and LPG stoves (6). Our study responds to implementation aspects of such calls by examining household demand for these new technologies. In so doing, we show how social science research on household preferences and field implementation can complement the research by epidemiologists and engineers on energy access (35).

Ultimately, we demonstrate that it is possible to overcome barriers to ICS adoption and that households are willing to pay substantial prices for ICS. Although the multifaceted intervention bundle looks resource-intensive on paper, in practice, private firms often engage in such concerted marketing and sales. Our calculations show that the learning and delivery costs of \$17 per household are generally lower than the full social net benefits of switching households out of dirty fuels (*SI Appendix, Appendix S2*). Because our experiment shows that poor rural households are highly sensitive to price, we cannot fully pass these supply costs on to consumers and must seek creative solutions, such as carbon financing (36). To scale up and sustain success, energy access programs and projects could start by better understanding local demand and developing robust regional supply chains.

Materials and Methods

Below, we summarize our sample design, survey implementation, and the statistical approaches for analyzing the experimental data.

Sample Design. The sampling frame for the experimental study consisted of 97 geographically distinct hamlets located in 38 *gram panchayats* (GPs) in the Bageshwar and Nainital districts of Uttarakhand (*SI Appendix*, Fig. S3).[‡] These 38 GPs were drawn from the prior census of 2,105 GPs using a statistical matching methodology. Specifically, half of the sample (19 villages) consisted of GPs where the nongovernmental organization (NGO) partner for the study had done prior work (not related to ICS promotion), while the other half of villages were observationally similar villages selected using propensity score matching to achieve institutional balance (37). As such, the sample may not be representative of all rural Uttarakhand. Nonetheless, it does allow us to argue that the results obtained are not wholly dependent on prior institutions.

Within each of the 38 selected GPs, we randomly selected households according to the size of the GP. In small GPs, a minimum of 20 surveys were collected; in medium GPs, 30 surveys were collected; and in large GPs, 40 surveys were collected. If a GP was divided by distinct landmarks (e.g., half the village was to the north of the main road, half the village was to the south), the target number of surveys was split equally among these groups. Upon arrival in the village, the population of the GP was divided by the target number of surveys, and every *n*th household (no more than every eighth house) was surveyed until the target number of surveys was reached. This strategy ensured that surveys were collected throughout the entire extent of the GP and created variation in the number of hamlets sampled in each GP. The "official" number of distinct hamlets sampled in this way was 106; the smallest of these were later combined with nearby hamlets for the purpose of the stove promotion intervention to yield the final set of 97 hamlets.

Efforts were made to interview each sampled household. If a randomly selected household was unavailable during the entire day of fieldwork in a particular hamlet, or if it did not have an eligible respondent (i.e., the primary cook and/or head of the household were unavailable) or refused to participate, neighboring houses were randomly selected as replacements. Field supervisors performed household introductions, recorded GPS coordinates and elevation data, and oversaw quality control checks in each village. The final sample at baseline consisted of 1,063 households.

[‡]The specific location in Uttarakhand was selected for two principal reasons. First, we wanted to work in northern India, which is a hot spot for cooking with traditional stoves and fuels and all of its associated harms. Second, we sought to leverage a new partnership—focused on clean energy—with a local NGO.

Survey Design and Implementation. Surveys were repeated at four points in the study: (*i*) at baseline, (*ii*) during the intervention, and (*iii*) at two follow-ups. Respondents in the baseline survey (both male and female heads of household) answered questions on environmental and stove-related perceptions, household sociodemographics, stove and fuel use, and socioeconomic characteristics, and participated in a stove decision exercise designed to elicit preferences for an ICS. In addition, we conducted a 24-h fuel weighing activity and recall of detailed cooking behavior. Respondents were asked at the beginning of the period to bring more than enough biomass fuel to meet their needs over the next 24 h, this amount was weighed, and the amount remaining 24 h later was also weighed to measure fuel consumption. In the survey, women answered questions related to sociodemographics, and stove and fuel use, whereas men typically completed the socioeconomic sections, unless they were unavailable.

The survey conducted during the intervention was short and only administered to treated households; it mainly aimed to document which households were purchasing which ICS option and why. The main (first-round) follow-up instrument was similar to the baseline survey except that questions about stove purchase were replaced with questions about exposure to the sales campaign. The second-round follow-up was conducted to evaluate continued ownership and use of improved devices ∼15 mo after the intervention.

Randomization. The experimental intervention was composed of community- and household-level randomized components. Communities (hamlets) were randomized at the first level, which entailed acquiring and transporting ICS (electric and improved natural draft biomass) from urban wholesalers, developing storage and maintenance systems, training sales personnel to provide home delivery and marketing (including information, communication, and cooking demonstrations), and providing installment finance spread over three payments provided every 2 wk. Within treatment communities, households were further randomized into one of three rebates, which provided one of three price discounts, the magnitude of which was revealed to the household before the purchase decision. Households in different rebate groups and the control arm were balanced on baseline factors, and household attrition in the experiment was similar across groups (*SI Appendix*, Tables S1 and S2). The final analytical sample is 987 households for the measurement of impacts after accounting for 7% attrition between the baseline and follow-up.

Statistical Analysis of RCT Data. Our main analyses (presented in Fig. 2) are based on simple means comparisons. These comparisons are generally supported by regression comparisons of treatment and control households at follow-up (presented in *SI Appendix*, Table S1). For the latter, we estimated the following model:

$$y_{ij} = \beta_0 + \beta_1 \cdot t_{ij} + \epsilon_{ij}, \quad [1]$$

where y_{ij} is the outcome of interest (stove purchase, ownership or use, fuel consumption, and time spent collecting fuel) for household i in hamlet j. The variable t_{ij} is an indicator for treatment status (0 if control, 1 if treated), β_0 and β_1 are coefficients obtained using ordinary least squares regression, and ϵ_{ij} is the household-specific error term. Given that exposure to the intervention was assigned at the hamlet level, all standard errors are clustered by hamlet. Fig. 2 highlights the 90% confidence interval for the mean of each outcome.

In some of the results we present (*SI Appendix*, Table S3), we also test for heterogeneity using the randomly assigned rebate level,

$$y_{ij} = \beta_0 + \beta_1 \cdot t_{ij} + \beta_2 \cdot t_{ij} \cdot R_{ij} + \epsilon_{ij}, \quad [2]$$

where R_{ij} is the rebate level expressed in INR.

In addition to these analyses, we also derived difference-in-differences estimates (*SI Appendix*, Table S2 without the rebate and *SI Appendix*, Table S4 with the rebate) that control for differences across households via the inclusion of household fixed effects, even though treatment and control households were balanced at baseline, as shown in *SI Appendix*, Tables S6 and S7. The full model (including tests for heterogeneity using the rebate level) is the following:

$$y_{ijt} = \beta_0 + \beta_1 \cdot post_{it} + \beta_2 \cdot t_{ij} \cdot post_{it} + \beta_3 \cdot t_{ij} \cdot R_{ij} \cdot post_{it} + \gamma_i + \epsilon_{ijt}, \quad [3]$$

where $post_{it}$ is equal to 1 if measured at follow-up and is equal to 0 at baseline, and γ_i represents a household fixed effect.

SI Appendix, Fig. S1 depicts our final study design and shows the timing of surveys and intervention activities: from selection of villages and households to surveys at baseline and follow-up, with the design and implementation of the intervention in between. This figure also summarizes the village selection process and the randomized assignment of the intervention. We report the sample sizes at each stage, and note that roughly 7% of households had dropped out by the time of the follow-up survey (as summarized in *SI Appendix*, Table S6, attrition was balanced across treatment and control arms), yielding a final follow-up and analytical sample of 987 households.

Informed Consent. The study protocol was reviewed and approved by Duke University's Institutional Review Board (IRB Protocol A0946); informed consent was obtained from all study households.

Data Availability. The data and code used in this study are available at https://osf.io/b5asn/.

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1. P. Dasgupta, V. Ramanathan, Pursuit of the common good. *Science* **345**, 1457–1458 (2014).
2. M. A. Jeuland, S. K. Pattanayak, Benefits and costs of improved cookstoves: Assessing the implications of variability in health, forest and climate impacts. *PLoS One* 7, e30338 (2012).
3. W. J. Martin, R. I. Glass, J. M. Balbus, F. S. Collins, A major environmental cause of death. *Science* **334**, 180–181 (2011).
4. T. Ramanathan *et al.*, Wireless sensors linked to climate financing for globally affordable clean cooking. *Nat. Clim. Change* **7**, 44–47 (2016).
5. D. G. Victor, C. F. Kennel, V. Ramanathan, The climate threat we can beat: What it is and how to deal with it. *Foreign Aff.* **91**, 112–121 (2012).
6. K. R. Smith, In praise of power. *Science* **345**, 603–603 (2014).
7. M. A. Jeuland *et al.*, Preferences for improved cook stoves: Evidence from rural villages in north India. *Energy Econ.* **52**, 287–298 (2015).
8. A. M. Mobarak, P. Dwivedi, R. Bailis, L. Hildemann, G. Miller, Low demand for non-traditional cookstove technologies. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 10815–10820 (2012).
9. T. Beltramo, G. Blalock, D. I. Levine, A. M. Simons, The effect of marketing messages and payment over time on willingness to pay for fuel-efficient cookstoves. *J. Econ. Behav. Organ.* **118**, 333–345 (2015).
10. G. Bensch, J. Peters, The intensive margin of technology adoption – Experimental evidence on improved cooking stoves in rural Senegal. *J. Health Econ.* **42**, 44–63 (2015).
11. M. A. Jeuland, S. K. Pattanayak, R. Bluffstone, The economics of household air pollution. *Annu. Rev. Resour. Econ.* **7**, 81–108 (2015).
12. G. Bensch, J. Peters, Alleviating deforestation pressures? Impacts of improved stove dissemination on charcoal consumption in urban Senegal. *Land Econ.* **89**, 676–698 (2013).
13. G. Bensch, M. Grimm, J. Peters, Why do households forego high returns from technology adoption? Evidence from improved cooking stoves in Burkina Faso. *J. Econ. Behav. Organ.* **116**, 187–205 (2015).
14. N. Brooks *et al.*, How much do alternative cookstoves reduce biomass fuel use? Evidence from north India. *Res. Energy Econ.* **43**, 153–171 (2016).
15. R. Meeks, K. R. E. Sims, H. Thompson, Waste not: Can household biogas deliver sustainable development? *Environ. Resour. Econ.* **72**, 763–794 (2018).
16. R. Hanna, E. Duflo, M. Greenstone, Up in smoke: The influence of household behavior on the long-run impact of improved cooking stoves. *Am. Econ. J. Econ. Policy* **8**, 80–114 (2016).
17. J. J. Lewis, S. K. Pattanayak, Who adopts improved fuels and cookstoves? A systematic review. *Environ. Health Perspect.* **120**, 637–645 (2012).
18. J. Rosenthal *et al.*, Implementation science to accelerate clean cooking for public health. *Environ. Health Perspect.* **125** A3–A7 (2017).
19. W. C. Clark, Sustainability science: A room of its own. *Proc. Natl. Acad. Sci. U.S.A.* **104**, 1737–1738 (2007).
20. S. K. Pattanayak, A. Pfaff, Behavior, environment, and health in developing countries: Evaluation and valuation. *Annu. Rev. Resour. Econ.* **1**, 183–217 (2009).
21. S. K. Pattanayak, E. L. Pakhtigian, E. L. Litzow, "Through the looking glass: Environmental health economics in low and middle income countries" in *Handbook of Environmental Economics*, P. Dasgupta, S. K. Pattanayak, V. Kerry Smith, Eds. (Elsevier, 2018), vol 4, pp 143–191.
22. A. Hamoudi *et al.*, The effect of water quality testing on household behavior: Evidence from an experiment in rural India. *Am. J. Trop. Med. Hyg.* **87**, 18–22 (2012).
23. C. Poulos *et al.*, Consumer preferences for household water treatment products in Andhra Pradesh, India. *Soc. Sci. Med.* **75**, 738–746 (2012).
24. S. K. Pattanayak *et al.*, Shame or subsidy revisited: Social mobilization for sanitation in Orissa, India. *Bull. World Health Organ.* **87**, 580–587 (2009).
25. J. J. Lewis *et al.*, Biogas stoves reduce firewood use, household air pollution, and hospital visits in Odisha, India. *Environ. Sci. Technol.* **51**, 560–569 (2016).
26. I. Ruiz-Mercado, O. Masera, H. Zamora, K. R. Smith, Adoption and sustained use of improved cookstoves. *Energy Policy* **39**, 7557–7566 (2011).
27. E. Somanathan, R. Bluffstone, Biogas: Clean energy access with low-cost mitigation of climate change. *Environ. Resour. Econ.* **62**, 265–277 (2015).
28. D. Stanistreet *et al.*, The role of mixed methods in improved cookstove research. *J. Health Commun.* **20** (Sup1), 84–93 (2015).
29. V. Bhojvaid *et al.*, How do people in rural India perceive improved stoves and clean fuel? Evidence from Uttar Pradesh and Uttarakhand. *Int. J. Environ. Res. Public Health* **11**, 1341–1358 (2014).
30. J. J. Lewis *et al.*, Piloting improved cookstoves in India. *J. Health Commun.* **20** (sup1), 28–42 (2015).
31. H. Girardeau, S. K. Pattanayak, "Household solar adoption in low- and middle-income countries: A systematic review" (EfD Discussion Pap. 18-10, Environ. Dev. Initiative, Gothenburg, Sweden, 2016).
32. M. Khandelwal *et al.*, Why have improved cook-stove initiatives in India failed? *World Dev* **92**, 13–27 (2017).
33. M. Subramanian, Global health: Deadly dinners. *Nature* **509**, 548–551 (2014).
34. The World Bank, Access to electricity, rural (% of rural population), https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS. Accessed 12 December 2018.
35. B. K. Sovacool, Diversity: Energy studies need social science. *Nature* **511**, 529–530 (2014).
36. F. Usmani, J. Steele, M. A. Jeuland, Can economic incentives enhance adoption and use of a household energy technology? Evidence from a pilot study in Cambodia. *Environ. Res. Lett.* 12, 035009 (2017).
37. G. King *et al.*, A "politically robust" experimental design for public policy evaluation, with application to the Mexican universal health insurance program. *J. Policy Anal. Manage.* **26**, 479–506 (2007).