SOCIAL SCIENCES

Does basic energy access generate socioeconomic benefits? A field experiment with off-grid solar power in India

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This article assesses the socioeconomic effects of solar microgrids. The lack of access to electricity is a major obstacle to the socioeconomic development of more than a billion people. Off-grid solar technologies hold potential as an affordable and clean solution to satisfy basic electricity needs. We conducted a randomized field experiment in India to estimate the causal effect of off-grid solar power on electricity access and broader socioeconomic development of 1281 rural households. Within a year, electrification rates in the treatment group increased by 29 to 36 percentage points. Daily hours of access to electricity increased only by 0.99 to 1.42 hours, and the confidence intervals are wide. Kerosene expenditure on the black market decreased by 47 to 49 rupees per month. Despite these strong electrification and expenditure effects, we found no systematic evidence for changes in savings, spending, business creation, time spent working or studying, or other broader indicators of socioeconomic development.

INTRODUCTION

Although the rate of household electricity access in developing countries increased from 64 to 78% between 2002 and 2013 (*1*), more than 1 billion people still remain without basic electricity access. Economic studies show that electricity access holds considerable potential to improve household incomes, increase educational attainment, enhance access to media, and boost convenience in everyday life (*2*–*7*). However, many households in remote rural communities are not electrified because of the high cost of extending the electricity grid (*8*). Together with a rapid decrease in the cost of solar panels, this high cost of grid extension has provoked interest in off-grid solar power as an alternative (*9*, *10*), especially because solar power is cleaner than fossil fuels (*10*). In remote rural communities, the cost of solar power can fall below the cost of grid extension when capital cost, along with transmission and distribution losses, is considered in full (*8*, *11*, *12*). The Global Tracking Framework of the United Nations Sustainable Energy for All (SE4ALL) initiative expects that by 2030, 70% of new connections in rural areas will be provided by decentralized solutions, with two-thirds of these through microgrid construction (*13*). Another recent study argues that "the present day is a unique moment in the history of electrification where decentralized energy networks are rapidly spreading, based on super-efficient end-use appliances and low-cost photovoltaics… disruptive technology systems can rapidly increase access to basic electricity services and directly inform the emerging Sustainable Development Goals for quality of life, while simultaneously driving action towards low-carbon, Earth-sustaining, inclusive energy systems" [(*10*), p. 305]. How beneficial is off-grid solar power for development? Technologies, such as solar micro-grids, picogrids, and home systems are now used by millions of households around the world (*14*–*16*). Although the socioeconomic benefits of grid electricity access have been established in various economic studies (*2*–*6*), a recent study (*17*) suggests that simple household electrification is not enough and quality of supply is equally important.

In general, much less evidence is available for the causal effects of off-grid solar power. Both practitioners and academic studies have suggested that the use of technologies, such as solar home systems and microgrids, is associated with various improvements, such as increased children's study time, higher household incomes, and reduced kerosene expenditure (see a comprehensive review in section S1) (*14*, *16*, *18*–*21*). According to these studies, even a minimal increase in the availability of electricity can generate substantial socioeconomic benefits. For example, one field experiment finds that in 15 villages in rural Rwanda, a simple "solar kit" (light, mobile charger, and radio) reduces energy expenditures and enhances productivity and convenience (*20*). Existing research suggests that off-grid technologies can produce socioeconomic effects similar to the ones from grid access, although the scale is likely to be smaller. However, all of these studies, except the small field experiment in Rwanda (*20*), are observational, so they are not suitable for the estimation of causal effects.

To conduct a randomized controlled trial (RCT) designed to measure the causal effects of solar microgrids, we partnered with an Indian solar service provider, Mera Gao Power (MGP). We randomized the assignment of 81 nonelectrified habitations—small rural communities—to treatment and control groups in the Barabanki district of the state of Uttar Pradesh, India. In the treatment group, the MGP team approached villagers and offered to set up a solar microgrid if at least 10 households within the habitation subscribed at the monthly per-household cost of 100 rupees (~1.67 USD)—about 2% of the monthly household expenditure in the baseline.

MGP made no intervention in the control group. The solar microgrid offered a basic level of electricity access comprising bright domestic lighting (through two light-emitting diode lights) and mobile charging. Information on fuel expenditures, lighting hours, quality of lighting, and broader socioeconomic effects was collected from 1281 households surveyed on three occasions: a baseline (before treatment), a midline (half a year after treatment), and an endline (1 year after treatment). In the treatment group, 21 habitations saw the installation of the microgrid of MGP. Of the entire treatment group, one in seven households subscribed to the service during the experiment. The data are summarized

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in section S2. Adoption rate decreased slightly from 14% (midline) to 10% in the endline.

The results highlight the positive and negative aspects of the intervention. On the one hand, we uncover robust evidence for reduced kerosene expenditures and increased access to electricity (energy access effects). Kerosene purchases from the private market decreased by 47 to 49 rupees per month (72 to 75% of preintervention SD). However, because households continued to purchase subsidized fuel from the public distribution system (PDS), it seems that solar power and kerosene are not perfect substitutes. Moreover, the intervention increased the percentage of households with basic electricity access rapidly compared to secular trends in the area, with an estimated impact of 29 to 36 percentage points. However, on the basis of the local average treatment effects, availability of electricity per day increased by only 0.99 to 1.42 hours, and the confidence intervals around these estimates are wide. On the other hand, we found no evidence for socioeconomic benefits during the study period. There were no consistent effects on savings, household expenditures, household business creation, time spent in productive work by women, use of lighting for study, or other indicators of socioeconomic development, including female empowerment.

The findings underscore both the potentials and limitations of providing minimal electricity access through off-grid solar power. It is notable that an inexpensive, business-driven intervention without any state subsidies can have such a positive effect on the access to electric lighting in previously nonelectrified habitations. Because MGP offers electricity at night, the service contributes to serving households at peak demand time—typically around 7:00 to 8:00 p.m., when families gather for dinner—when electricity access is generally the weakest. At the same time, the lack of broader socioeconomic effects underscores the limits of minimal energy access.

When only small loads of power are available, households may not have enough energy for productive uses with transformative potential. Electrification programs that rely on off-grid technologies must consider the trade-offs between the complexity, the costs, and the benefits of these systems. Our findings do not imply that larger systems for generating off-grid solar power cannot produce broader socioeconomic benefits but generating these benefits may require more expensive interventions.

EXPERIMENTAL DESIGN AND RESULTS

The RCT was conducted between February 2014 and July 2015 in the district of Barabanki in Uttar Pradesh, India (see map in section S3). With a rural electrification rate of less than 24% in the 2011 census (*22*), Uttar Pradesh is ideal for investigating the benefits of alternatives to conventional grid extension. The Barabanki district itself has an even lower rural electrification rate (15%) than Uttar Pradesh overall, so it is an ideal location for the intervention (for a discussion of external validity, see section S4). Because our study habitations (small rural communities) are nonelectrified and very poor, they are ideal for assessing the benefits of basic energy access through solar microgrids. Most households in rural areas (95% of households in our baseline survey) still rely on kerosene as their main source of artificial lighting. Kerosene is obtained through both the PDS and the private (black) market (*23*). The former is subsidized and therefore cheaper, but households can only buy a fixed quantity that is often insufficient for their needs.

We estimate two kinds of effects. First, we estimate impacts on the cost and quality of household lighting (energy access effects). We expect our intervention to reduce kerosene spending primarily on the more expensive private market. We also expect it to increase electrification rates and the numbers of hours of electricity available to households. Second, we examine broader socioeconomic benefits. Improved lighting could bring socioeconomic benefits in the form of enhanced home business activity at night, better conditions for studying, and savings from kerosene expenditures (*14*, *16*, *20*). Because previous observational studies have found anecdotal evidence of off-grid solar power and female empowerment (*18*, *24*), we also test for these effects. When evaluating effects on female empowerment, we surveyed a female adult from the household. We report two kinds of treatment estimates: intent to treat (ITT) and local average treatment effects (LATE) (*25*). ITT measures the effectiveness of the intervention (randomized offer of MGP), considering that some habitations in the treatment group refused the treatment. It is an estimate of the lower bound of the treatment effect. LATE estimates measure the effect of the treatment only on households that live in habitations (21 of 50 in the treatment group) where an MGP system was actually installed. This is our preferred estimate. For the full experimental design, see section S3. A preanalysis plan was posted on a public website to avoid data mining (see sections S5 and S6). Section S7 shows balance statistics, suggesting that the randomization succeeded. For information about the use of different lighting solutions in different groups over time, see section S8 and note that the use of non-MGP solar technologies increased in both the treatment and control groups, again illustrating the importance of randomization for causal inference.

The ITT estimates are obtained by a least-squares regression of the following equation

$$Y_{i,h,t} = \alpha_i + \omega_t + \tau^{\mathrm{ITT}}\ \mathrm{treatment}_{h,t} + \varepsilon_{i,h,t} \qquad (1)$$

where i indicates households, h stands for habitation, and t is the survey wave. The parameters α and ω are household and wave fixed effects, respectively. The outcome Y is defined as indicated below. Treatment takes a value of 1 for habitations that were assigned to the treatment group, regardless of whether they became MGP subscribers or not. Thus, for a given habitation, all individual households have the same treatment status.

The LATE estimates are obtained by a two-stage least-squares regression of the following two equations. The first stage is given by

$$\mathrm{Installed}_{h,t} = \beta_h + \theta_t + \delta \mathrm{treatment}_{h,t} + \mu_{h,t} \qquad (2)$$

and the second stage is given by

$$Y_{i,h,t} = \alpha_i + \omega_t + \tau^{\mathrm{LATE}}\widehat{\mathrm{installed}}_{h,t} + \varepsilon_{i,h,t} \qquad (3)$$

Installed, similar to treatment, is measured at the habitation level (and thus varies by h and t). Again, household and wave fixed effects are included. If a microgrid was installed in the habitation, all subjects in the habitation were conservatively considered to be treated. (In section S9, we replicate the LATE results with household-level subscription, with similar results.) In a two-stage least-squares approach, the first stage is estimated by ordinary least squares. The predicted values of the dependent variable are then used as the independent variables in the second stage, also estimated with least squares. Two-stage least-squares estimates are possibly biased if the instruments are weak. Staiger and Stock (*26*) recommend a first-stage F statistic above 10 as a cutoff point. In the results tables below, we show that our F statistic is always above 10, except for mobile charging (the F statistic decreases because some households do not have mobile phones, with a corresponding decrease in sample size). Throughout, we cluster all SEs by habitation. In section S10, we replicate these results using additional observations from habitations located outside the Suratganj block, where our study took place, as a third comparison group. As a precaution against spatial spillovers, we collected these data to ensure that we could observe habitations far removed from MGP operations. We find little evidence for these spillovers.

Energy access effects

We report our energy access effects in Tables 1 and 2. In Table 1, we report the effect of our intervention on the likelihood of having electricity (Table 1A) and the hours of electricity available to households (Table 1B). Starting with models 1 and 2 in Table 1A, we find that the intervention overall increased electrification rates by 8 to 10 percentage points, with statistically significant coefficients. LATE estimates suggest larger increases in habitations with MGP service. The estimated increase in these habitations ranges between 29 and 36 percentage points, depending on the specification.

Turning to Table 1B, we find that the numbers of hours of electricity available per day increased both overall and specifically in habitations with MGP system installations. The increase due to the intervention, given by the ITT estimates, ranges from 0.29 to 0.42 hours, although here, the confidence intervals are wide. For households located in habitations that adopted service of MGP, the increase is 0.99 to 1.42 hours, a relatively low number with wide confidence intervals. In section S8, we show that households motivated the cancellation of a subscription mostly with problems related to the quality of the lighting provided. In section S11, we report results on perceived quality of lighting and overall lighting hours, with much smaller and less precise estimates. Overall, the key effect of the MGP intervention is the rapid spread of household electrification relative to the control group; changes in overall electricity consumption are less impressive. In turn, Table 2 shows the effects of our treatment on kerosene expenditures, measured in rupees per month. Table 2A examines household spending for kerosene on the (expensive) private market, and Table 2B is for spending through the (inexpensive and subsidized) PDS. In each panel, the first two models report the ITT estimates, and the last two show the LATE estimates. Specifications differ on the basis of the inclusion of household fixed effects. For p values corrected for multiple comparisons within a family of outcomes (*27*), see section S12. We only correct the p values for energy access outcomes because the socioeconomic effects are not statistically significant to begin with. For randomization inference to deal with small sample issues, see section S13.

Table 1. Effect of MGP solar microgrids on household electrification and hours of electricity. Results are shown for household electrification (A) and hours of electricity per day (B). The SEs are clustered by habitation and are given in parentheses. The dependent variable in (A) is a dichotomous variable that takes a value of 1 if the household reports having electricity and 0 otherwise. The dependent variable in (B) is the number of hours of electricity available per day. $n = 3825$; number of households, 1281. *$p < 0.10$, **$p < 0.05$, ***$p < 0.01$. FE, fixed effects.

	ITT (OLS)		LATE (IV)	
	(1)	(2)	(3)	(4)
(A) Access to electricity				
Treatment	0.10**(0.04)	0.08* (0.04)	0.36** (0.14)	0.29** (0.14)
Household FE		Yes		Yes
Wave FE	Yes	Yes	Yes	Yes
Pretreatment mean for control group = 0.01				
First-stage estimate			0.29	0.29
First-stage F statistic			10.15	10.01
(B) Hours of electricity				
Treatment	0.42 (0.26)	0.29 (0.27)	1.42 (0.91)	0.99 (0.92)
Household FE		Yes		Yes
Wave FE	Yes	Yes	Yes	Yes
Pretreatment mean for control group = 0.12				
First-stage estimate			0.29	0.29
First-stage F statistic			10.13	10

With respect to our ITT estimates, we find that the MGP solar microgrids reduce household spending on the private kerosene market by 14 rupees (~0.23 USD). The effect is statistically different from zero at least at the 5% confidence level. Note that total kerosene spending in the first survey (pretreatment) was 109 rupees, of which 73 rupees went toward kerosene from the private market. Thus, our intervention reduced private kerosene spending by about 20%.

The estimated reductions are larger when based on LATE, ranging from 47 to 49 rupees per month. The effects are statistically significant. Substantively, these estimates show that MGP service reduced spending of households on kerosene from private markets among subscribers. However, the effects are smaller than the MGP monthly fee (100 rupees per month), suggesting that net spending on electricity (primarily kerosene and MGP service) among these households increased on average.

Table 2B reports effects on spending on kerosene in the PDS. Unsurprisingly, the effects are indistinguishable from zero in all four models. Reduction in kerosene is limited to expensive private market supply because households continue to find kerosene useful as a secondary lighting solution or for alternative uses, such as fuel for diesel pumpsets or lighting a fire in their stove.

Finally, Table 2C shows the estimates for total kerosene spending (private and PDS). The treatment reduces overall kerosene spending, although unsurprisingly, the effect is smaller than for spending on the private market. In section S11, we further show that the intervention reduced the number of households using kerosene as their primary lighting source, consistent with the substitution of solar-powered lighting for private kerosene.

Socioeconomic effects

The next set of results concerns the socioeconomic effects of the MGP solar microgrids (Table 3). Besides household savings and expenditures, we pay attention to both economic activity (because improved lighting could contribute to home business) and educational benefits from improved lighting. We do not measure changes in existing businesses because very few households (7%) were involved in this activity before the intervention. Although we generally find weak evidence for socioeconomic effects, for some outcomes, the coefficients have wide confidence intervals. In particular, the estimated coefficients for savings and expenses, although not statistically significant, are relatively large. In the LATE esti-

Table 2. Effect of MGP solar microgrids on household kerosene spending. Effects are shown for spending in the private market (A), the PDS (B), and overall (C). The SEs are clustered by habitation and are shown in parentheses. All dependent variables are measured in rupees per month. $n = 3825$; number of households, 1281. $^{*}p < 0.10$, $^{**}p < 0.05$, $^{***}p < 0.01$.

	ITT (OLS)		**LATE (IV)**	
	(1)	**(2)**	**(3)**	**(4)**
(A) Kerosene spending on private market				
Treatment	−14.01*** (5.28)	−14.49** (6.91)	−47.49** (19.83)	−49.36** (24.62)
Household FE		Yes		Yes
Wave FE	Yes	Yes	Yes	Yes
Pretreatment mean for control group = 72				
First-stage estimate			0.29	0.29
First-stage *F* statistic			10.15	10.01
(B) Kerosene spending on PDS				
Treatment	3.37 (2.71)	1.23 (2.62)	11.41 (9.81)	4.18 (8.79)
Household FE		Yes		Yes
Wave FE	Yes	Yes	Yes	Yes
Pretreatment mean for control group = 35				
First-stage estimate			0.29	0.29
First-stage *F* statistic			10.15	10.01
(C) Total kerosene spending				
Treatment	−10.64** (4.56)	−13.26** (6.01)	−36.08** (15.93)	−45.18** (22.21)
Household FE		Yes		Yes
Wave FE	Yes	Yes	Yes	Yes
Pretreatment mean for control group = 107				
First-stage estimate			0.29	0.29
First-stage *F* statistic			10.15	10.01

mations, monthly savings and expenses are expected to increase by 25 and 15%, respectively, over pretreatment values. These are sizeable substantive effects, and the wide confidence intervals prevent us from rejecting potentially large effects. On the other hand, the effects on business ownership, time spent working by women, and time spent studying are fairly precisely estimated zero effects. It is thus unlikely that any of these outcome measures is affected by our treatment. See also sections S11 and S14 for treatment effects by wave.

One surprising result is the only weakly positive estimate for mobile charging costs. In section S15, we show that this null effect can be explained by noting that many households both in the control and treatment group are now using cheap batteries and other sources of electricity to charge their mobile phones, significantly reducing overall mobile charging costs regardless of treatment status. Overall, we conclude that the intervention had few socioeconomic effects during the evaluation period. Full results are reported in section S15.

The effects on indicators for female empowerment are negligible, as reported in section S15. No effects on violence and harassment of women are detected. Also, no effect on women's perceptions of a need for better lighting to improve safety or the safety of going outside after sunset is seen. Time spent cooking also does not change. In each case, the coefficients are tiny and statistically indistinguishable from zero. Overall, we find no evidence of broader socioeconomic transformations through female empowerment.

DISCUSSION

The impact evaluation produced two primary results. On the one hand, the intervention succeeded in reducing kerosene expenditures and increasing the availability of electricity to a large number of previously nonelectrified households. It did so quickly and without subsidies by the central or state governments of India. Although MGP did receive grant support for initial operations, the dependence of the company on subsidies overall is low (see section S16 for a description of the MGP business model). On the other hand, the socioeconomic effects were underwhelming. Within a year of implementation, the intervention did not contribute to social or economic development more broadly. Although the intervention improved access to modern energy, it did not have transformative effects on village economies or social life in the targeted habitations. Given that MGP offers only improved lighting and mobile charging and that changes in hours of electricity access were limited, a plausible explanation for this null result is that the intervention did not enable households to use these loads of power that would significantly enhance productivity.

In considering the external validity of the results, three factors stand out. First, we targeted nonelectrified habitations. In habitations with access to heavily subsidized grid electricity, demand for the service would have probably been lower. Second, the study area has, similar to most of Uttar Pradesh, low household electrification rates and levels of socioeconomic development. Finally, India's kerosene subsidies reduce the opportunity cost of using kerosene, possibly explaining the lack of positive effects on household savings. In settings with nonelectrified rural communities and more expensive kerosene (for example, many Sub-Saharan African countries), the intervention could have performed better.

The results should be evaluated in light of (i) the low cost of the intervention and (ii) the minimal level of electricity access provided to the households. Because the intervention did not require any subsidies, the lack of socioeconomic effects does not mean that the intervention was a failure. The MGP business model provided many households in the targeted habitations with electric lighting and mobile charging solutions. Even a modest subsidy could have increased the relatively low adoption rate in the habitations, especially among the poorer households. Because the capital cost of an MGP system falls below 1000 USD, the fixed cost of expanding the service would not be very high. Because MGP offers electricity at night, it contributes to meeting rural demand at peak time when supply interruptions by electric utilities are the most common. Kerosene subsidies carry a high cost for the government (*28*), and small-scale, off-grid solar power can offer a cleaner, safer alternative for basic household lighting. On the other hand, the results highlight the limits of off-grid solar power as an intervention for sustainable development. The results from our RCT show that there is a major difference

Table 3. Socioeconomic effects of MGP solar microgrids. The SEs are clustered by habitation and are shown in parentheses. "Savings" indicate household savings, measured in rupees per month. "Expenses" are household expenditures, measured in rupees per month. "Business" is a dichotomous indicator that takes a value of 1 if the household head owns a business. "Work time" is the time women spent working per day in hours. "Study" is a dichotomous variable that takes a value of 1 if the respondent or the children use lighting to study. "Phone charging" is the amount spent on phone charging, measured in rupees per week.

	Savings		Expenses		Business		Work time		Study		Phone charging	
	(1) ITT	(2) LATE	(3) ITT	(4) LATE	(5) ITT	(6) LATE	(7) ITT	(8) LATE	(9) ITT	(10) LATE	(11) ITT	(12) LATE
Treatment	65.82 (88.96)	224.17 (316.67)	192.81 (174.24)	656.69 (638.43)	−0.01 (0.02)	−0.03 (0.06)	−0.05 (0.21)	−0.18 (0.71)	−0.01 (0.03)	−0.02 (0.10)	0.66 (1.11)	2.55 (4.34)
Household FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wave FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pretreatment mean for control group	912		4455		0.06		4.07		0.61		8.84	
First-stage estimate		0.29		0.29		0.29		0.3		0.29		0.26
First-stage *F* statistic		10.01		10.01		10.01		10.65		10.01		7.66
Observations	3825	3825	3825	3825	3825	3825	3529	3529	3825	3825	2532	2532
Number of households	1281	1281	1281	1281	1281	1281	1263	1263	1281	1281	1103	1103

in the provision of comprehensive and minimal energy access. The large positive benefits of grid extension with high-quality supply were not realized in this intervention at least within a 1-year time window because minimal energy access did not allow households to use power for completely new, productive purposes. Larger distributed energy systems could have had larger effects because they would offer larger loads of power, but their capital costs would also have been much higher and would have required state subsidies. The effects could also have been different in areas with higher levels of preexisting economic activity and social capital, but these areas may see less need for off-grid solutions in any case. Another possible way to improve the effects of off-grid solar power would be a complementary intervention to create new social and economic opportunities in the community. Areas with more potential for rural business development could generate different results, underscoring the need to replicate and extend our study in other areas of India and the world.

MATERIALS AND METHODS

Experimental design

The experiment was conducted in the Barabanki district in the Uttar Pradesh state in India between February 2014 and July 2015. We first selected a total of 81 nonelectrified habitations in the Suratganj block of this district. By nonelectrified habitations, we mean habitations that are not connected to the national electricity grid. Of these habitations, a random half was selected into the treatment group, whereas the other half was selected into the control group. The control group habitations were also randomly assigned a spot on a wait list before the treatment assignment, in case additional habitations would have to be included to the treatment for reasons of statistical power.

Given the proximity of habitations in India, we also randomly selected 20 more habitations from two blocks, neighboring the Suratganj block, Ramnagar and Fatehpur, as part of the control group (labeled as the remote control group). These habitations were not used in the main analysis, but in section S10, we report the results when they were added as part of the control group. To foreshadow, this variant showed that geographic spillovers between the treatment and control group were not biasing our main estimates.

We first conducted a baseline survey for all 101 habitations, randomly selecting 16 households within each habitation. In some habitations, we could not get 16 households, and so, the baseline survey consisted of 1597 survey respondents (1281 if the remote control habitations were excluded). In this survey, we asked the respondents questions about their monthly kerosene expenditures, savings, time spent working and studying, phone charging, and demographic household characteristics. Through this survey, we were able to identify the baseline characteristics of households in the study sample.

The treatment in this experiment consisted of providing households in the treatment habitations with an opportunity to subscribe to the service of an off-grid electricity company. This offer was directly made to the households by our project partner, MGP, the local solar electricity provider. Then, MGP representatives went to the treatment habitations and offered households an opportunity to subscribe to a microgrid service for two light sources and a phone charging outlet for 5 hours per day at a cost of 100 rupees per month. After the offer was made, the households decided whether they wanted to subscribe to the MGP service. Among the 785 treatment households that were surveyed in midline, 112 had accepted the offer of MGP, meaning that the adoption rate was 14.2% in our survey (of course, there were many more households outside the survey that may or may not have adopted). Households did not have to commit to the service; they were free to discontinue the subscription at any time. Because our goal was to assess the impact of MGP service, we did not, in any way, try to influence their business model or amplify its impact. For example, we did not encourage community participation beyond what MGP did on its own.

On average, about half a year after the treatment, we resurveyed all 1597 households across the 101 habitations. We asked the same questions as we did in the baseline survey as well as some additional ones to understand the reasons for (non)adoption of the MGP service.

This panel design allowed us to effectively estimate the change in behavior at the household level. To ascertain whether any change in household behavior because of the treatment had only a short-term effect, we resurveyed all 1597 households again, about a year after the treatment. In summary, we conducted three waves of surveys—a baseline before the administration of treatment, a midline about half a year after, and an endline a year after the treatment.

During the study period, alternatives to kerosene were rapidly growing in the study area because people increasingly bought batteries, solar home systems, and grid connections for their use. We show in section S8 that alternatives to kerosene, excluding MGP service, increased from 4 to 20% during the 18 months between baseline and endline. These trends could not confound the causal estimates because MGP offerings were randomized, but they should be considered in evaluating the external validity of the analysis.

The timeline was as follows:

(1) February 2014 to March 2014: Baseline survey
(2) April 2014 to July 2014: Administration of treatment
(3) September 2014 to October 2014: Midline survey
(4) May 2015 to June 2015: Endline survey

Primary outcome variables

We asked the respondents a number of questions in all three waves. This allowed us to measure changes in reported behavior at the household level and to identify whether the treatment contributed to this change. In this section, we list the questions and coding of the outcome variables used in this study; we also indicate, for each measure, in which tables/models they were used. All primary outcome variables listed below refer to the tables in the main text. In addition to the main results, sections S17 to S21 contain a number of additional robustness tests.

(1) Does your household have any electricity?: A dichotomous variable that measures whether the household has any electricity (Table 1A).

(2) How many hours a day is electricity usually available for your household?: A continuous variable between 0 and 24 that measures the number of hours on an average day that the household has electricity (Table 1B).

(3) How many rupees do you spend buying kerosene per month from the private market?: A continuous variable that measures the average monthly amount spent on kerosene purchased from the private market by the household (Table 2A).

(4) How many rupees do you spend buying kerosene per month from PDS?: A continuous variable that measures the average monthly amount spent on kerosene from the PDS by the household (Table 2B).

(5) We sum up the responses to the two previous questions to generate a variable measuring total kerosene spending (Table 2C).

(6) How many rupees a month does your household save?: A continuous variable that measures the average monthly savings of a household (Table 3, models 1 and 2).

(7) How many rupees a month does your household spend?: A continuous variable that measures the average monthly expenses of a household (Table 3, models 3 and 4).

(8) Do you or anyone in your household run your own business?: A dichotomous variable that measures whether any household member runs a business (Table 3, models 5 and 6).

(9) How much time do you spend working every day?: A continuous variable that measures the average number of hours spent working by an adult female in the household. We survey the adult female because most male household heads are engaged in agriculture, so that their working hours may not respond to improved lighting (Table 3, models 7 and 8).

(10) What do you use your lighting for? Studying? Do your children also use lighting? If yes, do they use it for studying?: These two questions are combined to construct a dichotomous variable to determine whether the household head or any of the children use lighting to study (Table 3, models 9 and 10).

(11) How much money do you spend on charging your battery in your mobile phone per week?: A continuous variable that measures the amount of money the household spent on charging their mobile phone battery in an average week (Table 3, models 11 and 12).

Additional outcome variables on women's safety

(1) How often are women subject to domestic violence in your hamlet?: An ordinal variable (scale, 1 to 4) that measures perceptions of domestic violence in the habitation. Respondent is an adult female from the household. Because lighting could improve women's safety at night, we test for the effects on violence against women.

(2) How often are women eve-teased in your hamlet?: An ordinal variable (scale, 1 to 4) that measures perceptions of eve-teasing of women in the habitation. Respondent is an adult female from the household. This question is intended to capture positive effects on female safety in the case of less serious harassment.

(3) Would you feel safer if there were more light?: An ordinal variable (scale, 1 to 3) that measures perceptions of whether improved lighting would enhance safety. Respondent is an adult female from the household. This question focuses on women's perception of their own safety.

(4) Is there sufficient lighting for you to go outside during the dark?: An ordinal variable (scale, 1 to 5) that measures perceptions of whether there is enough light to go outside safely. Respondent is an adult female from the household. This question focuses on women's perception to act independently after sunset.

(5) How much time do you spend cooking every day?: A continuous variable (scale, 0 to 24) that measures the time spent per day for cooking. Respondent is an adult female from the household.

As we collected the data, we chose not to request the respondents to tell about their recent behavior. Instead, we framed the questions more generally, focusing on a typical day, week, or month. The disadvantage of this approach is that it may dilute some effects over time because respondents may be less sensitive to changes with this question framing. On the other hand, it also abstracts away from seasonal variations unrelated to the provision of off-grid solar power. In the end, it seems that we were able to detect changes, given the strong and robust results on changes in PDS kerosene expenditures.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/3/5/e1602153/DC1
section S1. A comprehensive literature review of the effects of electricity access
section S2. Summary statistics
section S3. Study setting
section S4. Site selection and external validity
section S5. Preanalysis plan
section S6. Additional estimates based on the preanalysis plan
section S7. Balance statistics
section S8. Additional descriptive data
section S9. Different LATE
section S10. Testing for geographic spillovers
section S11. Additional regression output for energy access effects

section S12. Multiple comparisons
section S13. Placebo tests from randomization inference
section S14. Additional regression output for socioeconomic effects
section S15. Socioeconomic effects: Full results
section S16. MGP
section S17. Robustness: Energy access effects without flooded villages
section S18. Robustness: Energy access effects without contaminated villages
section S19. Robustness: Energy access effects without suspicious case
section S20. Robustness: Energy access effects without treatment from wait list
section S21. Robustness: Energy access effects without households with 24 hours of electricity
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table S2. Summary statistics for outcome and other key variables, separate for treatment, control, and remote control group and by wave.
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fig. S2. Spending on kerosene on the private (black) market in the pretreatment period (baseline survey).
fig. S3. Spending on kerosene through the PDS in the pretreatment period (baseline survey).
fig. S4. Hours of electricity per day in the pretreatment period (baseline survey).
fig. S5. Placebo estimates for electricity access, private kerosene expenses, and total kerosene expenses.
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