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The behavioral impact of basic energy access: A randomized controlled trial with solar lanterns in rural India

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ABSTRACT

How beneficial is basic energy access – typically lighting and mobile charging – for rural households? Despite research on the economic impacts of basic energy access, few studies have investigated how it changes household behavior. Here we report results from a randomized controlled trial in rural Uttar Pradesh, India, which identifies the behavioral impacts of providing solar lanterns to households that normally rely on kerosene as their primary source of lighting. Eighty-nine of the 184 households participating in the study were given a free, high-quality solar lantern. Comparing changes in responses from the baseline questionnaire and an endline questionnaires administered six months later, we find that the lanterns reduced energy expenditures, improved lighting, improved satisfaction with lighting, more use of lighting for domestic activities (e.g., reading), and improved satisfaction with lighting for domestic activities. Overall, our results show that basic energy access can offer substantial benefits within the households, even if broader rural economic transformation is not plausible.

Introduction

The falling cost of solar panels has drawn global attention to distributed solar power as a solution to energy poverty (Bazilian et al., 2013; Aklin, Bayer, Harish, & Urpelainen, 2017). Considering the high costs of grid extension and the governance problems that continue to plague many emerging countries, distributed solar power – from lanterns to mini-grids – is an appealing alternative with potential for lower capital costs and better reliability. However, previous studies leave at best a mixed impression of the social and economic benefits of distributed solar power. While randomized controlled trials suggest that it reduces energy expenditure (Aklin et al., 2017; Grimm, Munyehirwe, Peters, & Sievert, 2015) and provides modest health benefits (Kudo, Shonchoy, & Takahashi, 2018), they find little evidence for more fundamental changes such as business development or increased savings rates.

Here we contribute to the literature by focusing sharply on behavioral, time use, and subjective benefits. Considering the complexity of economic development, it is unrealistic to expect lighting and mobile charging to produce large socio-economic changes, and yet both lighting and mobile connectivity can provide consumers with easier and more productive lives. In particular, the technology can facilitate various domestic and leisure activities that require lighting and offer flexibility around when households choose to engage in them (Kabir, Kim, & Szulejko, 2017; Rom, Günther, & Harrison, 2017; Khandker, Samad, Sadeque, Yunus, & Haque, 2014). We thus formulate hypotheses based on the kinds of outcomes that have a good chance of being improved by basic energy access through distributed solar lantern. To evaluate these benefits, we conduct a randomized controlled trial (RCT) in rural Uttar Pradesh, India. In collaboration with a non-governmental organization, we randomly provided free lights to 89 of the 184 households using a balanced complete block design with villages as relevant blocking factors.[1] We measured their effects on households' behavior and attitudes six months later.

The paper proceeds as follows. Section 2 contextualizes this paper in the context of related policy and academic literature. Section 3 summarizes the theoretical framework of the paper and inductively develops five sets of hypotheses. Section 4 describes the research design used to

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[1] Half of the 200 households originally participating in the study were given a free lantern. After accounting for attrition and non-compliance, we analyze data from 184 households, of which 89 had randomly been given a solar lantern.

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test the hypotheses. Finally, section 5 describes and discusses our results and their policy implications.

Background and literature

This section first situates our study in the context of current policy and academic literature. Through 2017, India's non-electrified population was the largest in the world, and due to the high costs of extending electricity grids to rural communities, they composed the overwhelming majority of non-electrified households (Mahapatra & Dasappa, 2012; World Bank, 2017; International Energy Agency, 2017). Due to their cost-efficiency in providing electricity to less concentrated areas, decentralized standalone solutions are expected to become the primary means of global rural electrification by 2030 (World Bank, 2014). The promise of such "off-grid" solutions has spurred research exploring their impacts on job creation, educational outcomes, and subjective measures of wellbeing in rural communities (Lemaire, 2018). Until recently, few experimental studies had considered the impact of off-grid energy access on consumers' behavior, but novel findings identify the effects of solar home systems (SHS) and mini-grids on households' consumption patterns and daily schedules (Barman, Mahapatra, Palit, & Chaudhury, 2017; Aklin et al., 2017). Given their affordability, solar lanterns remain comparatively under-studied, yet we know of no experimental research that evaluates their behavioral impacts in India.

Impact of rural electrification

Despite India's large non-electrified population, the country has successfully increased its electrification rate by nearly 57 percentage points since 2000, extending energy access to more than half a billion people (International Energy Agency, 2017; Government of India, 2019).[2] Late 2017 saw the commencement of the *Pradhan Mantri Gramodaya Yojana* (*Saubhaghya* scheme) to provide free electricity connections to all rural and poor urban households through the Rural Electrification Corporation. The *Saubhagya* scheme aims to electrify all households by early 2019 by requiring distribution companies (DISCOMs) to organize camps (for villages and clusters of villages) where households can complete application forms for energy connections. Electricity is then provided through extensions of existing delivery systems ("last mile connectivity") or standalone SHS.

In late April 2018, the Government of India announced 100% village electrification, with villages classified as electrified if electricity infrastructure is available in their inhabited hamlets, electricity is provided in public spaces, and at least 10% of households are electrified (Government of India, 2004). Despite its aim to electrify all 24.8 million households that were non-electrified as of October 2017 by December 2018, government figures indicate that as of late March 2019, approximately 19,000 households remained non-electrified (Goverment of India, 2018a). Historically, the share of non-electrified households has remained high in Uttar Pradesh, and as recently as December 2018, government figures indicated that 24% of households remained non-electrified (Goverment of India, 2018b). Current figures, which indicate 100% electrification, exclude households classified as "unwilling" to obtain electricity (Urpelainen, 2019). In 2018, the majority of non-electrified households in the state reported that they were unable to afford electricity connection costs, and 20% reported lacking the necessary infrastructure to connect to the grid (Jain et al., 2018). Even nominally electrified households saw high variation in electricity quality, with Jain et al. (2018, 38) noting that nearly 43% of the state's households obtain only limited grid capacity and report poor reliability and quality leading to blackouts and high- and low-voltage days.

These obstacles to grid electrification have led to a growing interest, among policymakers and researchers, in decentralized electricity generation (Alstone, Gershenson, & Kammen, 2015; Arunachalam, Pedinti, & Goel, 2016). While most developing countries have always struggled to achieve adequate rural electrification with grid-connected systems, the emergence of decentralized systems in India's policy discussions is relatively new.[3] Centralized systems, which require large investments in transmission and distribution grids, are less profitable in rural communities due to lower local load densities and capacity utilization, and higher construction and maintenance costs (Hiremath, Shikha, & Ravindranath, 2007; Kaundinya, Balachandra, & Ravindranath, 2009; Liming, 2009). These challenges have historically been compounded by India's deteriorating grid infrastructure (Palit & Bandyopadhyay, 2017)[4] and persist due to disorganized institutional capacity and communication between them (Blankenship, Harish, Wong, & Urpelainen, 2020; Aklin, Bayer, Harish, & Urpelainen, 2015; Urpelainen, 2014).

A growing body of research explores off-grid systems, which rely on biomass gasification or solar PV processes to generate energy, as promising low-carbon alternatives to centralized systems (Khan, Ahmad, Nasir, Nadeem, & Zaffar, 2018; Moner-Girona et al., 2019; Mahapatra & Dasappa, 2012). Standalone solar PV systems generate power without relying on a utility grid. As opposed to grid connected systems, which use a bi-directional interface to back-feed the grid when electricity supply exceeds demand, standalone systems require batteries to provide electricity at night (Balfour & Shaw, 2011). They also typically lack inverters, which convert PV output from direct to alternating current. Consequently, compared to grid connected systems, standalone PV systems face greater limitations in the electrical loads that can be delivered at stable voltages and the end-use equipment that they can power (Florida Solar Energy Center, 2019; Chaurey & Kandpal, 2010). For rural villages, where local demand can be satisfied without high plant load factors, standalone PV systems can provide electricity for basic services, such as lighting, charging mobile phones, and operating fans (Kaundinya et al., 2009; Tongia, 2018). Decentralized systems have grown in popularity among policymakers and consumers. *Saubhagya* provides SHS standalone systems where grid extensions are infeasible or cost-prohibitive, and their adoption has grown rapidly across Asia (Sovacool & Drupady, 2011). Globally, off-grid solar technology is anticipated to compose 70% of the total increase in electricity access among households by 2030 (World Bank, 2014).

Despite the promise of decentralized systems, there remain barriers to their adoption. First, rural and poor non-electrified households often cannot afford solar technology and associated services. In an impact evaluation survey in Uttar Pradesh, India, Aklin, Bayer, Harish, and Urpelainen (2018) find that households' incomes and savings increase their likelihood of adopting solar microgrids.[5] The problem of affordability is further exacerbated in the case of solar lighting technologies, which face competition from subsidized kerosene (Garg, Sharma, Clarke, & Bridle, 2017; Mills, 2016). Second, liquidity constraints also prevent consumers and communities from obtaining funds necessary to invest in off-grid technology. An RCT in Uttar Pradesh India conducted by Urpelainen and Yoon (2017) finds that households' decision not to purchase solar technology appears to be the product of their

[2] While efforts to electrify rural households date back to the 1970s, they have accelerated since the early 2000s with the passage of the Electricity Act of 2003 (Banerjee, Barnes, Singh, Mayer, & Hussain, 2015; Bhattacharyya & Jana, 2009).

[3] It should be noted that early electrification was conducted on a small scale through small generation plans and batteries in the 19th century, but ended with the diffusion of Alternating Current (AC) grid technology, which required larger transmission grids and generation plans (Mandelli, Barbieri, Mereu, & Colombo, 2016). Nonetheless, due to India's relatively late electrification, the country developed a centralized electrical system.

[4] Grid infrastructure has improved following a 2005 push to increase investments and *Saubhagya*, though there remains variation in the quality of supply (Kennedy, Mahajan, & Urpelainen, 2019).

[5] Urpelainen (2018) proposes a voucher system to create a market among such populations and overcome entrepreneurs' hesitance to invested in distributed technology due to low expected returns.

inability to obtain credit rather than their lack of knowledge about the technology. However, in a previous study eliciting households' willingness to pay for solar lanterns in rural Uttar Pradesh, Yoon, Urpelainen, and Kandlikar (2016) find that allowing households to postpone payments on lanterns (to increase the window of time over which they obtain funds) does not increase their willingness to pay (WTP). Grimm, Lenz, Peters, and Sievert (2020) similarly elicit WTP for solar technology among 325 rural households in Rwanda, but find that relaxing liquidity constraints does not increase WTP. Finally, even without credit constraints, households may face risk aversion, which may bias them against adopting new technologies (Aklin et al., 2018).

Solar lighting and behavioral change

In India, lighting composes a greater share of residential electricity consumption than any other activity, with estimates ranging from 20 to 40% (World Bank, 2008; Boegle, Singh, & Sant, 2010; Banerjee et al., 2015; NITI Aayog, 2016). Over the last decade, the share of urban households relying on electricity as their primary source of lighting was nearly double that of rural households, which have relied primarily on kerosene lamps (Banerjee et al., 2015). While the difference can be explained, in part, by varying grid connectivity, it is also the product of India's historical prioritization of agricultural over residential electrification in rural areas. This led to under-investment in infrastructure to provide electricity for rural residential consumption and to rationing and tariffs to appease farm lobbies, which distorted markets.[6] While there is a well-developed literature illustrating the benefits of grid electrification in India and other developing countries (Barnes, 1988; Independent Evaluation Group, 2008; Barnes, 2010; Van de Walle, Ravallion, Mendiratta, & Koolwal, 2013; Aklin, Cheng, Ganesan, Jain, & Urpelainen, 2016), research on the impacts of off-grid solutions is comparatively recent.[7]

Research on the effects of solar lanterns on socioeconomic outcomes is limited (Grimm et al., 2015; Rom et al., 2017; Rom, 2019), and to date, we are aware of no such studies conducted in India. More broadly, research on the effects of off-grid solutions is generally descriptive and is consequently unable to causally identify the effects of renewable energy sources.

A number of these studies rely on case studies. Kirubi, Jacobson, Kammen, and Mills (2009), for instance, focus on the Mpeketoni Electricity Project in rural Kenya. To study the effects of micro-grids on the productivity of small- and medium-sized enterprises and the effectiveness of social and business service delivery, they rely on surveys of business-owners, interviews with local groups and stakeholders, and the project's financial records. They find that community micro-grids increase productivity and the effectiveness of social and business service delivery. Szakonyi and Urpelainen (2015, 2016) conduct field studies in a marketplace in Bihar, India, measuring community-level outcomes following the installation of a solar panel in a local marketplace. While the panel was meant to provide electricity to local vendors who rely on rented lamps that require chargeable batteries, the program was stymied due to institutional and financial obstacles and opposition by local competitors. Wong (2012) interviews households in Char Kajal, Bangladesh, where a World Bank program provided individual solar home systems, and in Rajasthan, India, where an NGO subsidized the rental of solar lantern systems. Bisaga and Parikh (2018) conduct a case study of twenty SHS users in Rwanda and collect detailed information about their energy and appliance use. Among their findings are that the impacts of SHS on social practices depend on the appliances available to households, and that SHS displace kerosene as a source of lighting. Winther (2008) studies the electrification of a rural community in Zanzibar, using the case to understand how the introduction of new technology impacts social relationships between different generations, genders, and patterns of marriage. A related and growing body of case studies and descriptive research also explores the impact of electrification on women's empowerment (Winther, Matinga, Ulsrud, & Standal, 2017).

Based on these cases, it argues that the acquisition of solar lighting among poor households in Bangladesh and India is limited by their financial exclusion, weak local governance, and passive NGO and customer participation. While these case studies provide useful exploratory data, their small samples limit the generalizability of their findings. Moreover, because they do not control for confounding variables, it is difficult to disentangle the impacts of the technology itself from other variables affecting uptake and behavioral or economic outcomes.

As opposed to these case studies, Rao, Agarwal, and Wood (2015) use a larger survey dataset with propensity score matching to compare the effects of grid, microgrid, and SHS electricity in Nepal and India. They survey 859 households and 74 small- and medium-sized enterprises across two districts in Bihar and one in Nepal, using random sampling to select households and matching households on the basis of their assets, the household head's education level, their distance from paved roads and water sources, and their size. The study finds off-grid solutions to increase women's leisure time and households' perceptions of lighting quality available to children for studying at night. Businesses report losses from unreliable electricity, but other economic outcomes from non-grid solutions are mixed. Compared to non-electrified households, Rao et al. find similar households with SHS to consume less kerosene but those with grids or micro-grids to consume similar amounts. By randomly sampling households to interview, Rao et al. (2015) draws a sample more representative of its target population than case studies. By comparing similar households, it also suffers from less confounding than the case studies. Nonetheless, it is unable to control for sources of unobserved confounding among households and, due to the imbalance in the number of households across districts and electricity source, sampling error may reduce the strength of its identification. Stojanovski, Thurber, and Wolak (2017) survey and track 500 early adopters of SHS in Uganda and Kenya, and find that SHS are associated decreases households' reliance on kerosene for lighting and external vendors for charging their mobile homes. The study compiles a detailed dataset, though the authors note that their results are descriptive and that the results do not necessarily generalize beyond early adopters of the technology.

While studies that rely on observational data are less likely to identify the causal effects of technology, RCTs allow for more credible causal inference. There are few RCTs measuring the socioeconomic effects of off-grid technology, and none conducted in India. Evidence concerning socioeconomic effects of solar lanterns in other countries is mixed. Grimm et al. (2015) conduct an RCT in Rwanda, finding that pico-PV kits reduce air pollution and decrease households' energy expenditures and reliance on traditional lamps. While they also measure the effects of pico-PV kits on the time spent by women on housework and by children on studying, the effects are limited.[8] Rom et al. (2017) conduct a similar RCT in rural Kenya. In addition to their primary focus on the demand for small-scale solar products and their use, they also measure effects of solar lights on household energy expenditure and their allocation of time. The study does not measure the effect of solar lanterns on household satisfaction, though the authors note that greater time spent on studying by children suggests some gains in welfare. Evidence from an RCT in Bangladesh similarly finds that solar lanterns measurably increase children's time spent studying and school attendance, but

[6] Attempts, in the 1980s, to expand household lighting through the Integrated Rural Energy Programme and *Kutir Jyoti Yojana* were hindered by farm lobbies, who opposed proactive rationing and demanded a low agricultural flat tariff (Palit & Bandyopadhyay, 2017). State Electricity Boards (SEBs) sought to cross-subsidize by increasing tariffs on other commercial units, who, in turn, tampered with meters and evaded payments. Consequently, SEBs were unable to provide reliable power, leading to frequent blackouts.

[7] See Aklin et al. (2017, Appendix S1) for a comprehensive review of literature measuring the impacts of solar micro-grids, SHS, and solar lanterns.

[8] Surveys from Zambia (Gustavsson & Ellegård, 2004; Gustavsson, 2007) and a case study from Bangladesh (Mondal & Klein, 2011) suggest that solar lanterns increase children's access to educational opportunities, but a recent RCT conducted in Uganda suggests otherwise (Furukawa, 2014).

that these behavioral changes are not reflected in higher academic results (Kudo, Shonchoy, & Takahashi, 2017). As opposed to other studies, Stojanovski, Thurber, Wolak, Muwowo, and Harrison (2018) conduct an RCT in Zambia to measure the effect of solar lanterns *net* of an income effect (of having received an item of comparable value to the solar lantern). Using a lottery to assign various treatments at a school in addition to the lantern — backpacks, a battery-powered alarm clock, soap — and assigning candy to a control group of students, Stojanovski et al. (2018) find no measureable effect of lanterns on standardized exam scores or students' self-reported study habits. In Ghana and India, Sekyere, Forson, and Akuffo (2012) and Chaurey and Kandpal (2009) provide solar lanterns to participants through randomly assigned rental package and fee-for-service offers. These studies, while important, focus primarily on understanding households' economic behavior and collect little to no information about their satisfaction, perceptions toward solar technology, or their time allocation.

Considering off-grid technologies more broadly, Aklin et al. (2017) conduct an RCT in Uttar Pradesh, offering free installations of solar micro-grid systems to habitations if at least ten members sign up for a monthly subscription of 100 rupees. Habitations offered a subscription exhibit higher electrification rates and report lower kerosene expenditures than others, but they find that the availability and free installation of solar micro-grids has no systematic causal effect on their households' savings, spending, business creation, time spent working or studying, or other broader indicators of socioeconomic development. This study and Aklin et al. (2017) are similar insofar as measure the socioeconomic effects of off-grid technology, but whereas Aklin et al. (2017) rely on a subscription-based intervention (and consequently face high rates of non-compliance), the one in this study, while more modest than solar micro-grid systems, is more affordable and provided to the treatment group at no cost.

Despite the strong internal validity of RCTs and their ability to allow for unbiased estimation of causal effects, they also face a number of limitations (see Deaton and Cartwright (2018) for a review). First, while well-conducted RCTs can produced unbiased estimates of *average* treatment effects in a given population by randomizing treatment, they provide limited to no insight on heterogeneity in treatment effects, if any (Imbens & Wooldridge, 2009), and variance in effects within populations (Subramanian, Kim, & Christakis, 2018). Second, even the random assignment of treatment may produce treated and untreated groups that differ in ways that affect outcomes. Econometricians have sought to account for differences by matching observations in each group Heckman, Ichimura, and Todd (1998) or relying on block designs, but even these require making assumptions about causes that affect outcomes and fail to account for unobservable or unknown causes (Deaton & Cartwright, 2018). Third, the role of the researcher in monitoring post-randomization activity (e.g., compliance), categorizing and defining outcomes, and administering treatments may also bias outcome. Finally, the extent to which results from an RCT can be extended to other settings is limited, and the results from RCTs may even differ from those observed when the treatment is incorporated into public policy.

Our study is not exempt from these limitations, but it nonetheless makes three related contributions to existing literature. First, it extends growing research on the socioeconomic and behavioral impacts of solar technology — namely SHS and solar micro-grids — to solar lanterns. Although solar lanterns generate less power than SHS and micro-grids, they are also significantly cheaper and may thereby serve as one of the few options for poor households to obtain electricity. Solar lanterns can provide high marginal benefits to a vulnerable population, and so it is important — for the purpose of policymaking and welfare maximization — to causally identify their effects on household behavior and well-being. In collecting granular data on household lighting and non-lighting expenditures and by measuring household satisfaction along a number of dimensions, this study also draws conclusions that are comparable to existing work (Aklin et al., 2017). In this sense, it contributes to research needed to adjudicate whether or not off-grid solutions provide socioeconomic benefits to households.

Second, it extends a limited body of research on the socioeconomic effects of solar lanterns to India. As opposed to studies that use large-scale interventions measured on the basis of generating transformational economic change (Chaplin et al., 2017; Lenz, Munyehirwe, Peters, & Sievert, 2017), growing research on solar lanterns focuses on precisely measuring the causal impact of a smaller intervention on socioeconomic outcomes at the household-level. This study extends previous work to a new and important setting. Moreover, by gathering data pertaining to spouses' and children's perceptions toward and satisfaction with solar technology and its impact on how they spend their time, it sheds light on populations that have, previously, been understudied. Third, by relying on an RCT with stratified randomization, it draws more credible causal inferences about socioeconomic and behavioral effects — rather than broader measures of economic development — of solar lanterns on households.

Theory and predicted effects

The predicted effects outlined in the following section rest on traditional consumer choice theory and on previous studies demonstrating relationships between a technology's quality and its users' satisfaction with and perceptions toward the technology. Consumer choice theory predicts that a decrease in the price of a good produces a (i) substitution effect, decreasing demand for substitutes and increasing demand for complements[9]; and (ii) an income effect, wherein the lower price increases the consumer's purchasing power, spurring demand for normal goods and decreasing demand for inferior goods.[10] While the income and substitution effects motivate substantial research on rural electrification in developing countries (Gunatilake, Maddipati, & Patail, 2012; Rao, 2013; Barnes, Samad, & Banerjee, 2014),[11] it remains unclear whether their implications extend to solar lanterns, which are highly affordable compared to SHS and micro-grids but limited in their capacity to generate and store electricity. The theoretical relationship between the quality of electricity and consumers' satisfaction with and perceptions toward it is more apparent. Empirical studies have identified positive relationships between the quality of electricity generated by SHS and micro-grids and consumers' attitudes toward it (Rao et al., 2015; Aklin, Cheng, Urpelainen, Ganesan, & Jain, 2016), but to date, there has been limited research measuring the causal effect of high quality solar lanterns on consumers' satisfaction with lighting and perceptions toward solar lanterns. Whether high quality solar lanterns induce favorable attitudes and perceptions is, once again, unclear due to the limited capacity of solar lanterns compared to other off-grid alternatives.

Applying the theories outlined above, we expect treated households that receive solar lanterns to spend less on kerosene and other lighting expenditures. Solar lanterns are substitutes for alternative forms of lighting, and among treated households, they will likely crowd out expenditures on kerosene lamps, which are currently the most common source of lighting in the sample. We also expect the purchasing power of treated households to increase due to cost savings[12] from solar lanterns.[13] Thus we expect an increase in their non-lighting expenditures, composed predominantly of normal goods.

[9] Substitutes (complements) are goods that have a positive (negative) cross-elasticity of demand in relation to the good whose price has changed.

[10] Normal (inferior) goods are those with a positive (negative) income elasticity of demand.

[11] The income and substitution effect underpin explanations for the rebound effect (Khazzoom, 1980), wherein the development of efficient energy technology may fail to contain demand, as lower energy prices and consumers' higher disposable incomes increase energy consumption (Berkhout, Muskens, & Velthuijsen, 2000). See Roy (2000); Greening, Greene, and Difiglio (2000) for further empirical research on the rebound effect in the context of Indian electrification.

[12] These cost savings can be measured using the market price of solar lanterns.

[13] Solar lanterns that also function as mobile chargers produce additional cost savings by allowing households to avoid paying fees to vendors to charge their mobile phones. This likely contributes further to an increase in purchasing power.

Hypothesis 1a. *Treated households should have lower kerosene and other lighting expenditures than untreated households.*

Hypothesis 1b. *Treated households should have higher non-lighting expenditures on normal goods than untreated households.*[14]

Solar lanterns decrease absolute and marginal costs of lighting among treated households. Consequently, we anticipate that such households will decrease expenditures on substitutes (kerosene, liquified petroleum gas or "LPG", and batteries) and enjoy greater purchasing power.

Additionally, because solar lanterns reduce the marginal cost of lighting (each additional hours) to zero, we expect that households will use more hours of lighting per day. Moreover, because solar lanterns provide a better quality of lighting at a lower marginal cost than alternatives, households' reliance on the alternatives should decrease.

Hypothesis 2a. *Treated households should use more hours of lighting per day.*

Hypothesis 2b. *Treated households should use fewer hours of kerosene, generator, LPG, and battery lighting per day.*

In line with other research demonstrating an association between electrification and well-being — due to cost-savings, convenience, more flexibility in available leisure activities, and a reduction in health risks from kerosene such as indoor air pollution and burns (Komatsu, Kaneko, & Ghosh, 2011; Sharma & Chan, 2016; Mills, 2016; Barron & Torero, 2017) — we anticipate that treated households will express more satisfaction with their lighting and activities that rely on it.

Hypothesis 3a. *Treated households should be more satisfied with their lighting.*

Hypothesis 3b. *Treated households should be more satisfied with their lighting for activities: reading, working, cooking, studying.*

We anticipate that treated households will hold a more positive perception of solar technology than untreated households.

Hypothesis 4a. *Treated households should have a more positive perception of solar technology.*

Just as Hypothesis 3b suggested that households with solar lanterns should express more satisfaction with activities that rely on lighting, we anticipate that they will spend more time engaging in these activities. Theoretically, households face constraints on their time, and will thereby increase time spent on activities which complement lighting.[15]

Hypothesis 5a. *Treated households should spend more time reading, working, and cooking at home. Children in treated households should spend more time studying than children in untreated households.*

Hypothesis 5b. *Treated households should spend more time charging their mobile phones at home.*

Research design

To evaluate the impacts, we conducted a randomized controlled trial with 200 households, evenly distributed across 50 villages in the Bahraich district (see Fig. 1), located in the state of Uttar Pradesh, India. Information about the 200 non-electrified households was then gathered using an in-person baseline survey, conducted in January 2018. Treatment was then assigned to two of the four households in each village using a balanced complete block design, with the remaining two household serving as controls, illustrated in Fig. 2. Treated households were given solar lanterns along with a demonstration of how to use the product.

In our design, we provide our lanterns for free. This design choice allows a high level of adoption, as poor households need to consider the opportunity cost of purchasing a lantern. However, free provision may also change behavior if people do not develop a sense of ownership. We acknowledge this weakness and note that some of the benefits of the lanterns might have been greater if households had to purchase them.

In August 2018, six months after the lanterns' distribution, enumerators administered an endline survey to treated and untreated households. The questions posed in the baseline survey were all posed in the endline survey, but the endline survey asked treated households four additional post-treatment questions to assess their use of the solar lanterns.

Outcomes

Hypotheses 1a, 1b, 2a, 2b, 3a, 3b, 4a, 5a, 5b are evaluated using households' lighting and non-lighting expenditures, hours of solar and non-solar lighting used per day, self-reported measures of satisfaction from lighting and complementary leisure activities, perceptions of solar technology, allocation of time toward these leisure activities, and hours spent charging mobile phones. The following section summarizes the outcome variables, with further information — including the text from relevant survey questions — provided in Appendix A.

Expenditures

Expenditures on kerosene and other lighting (Hypothesis 1a) are directly measurable using survey questions asking households about their monthly expenditure, in Indian Rupees (INR), on kerosene fuel, generators, LPG lamps, battery-charged lamps, and solar-charged maps and alternative lighting sources.[16] Total lighting expenditures are then the sums of expenditures on each source. Non-lighting expenditures (Hypothesis 1b) are measured based on household non-lighting expenditures over the previous three months, which is constructed by subtracting lighting expenditures from total expenditures over the last three months. The outcome variables to test Hypotheses 1a and 1b, then, are the natural logarithms of the lighting and non-lighting expenditures, denoted as *Lighting Exp.* and *Non-lighting Exp.*[17]

We recognize that self-reported expenditure data is not ideal. Unfortunately, other measures of expenditure data collection are not feasible because most households work in the informal sector and do not file tax returns or track their finances. In an earlier study, Aklin, Cheng, Urpelainen, et al. (2016) compared self-reported expenditure data to official numbers from India's National Sample Survey Office. After adjusting inflation, they found that self-reported expenditure data generated very similar numbers. We also note that our expenditure measures are more specific than those in Aklin, Cheng, Urpelainen, et al. (2016), as we collect the data by category after extensive piloting and training for the enumerators.

Artificial lighting

The hours of lighting used per day (Hypothesis 2a) is the sum of daily lighting individuals report from kerosene fuel, generators, LPG lamps, battery-charged lamps, and solar-charged lamps and alternative

[14] This hypothesis also suggests that treated households would save more than non-treated households, though measuring the effects of solar lanterns on savings is beyond the scope of this study.

[15] Complementary activities, in this case, are those whose marginal benefits (costs) increase (decrease) as a result of affordable lighting. Solar lanterns relax the constraint on households' time by providing them with an additional source of lighting. When sunlight is limited, households may revert to kerosene for lighting.

[16] Unless otherwise stated, all expenditures are measured in INR.

[17] We rely on a $\ln(x + 1)$ transformation to include incidents of zero lighting expenditures.

Fig. 1. Map of Bahraich district in Uttar Pradesh, India, where experiment was conducted.

artificial lighting sources, denoted as *Total Hrs*. Likewise, households' total hours of lighting per day obtained from kerosene lamps, generators, LPG lamps, battery-charged lamps, and solar-charged lamps (Hypothesis 2b) is constructed in an identical manner as the total hours of lighting used per day, netting out hours obtained from solar-charged lamps. This is denoted as *Total Non-solar Hrs*. The outcome variables used to test Hypotheses 2a and 2b are *Total Hrs.* and *Total Non-solar Hrs.*

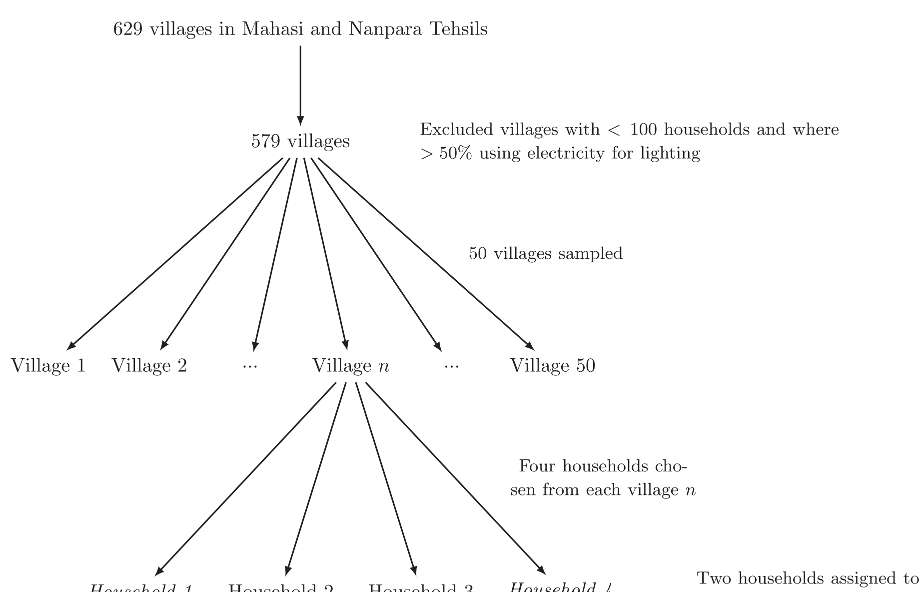

Fig. 2. Illustration of sampling and treatment assignment using complete blocked randomization. For each village $n \in \{1, 2, \ldots, 50\}$, two households are assigned the treatment and two are controls.

Table 1
Summary of outcome variables.

Hypothesis	Description	Outcome variable
1a	Lighting expenditures	*Lighting Exp.*
1b	Non-lighting expenditures	*Non-lighting Exp.*
2a	Hours of lighting per day	*Total Hrs.*
2b	Hours of lighting per day (non-solar)	*Total Non-solar Hrs.*
3a	Satisfaction from lighting	*Lighting Sat.*
3b	Satisfaction from leisure activities	*Activity Sat.*
4a	Perceptions of solar technology	*Perception*
5a	Time use	*Activity Time*
5b	Time use mobile	*Mobile Time*

Satisfaction

General satisfaction (Hypothesis 3a) is measured using the average of measurements of satisfaction across cost, safety, quality, reliability using a five-point Likert scale (1, Very unsatisfied, 2: Unsatisfied, 3: Neutral, 4: Satisfied, 5: Very satisfied), denoted as *Lighting Sat.*[18] To measure satisfaction from leisure activities (Hypothesis 3b), we use an index of satisfaction as our outcome variable, constructed by averaging respondents' reported satisfaction from reading, working, cooking, and studying, denoted as *Activity Sat.*[19] The use of such indices to measure satisfaction is common in the literature.[20] The relevant outcome variables are then *Lighting Sat.* and *Activity Sat.*

Perceptions of solar technology

To measure households' perceptions of solar technology (Hypothesis 4a), we use an index of perceptions as our outcome variable, constructed by averaging respondents' self-reported perceptions about solar lanterns, compared to kerosene lamps, on the dimensions of quality, reliability, ease of use, cost, and impact on households' economic productivity.[21] As with satisfaction, perception is commonly measured using similar scales (Jamil, 2018; Aklin et al., 2018). The relevant outcome variable is the measurement of respondents' perceptions, *Perception*.

Time use

To measure time use on specific activities (Hypothesis 5a), we use an index of time use as our outcome variable, constructed by averaging the hours per day spent by respondents on reading, working, cooking, and studying, denoted as *Activity Time*.[22] Time spent on charging mobile phones (Hypothesis 5b) is measured using the hours spent by the household head, his/her spouse, and his/her children in charging their mobile phones, denoted as *Mobile Time*. The outcome variables, then, are the measurements of each variable, *Activity Time* and *Mobile Time*. The nine outcome variables are summarized in Table 1.

Fig. 3. Photograph of the d.light S100 solar-powered mobile-charging lantern, provided to each of the 100 treated households.

Treatment

Each treated household was given a solar lantern, donated by the Solar Village Project (SVP) a non-profit, 501(c)(3) organization that provides non-electrified households with access to and maintenance of solar power systems. SVP obtained S100 solar lanterns, shown in Fig. 3, from d.light, a social enterprise that provides solar powered solutions across the Africa, China, South Asia, and the US. The S100 lanterns, which were marked with clear SVP branding, function as mobile chargers by day and lanterns by night. Equipped with a 1.5 watt solar panel, the lanterns generate up to 8 h of light per charge with a light-emitting diode lifetime of 60,000 h.[23] The lantern takes 2 to 3 h to charge in full sunlight and 6 h to charge when it is cloudy, with the charge lasting 4 h with high power and 8 h with low power. When given lanterns, households received instructions on how to use them. They were also given instructions not to share the lantern with anyone outside the household, and that there would be periodic checks to ensure that they still have it. Enumerators distributing the lantern told households that they would not be charged for the lantern if it breaks or suffers damage as long as they retained it, and that the lantern was a gift, conditional on it remaining in the household.

Estimation strategy

We hypothesize that the treatment will change household expenditure (Hypotheses 1a and 1b), the use of artificial lighting (Hypotheses 2a and 2b), households' satisfaction with lighting and activities that rely on it (Hypotheses 3a and 3b), their perceptions about solar technology (Hypothesis 4a) and their use of time (Hypotheses 5a and 5b). For a household i in round t, we test each of Hypotheses 1a, 1b, 2a, 2b, 3a, 3b, 4a, 5a, 5b using the model

$$Y_{it} = \lambda_i + \gamma_t + \beta \mathrm{Lantern}_{it} + \varepsilon_{it} \quad (1)$$

which allows us to measure the intention to treat effect (ITT). All treated respondents accepted the lantern, so the ITT converges to the local average treatment effect. In (1), Y_{it} denotes the outcome variables described

[18] For robustness checks, we also use a single measurement of overall satisfaction and an index of satisfaction constructed from binary variables measuring reliability, safety, cost, and adequacy of lighting. For descriptive purposes, we can also measure variation, across treated and untreated households, individually for each dimension of satisfaction.

[19] For robustness checks, we also construct a weighted average of these variables based on the sum of the number of hours in which respondents engaged in each activity following treatment. For descriptive purposes, we can also measure variation, across treated and untreated households, individually for each activity.

[20] For instance, in assessing the impact of various dimensions of electricity quality on household satisfaction, Aklin, Cheng, Urpelainen, et al. (2016) measures its dependent variable using a 0–2 scale; and Carvalho (2017) relies on a scale ranging from 1 (very unsatisfied) to 5 (very satisfied) when conducting a cross-country analysis on the impact of European regulatory reform on household satisfaction.

[21] For descriptive purposes, we can also measure variation, across treated and untreated households, individually for each dimension of perception.

[22] For descriptive purposes, we can also measure variation, across treated and untreated households, individually for each activity.

[23] Further information about the product is available at https://www.dlight.com/product/s100/.

Table 2
Classification of dependent coefficients into families. The final two columns present the hypothesized relationships between (i) the outcome variables within the family; and (ii) the treatment and each outcome variable.

Family	Coefficients	Outcome variable	Expected relationship	
			Between outcome variables	With treatment
1	β_1	*Lighting Exp.*	Negative	Negative
	β_2	*Non-lighting Exp.*		Positive
2	β_3	*Total Hrs.*	Negative	Positive
	β_4	*Total Non-solar Hrs.*		Negative
3	β_5	*Lighting Sat.*	Positive	Positive
	β_6	*Activity Sat.*		Positive
4	β_8	*Activity Time*	Positive	Positive
	β_6	*Mobile Time*		Positive

in Table 1, λ_i and γ_t denote household and round fixed-effects, and ε_{it} denotes random error. The indicator variable Lantern_{it} always takes the value zero in round 1 ($\text{Lantern}_{i1}=0$). In round 2, it takes the value $\text{Lantern}_{i2}=1$ for households that receive the solar lantern and $\text{Lantern}_{i2}=0$ otherwise. We estimate robust standard errors clustered by household.

Additionally, because we simultaneously test nine hypotheses, we correct *p*-values for family-wise discovery rate using Benjamini and Hochberg (1995) procedures, which control the false discovery rate, which is restricted to no more than 0.1.[24] Using the specification in (1) with the appropriate outcome variable from Table 1, we test nine hypotheses, each denoted by *j*, on the basis of the estimates of regression coefficients $\beta_1, \ldots, \beta_j$. We classify the coefficients associated with Hypotheses 1a, 1b, 2a, 2b, 3a, 3b and 5a–5b into four families based on their dependency with one another, as illustrated in Table 2. Hypothesis 4a is assumed to be independent of the others.

Sampling and fieldwork

We randomly select a sample of 200 non-electrified households,[25] evenly distributed across 50 villages — 15 in Mahasi Tehsil (subdistrict) and 35 in Nanpara Tehsil. Both subdistricts are located in UP's Bahraich district, shown in Fig. 1 and were selected due to their low rates of electrification, moderately dispersed populations and other demographic variation. Sub-districts were chosen relying on researchers' local knowledge and data from Government of India (2011). Households were selected only if (i) they were non-electrified; (ii) they were no closer than 50 m from another household in the sample; (iii) at least one married couple and at least one child, between the ages of five and eighteen, resided in them.

The sampling frame of villages was chosen to ensure a sufficient sample size of households that meet the three criteria outlined above. Each of the 225 villages in Mahasi Tehsil and 404 Napara Tehsil was excluded if it had (i) fewer than 100 households (19 villages in Mahasi and 26 in Nanpara); and (ii) more than half of its households reliant on electricity for lighting (three villages in Mahasi and one in Nanpara). In Mahasi Tehsil and Napara Tehsil, applying these criteria reduced the number of villages in each sub-district to 202 out of 225 and 377 out of 404 respectively. The researchers then chose a random sample of 50 villages from the remaining 579 villages and randomized the order of the remaining 529 villages to serve as alternates. Following the selection of the 50 villages, a team of experienced enumerators randomly selected four households from each village (200 in total) to participate in the study based on the three household criteria. If a village included no households meeting all three criteria, enumerators were told to sequentially choose the following village appearing in the same block from the list of alternates.[26] In each village where four participants were identified, the enumerators conducted a *baseline survey* in January 2018.

Researchers then assigned treatment to the 200 households using a balanced complete block design, with villages as the relevant blocking factors.[27] In each village, two of the four households were assigned the treatment and two were assigned the control. Consequently, the 100 households assigned to each level of the treatment were balanced across villages. Enumerators then administered the lanterns to treated households in early February 2018 and noted each household's compliance, which simply entailed accepting the lantern. Six months after the distributing the lanterns to treated households, enumerators returned to the study area to administer a *endline survey* to all households. In addition to the questions included on the baseline survey, the endline survey posed four additional post-treatment questions to treated households to assess how residents used solar lanterns. Both the baseline and endline surveys were in Hindi and administered using an Android smart phone app by Morsel India, an Uttar Pradesh-based survey company. All surveys were conducted in person. The full text of survey questions used in the analysis is provided in Appendix A, and descriptive statistics and comparisons between treated and untreated households are in Appendix C, Figs. C.8–C.10.[28]

Pre-analysis plan, ethical review, and implementation issues

Institutional Review Board (IRB) approval was obtained on February 1, 2018 and a pre-analysis plan with a power analysis was subsequently registered on the Evidence in Governance and Politics (EGAP) registry on February 3, 2018. The IRB number is HIRB00006846 and the registration ID is 20180204AA. The pre-analysis plan with power analysis can be accessed at http://egap.org/registration/3129. The research design was pre-registered through EGAP, where we outlined our sampling strategy, our data collection procedure, and hypotheses.

Implementation issues produced four deviations from the procedure anticipated in the pre-analysis plan. First, four of the 200 households did not respond to the endline survey.[29] Second, one respondent in the control group obtained a solar lantern between the administration of the baseline and endline survey, and was thus excluded from the analysis.[30] Third, in the endline survey, five households reported a malfunction in the solar lantern, one gave away the lantern to a household not participating in the study, and five obtained grid electricty between the administration of the baseline and endline survey. These 11 households were excluded from the analysis, though as shown in Appendix F, the results are robust to their inclusion. With 11 excluded households, one household in the control group that obtained a solar lantern, and four households that did not respond to the endline survey, our analysis includes observations from 184 of the 200 households originally sampled. Finally, in 30 of the 200 households, a different member responded to the baseline and endline questions. Such differences occurred among 16 untreated households and 14 treated households, which we did not exclude from the analysis.

[24] While controlling the family-wise error rate (FWER) reduces the probability of making any Type I errors, it also increases the rate of Type II errors and generates thresholds that suffer from low power.

[25] The sample size of 200 was chosen based on a power analysis, included in the replication file and summarized in Appendix B. The power analysis is conservative insofar as it only simulates the probability of finding a treatment effect on *Lighting Sat.*

[26] Three of the 50 initially chosen villages were replaced.

[27] The random assignment of treatment within blocks reduced possible endogeneity bias between the treatment and measured outcomes. Balance checks in Appendix C also demonstrate that baseline covariates are similar across treated and non-treated groups.

[28] The two groups are comparable across a number of dimensions, though treated households self-report higher initial levels of satisfaction with their lighting and its quality. The difference in baseline satisfaction is captured in the fixed effects for each treatment group.

[29] Two respondent' families moved; another became ill, leaving no other adults available to answer questions; and another simply refused to participate in the survey and denied having received the lantern, despite four attempts to administer the survey.

[30] None of the remaining households in the control group reported ownership or use of a solar lantern over the duration of the RCT.

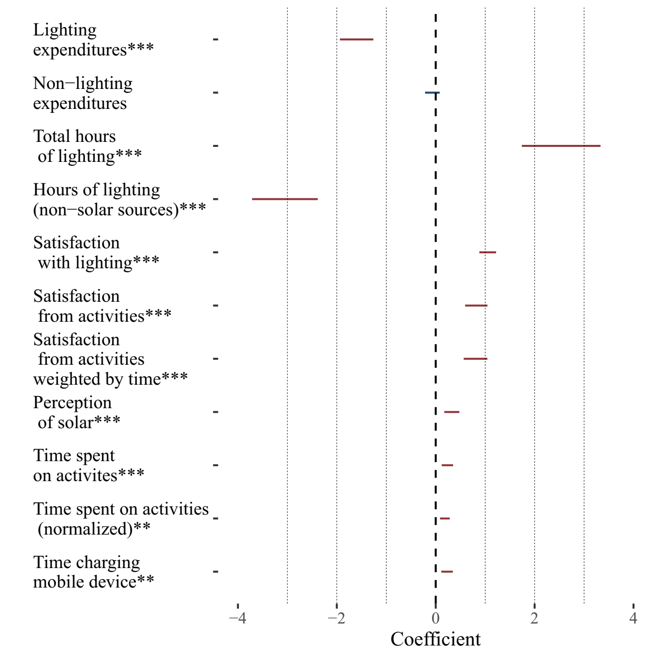

Fig. 4. Coefficient plot summarizing the effect of treatment (lighting) on outcome variables, with the outcome variable values among untreated observations normalized to zero. The lighting coefficient *p*-values are summarized as $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$, with household- and round- fixed effects and robust standard errors clustered at the household level.

Table 3
Effect of solar lanterns across households. Household and time fixed effects are omitted from the table. Standard errors, given in parentheses following each effect, are clustered at the household level, and significance tests are conducted using p-values with Benjamini-Hochberg multiple comparison adjustments.

Effects on household expenditures and hours of lighting	Lighting $	Non-lighting $	Lighting hrs.	Non-solar hrs
Treatment	−1.691***	−0.053	2.621***	−3.196***
	(0.183)	(0.080)	(0.391)	(0.347)
Observations	368	368	368	368
R^2	0.196	0.001	0.110	0.187
Adjusted R^2	−0.622	−1.014	−0.795	−0.639

Effects on satisfaction, perception, and time	Lighting sat.	Activity sat.	Perception	Activity time	Mobile time
Treatment	1.047***	0.806***	0.307***	0.252***	0.241***
	(0.088)	(0.121)	(0.128)	(0.081)	(0.060)
Observations	368	368	190	368	368
R^2	0.274	0.109	0.099	0.045	0.039
Adjusted R^2	−0.463	−0.797	−1.541	−0.925	−0.937

Three asterisks (***) indicate significance at a 1-percent level ($p < .01$), two asterisks (**) indicate significance at a 5-percent level ($p < .05$), and three asterisks (***) indicate significance at a 10-percent level ($p < .1$).

Results and discussion

Fig. 4 illustrates the effect of treatment on the outcome variables listed in Table 1 and associated confidence intervals.[31] Untreated observations, collected from all households in the baseline survey and untreated households in the endline survey, are normalized to zero. In comparison, the treatment increased outcome variables with positive coefficients and decreased those with negative coefficients. Variables with confidence intervals spanning zero were statistically indistinguishable among treated and untreated observations.

The results are robust to Benjamini and Hochberg (1995) multiple comparisons adjustments, included in Table 3, and to alternative measures of satisfaction with and time spent on leisure activities, shown in Appendix F.[32]

As predicted in Table 2, with fixed effects to control for differences over time and between households, solar lanterns decreased households' lighting expenditures by over 80%; increased their use of lighting by over 38% while decreasing daily hours obtained from artificial sources by more than 58%; increased satisfaction with lighting and associated activities; improved households' perceptions of solar lanterns relative to kerosene[33]; and increased time spent on leisure activities by approximately 14% and hours charging mobile devices by over 16%. Contrary to the prediction in Hypothesis 1b, however, we find no evidence that solar lanterns increase households' non-lighting expenditures. This is surprising given the decrease in their lighting expenditures, which would typically increase funds available for consumption and savings. One possible explanation is the composition of households' non-lighting expenses. As shown in Fig. 5, households

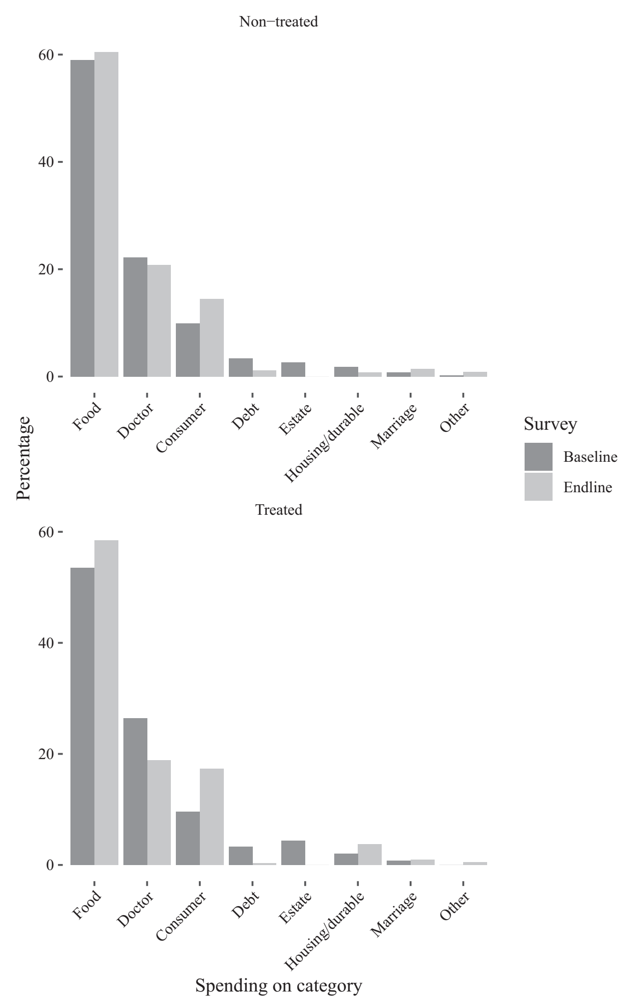

Fig. 5. Distribution of non-lighting expenditures among treated and untreated households, illustrating high share of expenditures on goods with a low income elasticity of demand.

[31] Standardized coefficients are plotted in Appendix D, Figure D.14.

[32] Robustness checks in Appendix F include weighting participants' self-reported satisfaction from leisure activities by the time spent on them, normalizing the time spent on leisure activities and mobile charging to account for the number of children residing in a given household, and segmenting the effects of treatment on hours spent on specific leisure activities. Table D.6 in Appendix D also provides the analogous table with standardized coefficients.

[33] Subjects were asked about their perceptions of the quality, reliability, ease, and cost of using solar lanterns relative to kerosene, and their responses were aggregated. See Appendix for further details.

allocated nearly 80% of their self-reported non-lighting expenditures toward food and medical expenses. Expenditures on such necessity goods are unlikely to respond to changes in income or purchasing power.[34] Significant shifts in non-lighting expenditures may also occur infrequently (e.g., weddings) or over a duration longer than that of our study (e.g., debt payments). In the context of existing literature, these findings are consistent with those observed in studies of solar micro-grids, which were also found to have negligible effects on non-lighting expenditures and savings (Aklin et al., 2017).[35] Still, confirming this explanation requires qualitative case studies, which can provide greater insight on and details about households' expenditures and savings, and any motivations for changing them.

The impact of solar lanterns' on households' time spent on associated leisure activities, however, seems to diverge from Aklin et al. (2017), who find no such effects from solar micro-grids. If households only make temporary adjustments in response to obtaining electricity and/or lighting, then each finding may be explained by the duration of the study, as Aklin et al. (2017) measured behavior after 18 months as opposed to six months. Additionally, the limited effects in Aklin et al. (2017) may be attributable to high rates of non-compliance. Differences may also be the product of sample characteristics or the technologies themselves. Aklin et al. (2017) rely on a subscription-based treatment, and so compliers may have more assets, earn greater incomes, or work more hours than non-compliers and households in the control group. These differences may be reflected in their willingness and ability to modify the time spent on leisure activities. Furthermore, Aklin et al. (2017) measure the effects of solar micro-grids as opposed to solar lanterns. Low-cost pico-PV kits, which are comparable to solar lanterns, have been found to have mixed effects on household time allocation (Grimm et al., 2015), so solar micro-grids may produce even more divergent effects.

Reductions in energy expenditures from micro-grids, SHS, and pico-PV kits (Grimm et al., 2015; Aklin et al., 2017) are also observed with solar lanterns, and like SHS (Aklin, Cheng, Urpelainen, et al., 2016), solar lanterns increase users' perceptions toward the technology and satisfaction with lighting. As shown in Table 4, solar lanterns' effects on satisfaction with lighting and associated leisure activities were uniform across the activities (reading, working, cooking, and studying) and dimensions by which we assessed the quality of lighting.

Beyond contributing to our understanding of an understudied lighting technology, these findings offer preliminary evidence that low-cost off-grid technologies can, like SHS and micro-grids, decrease energy costs and increase household satisfaction both with associated leisure activities and the quality of lighting itself across a number of dimensions. If replicated by future studies, these findings may have important implications in developing public policy to serve rural non-electrified households that are unable to afford other sources of electricity.

First, the findings contribute to understanding the extent to which additional capacity — more lights, electric appliances, productive loads — can increase benefits to households. In demonstrating that even the smallest possible energy technology can produce substantial benefits, the results suggest that solar lanterns — the most basic modern energy technology available — may serve as a cost-effective stopgap for non-electrified households. If these findings are substantiated by further studies, policymakers should explore strategies to replace kerosene and other traditional fuels with solar lanterns as a simple, rapid, and effective way to ensure basic energy access for all.

Further replication may also illustrate the need to incorporate the behavioral impacts of solar lanterns into cost-benefit analyses of various electrification policies. Beyond simply providing a substitute for traditional fuels, solar lanterns offer a number of ancillary benefits, such as increasing the time and ease with which children could study and improving households' perceptions of solar technology. These secondary effects may prove especially beneficial in increasing households' willingness to pay for other forms of solar technology as they become more affordable. Given these benefits, if households underestimate behavioral effects when making purchasing decisions, these findings may also justify policies subsidizing solar lanterns for poor households.

Table 4
Effects of solar lanterns across households on satisfaction with lighting, both for function purposes (leisure activities) and across different dimensions. Household and time fixed effects are omitted from the table. Standard errors are clustered at the household level, and significance tests are conducted using *p*-values with Benjamini-Hochberg multiple comparison adjustments.

Effects on satisfaction with lighting for leisure activities	Reading	Working	Cooking	Studying
Treatment	0.974***	0.954***	0.531***	0.765***
	(0.147)	(0.142)	(0.134)	(0.164)
Observations	368	368	368	368
R^2	0.107	0.111	0.041	0.056
Adjusted R^2	−0.802	−0.792	−0.933	−0.904

Effects on satisfaction with lighting across various dimensions	Cost	Safety	Quality	Reliability
Treatment	1.014***	0.834***	1.209***	1.131***
	(0.105)	(0.101)	(0.109)	(0.114)
Observations	368	368	368	368
R^2	0.204	0.153	0.249	0.207
Adjusted R^2	−0.605	−0.708	−0.515	−0.599

Three asterisks (***) indicate significance at a 1-percent level (p < .01), two asterisks (**) indicate significance at a 5-percent level (p < .05), and three asterisks (***) indicate significance at a 10-percent level (p < .1).

Conclusion

Here we have reported results from a RCT on the benefits of basic energy access – a solar lantern with a mobile charger. In a baseline-endline study with 184 households and randomized treatment assignment, we have found substantial benefits from reduced energy expenditures, improved lighting for domestic activities, and subjective satisfaction.

These results stand in contrast to a number of earlier studies that report weak benefits outside reduced kerosene expenditure. A key innovation of our study is to specify expectations that could plausibly be met with basic energy access, instead of focusing on high-level economic outcomes that would require deeper changes in rural society and economy. Rather than focusing on broad indicators of socioeconomic development such as job creation and economic growth, we demonstrate that an affordable intervention — at under USD 20, the solar lanterns are significantly cheaper than other lighting technologies — generate meaningful changes in households' daily behavior, well-being, and perceptions of solar lighting.[36]

Insofar as perceptions and adoption of technology are path-dependent, generate peer effects, and depend on entrepreneurial attitudes, small interventions such as this one may induce further effects (Bollinger & Gillingham, 2012; Aklin et al., 2018). In addition to its modest hypotheses, this study advances current research by relying on an

[34] These are goods with a low but non-negative income elasticity of demand.

[35] We do not believe that the stability of non-lighting expenditures is attributable to the "rebound effect," wherein households that received solar lanterns increased their lighting expenditures, leaving less for non-lighting expenditures. The primary obstacle to the adoption of solar lanterns is their fixed cost (Blankenship et al., 2020), and the lanterns themselves did not induce further variable costs.

[36] Appendix E summarizes estimated expenditure effects of solar lanterns, using an approach similar to Grimm and Peters (2016) and Bensch, Grimm, Huppertz, Langbein & Peters (2018). At low annual credit rates of 10% and 30% per annum and loans paid over one to three years, the cost savings from solar lanterns exceed its price for households with baseline lighting expenditures in the highest quartile. At 10% rates and a three-year term, solar lanterns are cost-effective for all quartiles of households, arranged by non-lighting expenditures; and at 30% rates and a three-year term, they remain cost-effective for households in the lowest quartile.

RCT, which provides stronger identification of causal effects than previous work based on observational data and case studies. Finally, it contributes to research on off-grid energy access, where solar lanterns have received limited attention.

To be sure, this study has its own limitations. Our sample is relatively small and drawn from particularly marginalized communities without alternative energy access. In the baseline survey, all households reported kerosene as their primary source of lighting.[37] With some grid connectivity or alternatives, such as batteries, the benefits of solar lanterns might have been smaller. Our study is also based on a survey, with possible social desirability bias and recall problems in the responses. Future studies of basic energy access could draw on our research by experimenting in different contexts and by developing innovative measurement techniques. Finally, participants in the study's treatment group bore no cost for obtaining solar lanterns and so this study is not able to measure the income effects of purchasing solar lanterns or factors driving their adoption. Purchasing solar lanterns may prompt households to modify their expenditures and behavior, and it may affect their satisfaction and perception toward solar technology. In this sense, this study raises two avenues of inquiry. First, what are the behavioral and attitudinal effects of providing households with the option to purchase solar lanterns? Do savings from households' reduced lighting expenditures compensate for the cost of solar lanterns? Second, what characteristics and interventions (e.g., subsidies or informational campaigns) induce households' adoption of solar lanterns?

Further extensions of our study include conducting similar experiments in other geographies, notably Sub-Saharan Africa. As India and other Asian countries approach universal electrification, Africa stands out as the final frontier for rural electrification. Low population densities, widespread poverty, and high fuel costs make distributed solar power particularly appealing in this geography. Another promising direction would be to contrast these benefits from basic energy access to those from access to larger loads of power.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The lanterns were provided by The Solar Village Project, which is based in the United States of America.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2020.04.005.

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