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Article

Assessing Opportunities for Solar Lanterns to Improve Educational Outcomes in Off-Grid Rural Areas: Results from a Randomized Controlled Trial

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Abstract

Solar lanterns are promoted across rural Sub-Saharan Africa as a way to improve educational outcomes. A randomized controlled trial in Zimba District, Zambia, evaluates whether solar lanterns help children study and improve academic performance. The research design accounts for potential income effects from receiving a lantern and also "blinds" participants to the study's purpose. There is no relationship detected between receipt of a solar lantern and improved performance on key examinations. Impacts on self-reported study habits are also not observed. A cost-effectiveness analysis suggests that solar lanterns are not an efficient way to improve educational outcomes in developing countries relative to other available options. Two phenomena, both of which are likely observed in other developing regions, may explain these results. First, flashlights have become the dominant lighting source in rural Zambia, so solar lanterns may have only limited appeal for prospective users who no longer rely on traditional lighting options like kerosene lamps. Second, improved energy access – whether through solar lanterns or other technologies – appears to be a relatively unimportant educational input in settings like Zimba.

JEL classification: I25, Q42, C93, R22

Keywords: energy access, education, solar lamps, randomized controlled trial, Zambia

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1. Introduction and Motivation

Rural areas of Sub-Saharan Africa, where children lack access to high-quality educational opportunities, also tend to be energy-poor. As a result, solar lanterns[1] have been promoted across the region as a promising first step toward improving both lighting in homes and educational outcomes (IEA 2017). Since 2010, manufacturers and distributors have sold over 15 million solar lanterns to rural households throughout Sub-Saharan Africa (GOGLA 2017). The potential educational benefits of these lights have been extensively highlighted. While planning fieldwork for this project in 2015, the research team identified 110 companies active in the sale, distribution, or manufacturing of solar lights in Sub-Saharan Africa. At the time, 40 of these companies highlighted potential educational benefits of their products, while an additional 16 mentioned that positive educational outcomes had been observed in case studies.[2] Commercial vendors of solar lanterns receive significant financial and policy support from governments and development agencies, and the existence of positive externalities in the form of improved educational outcomes could help justify such support.

However, the evidence base for the educational benefits of solar lights is limited. This paper addresses that gap through a randomized controlled trial (RCT) that investigates whether giving solar lanterns to children in off-grid areas of Sub-Saharan Africa results in more effective studying and improved academic performance. The experiment took place in rural Zambia and was designed to tease out the impacts of the lighting attribute of the solar lantern "treatment" relative to provision of other goods of comparable monetary value. This multi-treatment design helped isolate the "income effect" of having received something worth a certain amount of money from the specific effect of owning a solar-powered lighting source. The outcome variables are standardized examination scores and self-reported study habits: who children study with, where they study, and the time of day they study. The experiment failed to detect evidence that the lanterns affected these outcomes and presents quantitative evidence that the failure to observe impacts of practical interest was not the result of a lack of statistical power in the research design.

This study also finds that solar lanterns are not a cost-effective way to boost educational outcomes in developing settings relative to other available options. In contrast with the lack of observed impact from the solar lantern treatment, children in grade 7 who were randomly chosen to receive backpacks (and not solar lights) performed an estimated 0.3 standard deviations better on their standardized examinations. This could be because backpacks make it possible to protect scarce school supplies and thereby enable studying in the first place (as opposed to providing better illumination for an existing study environment). If the treatment effect of a solar light had been of this magnitude, a power calculation shows that there would have been a more than a 0.8 probability of detecting it.

In addition to measuring impact, this study seeks to enhance the understanding of mechanisms through which lights might possibly improve educational outcomes. To this end, this study collected and analyzed detailed survey data on the daily lives of the participants, which was then placed in context with the other literature on solar lights (as well as educational interventions in developing countries more broadly). This closer look suggests that solar lanterns' potential for positive educational impact may in fact be limited, for three main reasons. First, nearly all participants in this research were able to study at night even prior to the introduction of solar lanterns. Second, the significant penetration of flashlights across rural Sub-Saharan Africa (the adoption and use of which has not been tracked or reported on nearly as extensively as the off-grid solar market) may further reduce the appeal of solar lanterns for populations

1 These are stand-alone lamps where a single LED light bulb is powered by an attached photovoltaic (PV) solar panel, typically rated at less than 10 Watts. The lanterns usually require 5 to 10 hours of sunlight exposure to charge a built-in battery and then provide between 3 to 20 hours of light from that single charge, depending on the brightness setting of the LED bulb.

2 For example, the website of one of the most successful solar lantern vendors declares: "This easy-to-use solar-powered light enables children across the developing world to study during evening hours, improving their grades and creating a brighter future. Parents love the affordability, reliability and opportunity it provides" (D. light (2017)).

that have transitioned away from the traditional kerosene lamp. Third, household poverty appears to place significantly greater constraints on education than inadequate lighting. Children in this study were busy with work and chores that they prioritized over school, and their families struggled to pay school fees and purchase school supplies. In places where such barriers to schooling exist, household lighting may be a relatively unimportant educational input.[3] These factors likely help explain the failure to observe meaningful impacts of solar lanterns on examination scores and study habits in the RCT.

The remainder of this paper proceeds as follows. Section 2 summarizes the prior literature and provides context for the study in Zambia. Section 3 details the research design, while section 4 summarizes the empirical strategy. Section 5 presents the results of the RCT in which some children were given solar lanterns. Finally, section 6 concludes and suggests potential ways that impact-oriented stakeholders could adjust their strategies in promoting positive educational impacts.

2. Solar Lanterns and Educational Outcomes: Theory of Change and Evidence to Date

The theory for why solar lanterns might improve educational outcomes is that children could study longer and under better conditions than with traditional lights, and that in turn might translate into better academic performance. Studying conditions could improve due to brighter illumination, less eye strain and fatigue, the lack of fuel fumes, lower costs of lighting, and the provision of individualized, task-specific lighting to individual users. In addition, solar lights might unlock the possibility of studying at night for children who are busy with other tasks during the day or who live far from school (Hassan and Lucchino 2016). An improved study environment at home might also be associated with other at-home inputs for students that ultimately promote educational achievement (see, generally, Dufur, Parcel, and Troutman 2013). Moreover, if solar light ownership somehow generates more income or free time for a household, those resources could be directed toward children's education (see, generally, Das et al. 2013; IEA 2017). There could even be positive learning spillovers if children who own solar lanterns share them with classmates and thereby create a better learning environment for everyone (Gustavsson 2007). Finally, marketing and selling solar lanterns in schools through teachers may, by itself, increase the perceived returns on investment in education, thereby encouraging better educational outcomes (see, generally, Jensen 2010).

The off-grid solar industry has often referenced these potential benefits of solar lighting, but the scale and rigor of the evidence for educational impacts of solar lanterns remains limited. A handful of studies have probed potential educational benefits, but very few have focused on these specific questions and possible mechanisms. This paper is most closely related to the work of Kudo, Shonchoy, and Takahashi (2017), who undertook a similarly comprehensive RCT in rural Bangladesh. The authors observed short-term increases in school attendance rates by children who were given solar lanterns but no improvements in performance on school/grade-level annual examinations or any hints of spillovers through sharing of the lights.

Other studies on solar lanterns and education that inform this paper include Furukawa (2014) and Hassan and Lucchino (2016). Furukawa (2014), ran a small experiment in an urban setting in Uganda and observed *lower* average test scores for children who were randomly gifted a solar light relative to the control group, although he encountered significant technical problems with the lights (namely, a significant share of the lights did not work properly and may have distracted children). Hassan and Lucchino (2016)

3 There are well-documented challenges with teacher training and compensation, classroom size, lack of school supplies, nutrition, and other serious problems that hinder primary education throughout Sub-Saharan Africa (see, e.g., Lewin 2009; Hardman et al. 2011), including in regions where solar lights have been successfully sold. Whether such fundamental constraints to education mean that no amount of improved household lighting could realistically be expected to enable children to study more effectively and do better has not been closely examined.

undertook a larger experiment in 13 rural Kenyan schools but failed to observe positive impacts of solar lanterns on school-specific, end-of-term scores in any subject except mathematics, which they recovered using a complex methodology that accounted for possible spillovers. It is not clear why mathematics might have been uniquely impacted among the many other outcomes that were tracked.[4] This study also reported significant sharing of the lights between treatment and control groups.

This study also benefits from the studies undertaken by Gustavsson (2007), Grimm et al. (2016), and Lee, Miguel, and Wolfram (2018). Grimm et al. (2016), ran an experiment on the broader household-level social impacts of solar lanterns in Rwanda. That study reported children shifting studying from daylight hours to after dark, but it did not detect sharing of the lights, nor did it track academic performance. Gustavsson (2007) was one of the first studies to explore potential educational benefits of solar lighting. The paper cautions, however, that children in the study who had access to solar lights tended to have parents who worked as teachers, thus making it difficult to infer cause and effect relationships between solar light provision and better grades. The more recent work of Lee, Miguel, and Wolfram (2018) presents experimental evidence that energy-access initiatives in rural Kenya targeting energy poverty do not result in broader poverty relief or improved educational metrics tracked via a test the authors created.

This paper presents a field experiment investigating the relationship between access to solar lanterns and outcome variables measuring academic performance and study habits. It is among the largest studies of its kind in Sub-Saharan Africa, and it benefits from access to a direct and credible measure of academic performance – a mandatory standardized examination in Zambia. The examination was administered equally to all the subjects in this study (as well as to the entire population from which they were drawn), and the subjects would have been highly motivated to perform well on the examination even if the research had never taken place. The experimental treatment was designed to isolate the impact of the lighting attribute of solar lanterns on educational performance, as opposed to an income effect or any other mechanism that could have been triggered by receipt of a solar lantern. The research design sought to avoid experimental contamination and bias by undertaking the experiment in an area where solar lanterns were not otherwise readily available, "blinding" participants to the purpose of the research, and avoiding drawing undue attention to the lights' hoped-for benefits (while still encouraging children in the treatment group to use them). These features of the experimental design, along with the rich survey dataset the experiment produced, enable an evaluation of whether solar light ownership impacted educational outcomes, potential reasons for the observed results, and an exploration of broader conclusions that might be drawn about the potential of solar lights to improve educational outcomes in developing countries.

3. Research Design and Implementation

For the experiment to have external validity, the research team sought to introduce the solar lanterns in a manner similar to how they would be distributed outside of a research setting, which is typically the sale of lights by a social enterprise. This required finding a rural location similar to other places in Sub-Saharan Africa where solar lanterns had successfully been sold, but where such lights had not yet been widely promoted or offered for sale. That minimized the risk of contamination from participants' exposure to solar lanterns outside the experiment. To maximize the chances of observing an effect on educational performance, the design prioritized recruiting participants that would plausibly be motivated to use solar lanterns to study.

Zambia's Zimba District met all of these requirements. Zambia is a country where, until recently, there were few options for lighting homes in off-grid areas. Although Zambia's solar sector is active, it is

4 The authors did not appear to use Bonferroni corrections for the sizes of the many individual tests they ran to account for the fact that they performed multiple-hypothesis tests.

relatively new and underdeveloped compared to countries like Kenya and Uganda, lowering the risk that study participants would be exposed to solar lanterns from other sources. At the same time, the demand for solar lanterns in rural regions of Zambia appears to be as strong as in the rest of Sub-Saharan Africa. The Zambian government has previously invested in multiple projects to provide solar lighting to rural schools and households (see, e.g., Gustavsson (2007)), including in Zimba District. While these projects have focused on larger solar solutions that can electrify an entire structure rather than the individual task-specific solar lanterns studied here, they are indicative of the broader perception that rural Zambia is a place where solar-powered lighting might deliver meaningful educational benefits. Zimba District is located in the country's Southern Province and has a similar profile to a number of nearby districts where SolarAid – Africa's largest and most prominent distributor of solar lanterns – has successfully sold lights. SolarAid's distribution model is designed to sell lights through schools, and in 2015 the enterprise identified Zimba District as a promising location where lights would soon be sold. However, in the interest of supporting this research SolarAid agreed not to enter the district until after data collection for this study was complete.

This research focused on students in grades 7 through 9 – the last three grades of primary school in Zambia – for several reasons. First, children in earlier grades would likely have been too young to be able to answer the questions in the surveys. Second, the scoping for this research revealed that lower grades were generally not assigned much homework, making it less likely that improved lighting would influence studies and performance. Third, school officials pointed out that it is mostly at grade 7 and beyond when children drop out of school altogether, suggesting that interventions aimed at improving educational performance and encouraging ongoing enrollment might be particularly well targeted to those grades.

Fourth, children in grades 7 and 9 take standardized national examinations. It is widely believed that students across Zambia – as well as their parents and teachers – are aware of the importance of these tests and take them seriously. Children in grades 7 and 9 are focused on preparing for the examinations, especially during the months of September, October, and November. Scoring well on the grade 9 examination is often the best hope students from poor rural areas have to enroll in secondary school and continue their education. In short, it could plausibly be assumed that children would be quite motivated to use all tools at their disposal – including, potentially, solar lanterns – to improve their performance on the examinations. The fact that the examinations are standardized and graded on a national level, without differences between schools and classrooms, also makes them an ideal way to measure academic performance outcomes in an RCT.[5]

The RCT was carried out in 12 government-run primary schools, randomly selected from a master file of all schools in Zimba District.[6] A team of researchers then conducted fair lotteries at each school. These lotteries were the delivery mechanism for the RCT's different "treatments," including the provision of over 200 solar lanterns to randomly selected children. The lotteries took place at the start of the second school term in May 2016 (see further details in the "RCT Treatment Implementation" section below). The national examinations were administered six months later, with scores collected directly from Zambian education officials in early 2017.

Students also completed detailed baseline and endline surveys. Over 1,400 children in grades 7, 8, and 9 took in-school surveys at the start of the school year in February 2016, as well as during the

5 Zambian children must do well on these examinations in order to continue their studies. Although any standardized test could be criticized as measuring how well a student is able to take the test itself rather than being a measure of learning, the Zambian national examinations are nevertheless crucial for further educational attainment, especially in rural areas. This makes them an important and useful real-world educational outcome to track in research.

6 Zimba District's schools are spaced over a large rural area, with direct-route distances from the district's central educational offices ranging from 0.5 km to 160 km. When accessing schools, distance is only part of the equation, because travel to even relatively nearby schools is often heavily impaired by poor road quality or rains.

Table 1. Research Design Summary

Location	**Zimba District, Zambia**
Subjects	Students in grades 7–9 in 12 randomly-selected schools
RCT treatment definition	Gift of a solar lantern to a student (see section 3)
RCT outcomes	(1) National examination scores (grades 7 & 9 only)
	(2) Study habits
	(a) most used lights for studying in dark
	(b) most frequent time of day for studying
	(c) most frequent study location
	(d) most frequent study partner (if any)
Data collection summary	
Baseline surveys completed (February 2016)	1588 (36% grade 7, 35% grade 8, 29% grade 9)
Endline surveys completed (October 2016)	1409 (37% grade 7, 34% grade 8, 29% grade 9)
*Number of matched baseline-endline pairs**	1122 (80% of endline surveys)
Median age of those completing both surveys	15 (15 grade 7, 15 grade 8, 16 grade 9)
Gender ratio of those completing both surveys	47% girls (51% grade 7, 48% grade 8, 41% grade 9)
Number of participants in RCT lottery (May 2016)	1211 (76% of baseline survey participants, 86% of endline survey participants)

Source: Authors' summary of the research design and the data collected in the field.
Note: *It is likely that more students completed both the baseline and endline surveys but that their two surveys were not confirmed as a match. The manual matching process was labor- and time-intensive, and avoiding false matches was prioritized at the expense of potentially leaving out likely matches.

national examinations season in October and November 2016 (see table S3.1 in the supplementaty online appendix). Not all children attend school every day, but 80 percent of children who filled out the October survey were matched as having also completed the baseline one. The student surveys took about one hour to complete and were conducted by a different team of researchers from the ones that handed out solar lights and other lottery "prizes" in the middle of the school year.

Surveys were administered for several reasons. First, detecting impacts of solar lanterns on study habits irrespective of examination performance could be an important outcome. Study habit variables of interest included the times of day that children study, study locations, study partners, and types of lights used for nighttime studies. Second, the surveys enabled controlling for background variables and potentially obtaining more precise estimates of the impacts of solar lights. Third, the surveys helped reveal how and to what extent solar lights were actually used by the students. Fourth, the rich survey dataset, which covered many aspects of students' daily lives, provided important insights into the broader educational environment into which solar lanterns are deployed. A broader understanding of the relationships between household energy access, poverty, and children's academic opportunities is key to understanding how and why improved household lighting might or might not translate into improved educational outcomes. Making the surveys broad in scope had the additional benefit of helping blind participants to the study's primary purpose of evaluating the impact of solar lights on educational outcomes. It was important for students to not feel that there were "correct answers" when it came to reporting study habits, the use of solar lanterns and, most importantly, the relationship between the two.

Table 1 summarizes the experimental research design. For additional details on the data collected and RCT participation rates, see appendix S3 in the supplementary online appendix.

RCT Treatment Implementation

The priority for this experiment's implementation was ensuring that any given student within each grade at a particular school had an equal and random chance of being "treated." To do that, there were a series of 36 lotteries – one for each grade level at all 12 schools. Because not all children attend school every day, only those that both took the baseline survey *and* were present on the day of the lottery several months later were eligible to be included in the dataset. Children that missed school during either of the two surveys or the lottery are left out of the RCT's final sample used for analysis.

Precautions were taken to ensure that the lotteries were not perceived as solar lantern giveaways. Instead, the goal was for school officials, teachers, students, parents, and even (to the extent possible) the on-the-ground field research personnel to perceive the lottery as an exercise intended to thank children for participating in a wide-ranging study of Zambian schooling.[7] To this end, three other prizes or "treatments" were given away in addition to the solar lanterns: backpacks, battery-powered alarm clocks, and soap. The "control" students received a candy. There was no special emphasis placed on the lanterns; they were presented merely as one of several prizes that students were eligible to win as thanks for completing broad surveys about their daily lives. The lottery details are summarized in tables S3.2 and S3.3 of the supplementary online appendix.[8]

This approach enabled the delivery of the lights in an educational setting that encouraged students to use them, but at the same time hopefully avoided giving cues about any particular "desired" impacts, which could have resulted in data bias (or even potentially favorable treatment by teachers or enumerators towards certain students). Another benefit of awarding multiple prizes was that it allowed for a consistent approach for the "pure control" schools where no students received lights. Awarding prizes in those schools helped avoid the political and practical risks of control schools being perceived as different from the nine "treated" ones.

At the same time, because solar lanterns were likely not as familiar to the children as the other prizes, there were limited additional measures when handing them out. Lantern winners received an "information card" – a brief, easy-to-understand sheet, printed on high-quality cardstock, that provided instructions on proper use, emphasized that the lantern could be helpful for studying, and included a number to call in case the solar light stopped working (see fig. S3.1 in the supplementary online appendix). Research staff also demonstrated how to use the light and verbally delivered the messages on the information card when giving a child a lantern. The goal was to mimic the messages a vendor would provide when selling a solar lantern while not identifying the lights as somehow more special than the other prizes. A research team member also returned to the schools on four occasions to check whether students who had won a light still owned it and were using it. This was presented to participants as a routine part of warranty support for the lanterns by their distributor.

4. Empirical Strategy

4.1 Treatment Definition and ATE Interpretation

The primary objective of this study was to detect impacts of solar lanterns on educational performance, specifically on the grades 7 and 9 national examinations that are a key component of the Zambian schooling system. Although the solar lanterns were awarded to randomly-selected students, there was no guarantee that the children would use the lanterns. It was only possible to give students a light and encourage them to use it for studying. Therefore, the experiment estimates average treatment effects (ATE) for the treatment of randomly receiving a light (or another prize), which is conceptually equivalent to an intent-to-treat effect if the treatment were defined as using the lights for studies.

Giving out multiple prizes rather than just solar lanterns made it possible to isolate the solar-powered lighting attribute of the target intervention. The other prizes, which in some cases could also be considered

7 Although students, teachers and school officials in Zimba District were not aware of the solar lantern focus of the study, provincial and national education officials were fully informed of the research design.

8 In each school, approximately half of the students participating in the lottery won a prize (solar lantern or one of three alternatives), while the other half received candy as a consolation prize. In schools where a sizeable number of lights were awarded, only two of the three other possible prizes were given away. That avoided giving out very few of any one prize and thereby hopefully lowered the risk of students ranking the relative importance of the different prizes.

Table 2. RCT "Treatment Lottery" – Reported Status of Awarded Prizes at Endline

	Prize				
Endline status	Solar lantern (% of responses)	Backpack (%)	Alarm clock (%)	Soap (%)	Candy/control (%)
Still own prize	86.6	91.8	83	6.9	3.8
Prize has been used up	7.5	9.2	12.3	89.1	76.5
Sold or gifted prize	0.5	2	2.8	1	1
No longer own prize – other reason or reason not given	7.5*	2	6.6	4	20.1**

Source: Authors' analysis based on endline survey data collected in the field.

Note: Study participants were asked to provide an update of the status of the "prize" they were awarded during the lottery, which corresponds to the treatment arm they were assigned to. Totals add to slightly over 100 percent because some children selected multiple answers. This is primarily due to between 1 percent and 3.8 percent in each treatment arm reporting both that they still owned the prize and that it was "used up," suggesting that in these cases they perhaps held onto the prize but it was no longer usable or perhaps damaged.

*The "other" reasons given for why the solar lanterns were no longer owned were the lights no longer working (7 students), reportedly stolen (4 students), or lost (3 students).

**There is a notably large number of students in the control group who reported no longer having their prize but who did not provide a reason why. It is reasonable to assume that the vast majority of these children simply ate the candy they were given as their "prize."

helpful for education, were worth approximately the same as the retail price of a solar lantern (USD 15). This allowed for the control of any income effects that might have been triggered by the receipt of a solar lantern, meaning that the ATE estimate for the solar lantern treatment group can be considered to be an estimate of the impact of receiving a lighting product specifically, as distinct from the impact of receiving a generic good worth approximately USD 15 that could potentially be monetized and repurposed.[9] Furthermore, there was no evidence to suggest that a significant number of the prizes were monetized, repurposed, traded, or otherwise not used for their intended purpose. During the endline survey, 92 percent of backpack recipients and 87 percent of solar lantern recipients reported still owning the prizes they won in the lottery.[10] Very few children reported having sold or given away their prize (table 2). For the above reasons, this study measured the impact of the solar lighting attribute as opposed to possible income effects from the provision of solar lanterns.

4.2 Sample Balance and Attrition

To test the assumption of successful randomization, a covariate analysis checks for imbalance between the different experimental groups *prior* to the treatment. Data collected primarily through the detailed baseline surveys students filled out prior to implementing the treatments do not reveal any obvious imbalances with respect to covariates that were hypothesized to be predictive of the outcomes – namely, student's age, gender, and poverty index, as well as their self-reported comfort with the English language (which is the language of the examination). These covariates do not vary significantly between the different experimental groups (Table S2.1 in the supplementary online appendix). The assignment to the different experimental groups is also regressed on all of these covariates. Tests of joint significance do not offer evidence against the null hypothesis that these covariates do not predict treatment assignment more than would be expected by chance alone (see table S2.2). Finally, the fieldwork team did not experience

9 An additional advantage was that the other three prizes were familiar items that children would have been aware are valuable and not normally given away. They were therefore useful to signal the value of solar lanterns to children who might not have previously been exposed to solar lights (or may possibly have viewed them as free goods that charities hand out).

10 In contrast, well over 90 percent of children in the soap and control (candy) groups – prizes that were expected to be consumed fairly quickly – did, indeed, report that they no longer had their prize.

any logistical or political problems in the ability to run fair lotteries in the schools. It is therefore reasonable to assume a successful randomization.

There is also no evidence to suggest that the final dataset reflects systematically different attrition rates. Approximately 80 percent of children who completed an endline survey were successfully matched to a completed baseline survey. Of those students who were in grades 7 and 9, a further 80 percent were matched to an examination score provided by school authorities. It should be noted that many more children likely participated in both surveys and sat for the examinations. However, the matching was performed manually based on name, school, and grade level, and was time and labor intensive. A number of children appeared to have switched between their traditional names and English names when filling out the surveys, and they were sometimes inconsistent in the spelling of their traditional names and surnames. It is therefore likely that more potential matches were missed. Despite this logistical difficulty, overall attrition was low, and there is no evidence for differing attrition rates between the various experimental groups, as measured by the ability to match baseline and endline surveys and examination scores.

4.3 Empirical Model

In order to recover estimates of the solar light giveaway's impact on national examination scores, the following basic model is first estimated:

$$exscore_{ij} = \alpha + ATE_{solar}\left(solar_{ij}\right) + ATE_{bpack}\left(bpack_{ij}\right) + ATE_{clock}\left(clock_{ij}\right) + ATE_{soap}\left(soap_{ij}\right) + \lambda_{school,j} + \epsilon_{ij} \tag{1}$$

The outcome variable "$exscore_{ij}$" is the examination score for student i in school j, while "*solar*," "*bpack*," "*clock*" and "*soap*," are binary (0,1) variables indicating the different treatment groups in the experiment. The parameter $\lambda_{school,j}$ is the fixed effect for school j. Finally, α is a constant, while ϵ_{ij} is a mean zero idiosyncratic component unique to any given student, which is assumed to be mean-independent of the treatments and covariates. Because the official scoring of both the grade 7 and 9 examinations is fairly complex and the absolute scores have no intuitive interpretation, the examination score data was first standardized such that each of the grade 7 and grade 9 samples in the study can be interpreted as coming from a distribution with mean 0 and standard deviation 1.

Although the tests for successful randomization do not require a control for observed covariate imbalance, two additional models are nevertheless specified with additional variables, in an attempt to obtain more precise estimates of the average treatment effects of gifting the various prizes. During the initial phase of the study's design, it was assumed that in rural Zambia, as in most of the developing world, school performance is highly correlated with gender (with girls doing worse than boys), socioeconomics (with children from wealthier families doing better), and student age (with older students in a class likely doing worse than younger ones, because older children may have repeated grades or enrolled in school late due to family obligations). Therefore, a Model 2 was specified, with gender, age, and a socioeconomic variable added to account for the covariates that were believed *ex ante* to most strongly predict performance on the Zambian examinations. The socioeconomic variable is an index derived from the Zambia-specific Poverty Probability Index (PPI), a poverty measurement tool developed by the Grameen Foundation that uses information about a household's characteristics and asset ownership (which was asked about in the baseline surveys) to assess the likelihood that a household is living below the poverty line (PPI 2017).

A further Model 3 was also specified that controls for additional variables believed to be potentially predictive of examination performance. This was done in the hope of being able to recover even more precise estimates of the impacts of handing out solar lanterns. This final specification was based on prior internal research conducted by SolarAid in rural Africa that suggested certain study habits (such as studying at night or with a friend) resulted in better academic performance. Model 3 therefore added categorical variables to account for students' self-reported study patterns, specifically which type of light they use most when studying, the time of day at which they most often study, the place where they most often study, and whom they most often study with. The fieldwork scoping portion of this study – undertaken prior to collecting any data in Zimba District or implementing the treatment – also revealed that mastery of the English language would likely be highly predictive of examination performance,[11] so binary variables to account for students' self-reported difficulties with speaking or reading and writing in English were also added. Models 2 and 3 were specified prior to commencing fieldwork, and the covariates were collected pre-treatment from the baseline survey.

4.4 Defining and Evaluating Economically Meaningful Impacts

Within the literature on primary school education in developing countries, interventions that result in an increase of 0.1 standard deviations on test scores are typically not considered meaningful, whereas an increase of 0.3 standard deviations or more is usually viewed as a large and meaningful effect (J-PAL 2019). Such rules of thumb from literature reviews should be used cautiously, both because they are arbitrary and because care is required to make meaningful comparisons across studies based solely on standard deviation shifts. Nevertheless, impacts of solar lanterns of less than 0.3 standard deviations are likely to have little practical significance for the children in this research sample. Zimba District is a poor, rural area whose students generally perform far worse on the examinations than national averages. In 2016, the year of this study, the district ranked 94th in grade 7 and 90th in grade 9 examination performance out of the 101 educational districts in Zambia (ECZ 2017). Because the examination scores in this research sample are systematically lower than the national averages, a fairly large increase in the standardized scores *within* this below-average sample would be required in order to have a practical impact on the children's educational opportunities.[12] Using 0.3 standard deviations as a reference point for what would be considered a meaningful impact of the solar lanterns in this study is therefore reasonable.

In addition to comparing the results against this general 0.3 standard deviations reference point, this study also includes a cost-effectiveness analysis (CEA) as another way to characterize the economic meaningfulness of the interventions. In so doing, it follows the framework laid out by Dhaliwal et al. 2013 and J-PAL 2019, both of which advocate for cost-effectiveness metrics as a tool to inform policymaking, especially in education, in developing countries. In its simplest form, the CEA can be formulated as the ratio of the estimated standard deviation improvement in test scores over the cost incurred to carry out the program – or, conversely, as the dollar investment required to achieve a given "effect" on test scores (J-PAL 2019). The strength of CEA methodology is its ability to summarize potentially complex programs in terms of illustrative, intuitive metrics and then to use this common measure to compare across different contexts, years, and interventions targeting the same policy goal. Kremer, Brannen, and Glennerster 2013 used a CEA approach in their comparative analysis of 27 RCTs that applied diverse interventions across

11 That is because the national examinations are administered in English, which is the official language of school instruction in grades 7 through 9, even though many children and their teachers in rural areas like Zimba District do not have a strong grasp of the language and are generally not exposed to it outside of school. Not surprisingly, prior work by the Examinations Council of Zambia had revealed that English reading proficiency is, indeed, a strong predictor of examination performance in both grades and especially grade 7 (ECZ 2012).

12 A child in Zimba must not only pass the grade 9 examination, but also perform exceedingly well relative to peers, in order to enroll in secondary school. While 49 percent of students across Zambia passed the grade 9 examination, only 38 percent of students in Zimba District did (ECZ 2017; Ministry of Education 2017). Because the district has only one government-run secondary school, with a strictly limited number of spots, a passing score is not sufficient to enable a child to continue their schooling. Instead, the threshold score necessary to enroll in secondary school in Zimba (and other lower-performing and under-resourced rural districts) is much higher than it is in cities like Lusaka that already have other schooling advantages. As such, any educational interventions would need to have a large impact on examination performance *within* Zimba District in order to "move the needle" in practical terms for the educational opportunities of the district's children.

diverse settings in an effort to improve educational outcomes in developing countries. The common metric in Kremer, Brannen, and Glennerster (2013) was the total test score gains (measured in standard deviations) generated for every 100 US dollars (inflation adjusted to year 2011) spent by a program. This study adopts this metric for the CEA due to its simplicity and because it enables a straightforward comparison of the results of this study to the educational RCTs considered by Kremer, Brannen, and Glennerster (2013).

Of the 27 educational experiments covered by Kremer, Brannen, and Glennerster (2013), 15 were judged to have detectable impacts on test scores. These had a median CEA score of 2.28 standard deviation improvement in test scores for every 100 dollars spent by a program. This means that the solar lanterns studied here – which retailed in rural Zambia for 16.34 dollars (inflation-adjusted to year 2011) at the time of this study – would need to have an average impact of 0.37 standard deviations in order to fall in the "middle of the pack" in cost-effectiveness relative to the educational RCTs studied by Kremer, Brannen, and Glennerster (2013). If the solar lanterns were to improve test scores, on average, by 0.3 standard deviations, they would fall to the bottom third of the 15 interventions for which Kremer, Brannen, and Glennerster (2013) calculated cost-effectiveness.[13] This provides additional support for the assertion that solar light impacts of less than 0.3 standard deviations would not be economically meaningful, as they would not be cost-effective relative to other interventions available to policymakers who seek to improve educational outcomes in developing countries.[14]

5. Results

5.1 Impact on Examination Scores

Overall, the experiment failed to detect an impact of solar lanterns on examination scores under any specification (table 3 shows the abbreviated regression results for Model 1, with the full results for Models 1–3 in S1in the supplementary online appendix). The estimates of the treatments' impacts are consistent across the three specifications. A meaningful positive impact of backpacks on scores in grade 7 is detected, with an estimate that giving a seventh grade child a backpack resulted in an average increase in performance of approximately one third of a standard deviations relative to those that did not get backpacks. There were no similar results observed for backpacks in grade 9.

While being given a solar lantern was not associated with examination scores, the other variables that were expected to be predictive of scores generally were. Girls did worse, as did older children within each grade level and those who came from poorer households. These associations were weaker in grade 9 compared to grade 7, possibly because many underperforming students for whom these three variables (gender, age, and poverty index) are highly predictive of scores in grade 7 may drop out of school altogether by grade 9.

As expected for the additional covariates in Model 3, children who reported difficulties reading and writing in English also struggled. However, the variables that reflected students' self-reported study habits

13 Although solar lanterns were not readily available in Zimba District at the time of this study, the retail price in shops in neighboring districts of the model used was \$17.65 (or \$16.34 in 2011 dollars), which was also about the price that SolarAid charged for these lanterns when selling them in schools in other rural parts of Zambia. The conclusion that the lights would need to have impacts greater than 0.3 standard deviations in order to fall above the median cost-effectiveness of the interventions studied by Kremer, Brannan, and Glennerster (2013) holds true for any price above \$13.

14 It can also be argued that 0.3 standard deviations is a conservative reference point for what would be needed for the impacts of solar lanterns to be cost-effective because the purchase price is not the only cost associated with adopting this intervention. There are also costs associated with the time and effort it takes to charge the lanterns in the sun, as well as maintenance and servicing costs when the lanterns break down. These would normally be captured by the methods set forth in Kremer, Brannen, and Glennerster (2013), but they were set aside here for purposes of identifying a threshold that would deem as economically meaningful. The detailed CEA results are presented in section 5.4.

Table 3. Abbreviated Regression Results (see also table S1.1)

	(1) Model 1		(2) Pooled exam scores for grades 7 & 9*	(3) Pooled exam scores *and* pooled prizes**
	Grade 7	Grade 9		
	Standardized exam score (robust SE)		Standardized exam score (robust SE)	Standardized exam score (robust SE)
Treatment				
Solar light	0.129	–0.035	0.073	0.045
	(0.127)	(0.117)	(0.087)	(0.086)
Backpack	0.348	–0.222	0.111	0.080
	(0.137)	(0.198)	(0.121)	(0.120)
Clock	–0.017	–0.106	–0.046	–0.079
	(0.152)	(0.148)	(0.114)	(0.112)
Soap	0.248	0.111	0.175	N/A
	(0.147)	(0.133)	(0.109)	N/A
Observations	403	318	721	721

Source: Authors' analysis based on survey data collected in the field and exam records shared by school officials.

Note: Column (1) shows the estimated average treatment effect (in standard deviations) on standardized examinations for primary school grades 7 and 9 due to the receipt of four different "prizes" (solar lights, backpacks, alarm clocks, and soap) relative to a control group that received candy. Column (2) pools the standardized test scores for grades 7 and 9, thereby improving precision. The specification for column (3) is the same as column (2); however, the "soap" treatment arm is pooled together with the control group in an attempt to improve precision. Further pooling both the "backpack" and "clock" treatment arms into the control group would not change the results, as the point and standard error estimates are nearly the same.

For all columns, robust (heteroscedasticity-consistent) standard errors are shown in parentheses. School-level fixed effect results are omitted for brevity. Adding grade-level fixed effects in columns (2) and (3), where the exam scores are pooled, results in nearly the same point and standard error estimates.

were generally *not* associated with test scores. This pre-treatment study habit data was collected eight months before the examinations, so it is perhaps not surprising that how children reported studying in February was not predictive of their national examinations scores at year's end.

5.2 Additional Specifications, Precision, and Statistical Power of Results

In an effort to assess the robustness of the estimates for the impacts of solar lights on examination scores, several additional model specifications were considered beyond those in the initial analysis plan. This further analysis helps indicate whether the overall conclusions might change under specifications that could result in smaller standard errors, and therefore tighter confidence intervals, than those of the initial results. This could be helpful when comparing these results to other education-focused RCTs in developing countries (see "Comparison with Other Education-oriented RCTs and Cost-Effectiveness Analysis" in section 5.4).

First, additional variables collected from the student surveys were added to the initial model specifications. The focus was on how long it took children to walk to school and the extent to which they had missed school because their school fees were not paid. Throughout the fieldwork for this study, school and educational officials repeatedly cited the fees and long travel distances as leading reasons for school absenteeism, and it was therefore expected that children who missed school for these reasons might have lower examination scores. Somewhat surprisingly, however, the data did not reveal an association between these variables and examination scores, and therefore this additional specification did not meaningfully alter the precision of the results.

Next, the standardized examination scores for children in grades 7 and 9 were pooled. Pooling the grades nearly doubles the sample size of each specification, although the results should now be interpreted more broadly as the impacts of the solar lights on a standardized examination in Zimba District (as opposed to the impacts on the specific grade 7 and grade 9 tests, which are quite different from each other). Under this specification, the standard error for the estimated regression coefficient of the solar lights treatment is about 30 percent smaller than in the other specifications. However, there was still a failure to detect an impact of the lights on test scores. (Also, the impact of the backpacks on children in grade 7 was no longer detectable, as that effect is washed away by the inclusion of the grade 9 data). (see column (2) of table 3).

Models 1–3 and the models with the pooled examination scores were also rerun after additionally pooling the "soap" treatment arm with the control group that received candy. Because soap is theoretically not as direct of an educational input as the other prizes that were given away, it could be argued that those children were much like the control group. However, this additional pooling did not further improve precision, with point estimates and standard errors that were not appreciably different from the prior results (see column (3) of table 3). A further attempt to pool all of the non-solar treatments (backpacks, clocks, and soap) and treat them all as "controls" resulted in point estimates and standard errors that were once again very similar to the prior results.[15]

An exploratory heterogeneity analysis was also considered to try and uncover any impacts of the lights that might show up if the data were limited to those students who might stand to benefit the most from solar lanterns – for example, those who said that they did not primarily study in the dark at the time of the baseline survey. A further analysis looked at whether effects could be identified based on which activity the children self-identified as their most important daily task (for example, going to school versus domestic work). Additional heterogeneous treatment effects were estimated by gender and age (in light of the large negative coefficients in the initial models for girls and older children). Irrespective of which of these variables was interacted with the treatment variable, the F-statistics for joint hypothesis tests of the interacted variable coefficients were all far smaller than the critical value for a 0.05 test of the null hypothesis.

The failure to detect evidence of solar lights impacting examinations scores is likely not due to a lack of statistical power to detect economically meaningful impacts, for example because of too small a sample size. Appendix S4 in the supplementary online appendix presents the result of a power function calculation that suggests that if the solar lights did have economically meaningful impacts (around 0.3 standard deviations), our estimation procedure would have detected them with at least a 0.8 probability.

5.3 Impacts on Intermediate Outcomes (Study Habits or Solar Lantern Use)

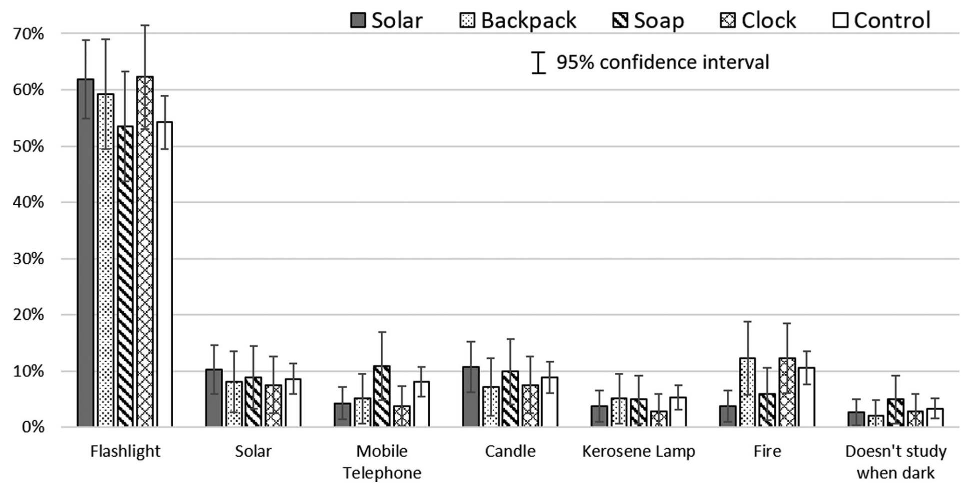
Much of the literature on educational impacts of solar lights has focused on the study habits of solar adopters, because it is assumed that how children study is the key intermediary outcome through which solar lantern adoption translates into improved educational performance. This study therefore investigated whether solar lanterns impacted study patterns, as it would be informative to detect potentially promising shifts in studying, even if they did not appear to lead to improved test scores in this study.

The focus was on four study habits that could plausibly change after the introduction of a new, brighter light source: the type of light children use most when they study in the dark, the time of day that they most often study, the location where they most often study, and whom they most often study with.[16] Figure S5.1 in the supplementary online appendix summarizes the responses that children who took both the baseline and endline surveys gave to the four study pattern questions.

15 The point estimates and associated 95 percent confidence intervals suggest it is unlikely that the treatment of distributing solar lights resulted in impacts greater than 0.35 standard deviations for grade 7 or 0.2 standard deviations for grade 9. If the specification with pooled grade 7 and 9 test scores is considered, as well as pooled control and soap treatments, overall impacts greater than 0.2 standard deviations can likely be ruled out.

16 One question that this study did not ask – even though it has been discussed in prior research – was how long students estimate they study. School officials and research team enumerators warned against asking this because there was no way to ask the question without prompting children towards a socially favored response of overestimating time spent studying.

Figure 1. Use of Different Lights for Nighttime Study (endline survey, by treatment arm)



Source: Authors' analysis based on survey data collected in the field.
Note: There is no notable difference among the treatment arms in the proportions of children using different types of lights for studies. About 10 percent of children reported using solar lights to study, regardless of which group they were assigned them to, while flashlights remained the dominant light source for each group (just as they were at baseline).

There were no meaningful differences detected between children who received solar lanterns and the control group on these dimensions (see fig. S5.2 in the supplementary online appendix). More broadly, none of the treatments seem to have obviously influenced the way in which children reported studying. The only detectable differences is the type of light used for studies, but even this was *not* due to children in the solar lantern group using the lights to study. Instead, there was a higher reported use of *flashlights* by the solar group relative to the control (and, to a lesser extent, a reduced use of phones or a fire as a light source).[17] One theory for this observed result is that receiving a solar light may have exposed children to the desirability of LED task lights, but that flashlights ultimately proved to be a preferred way to access such lighting.[18]

Slightly less than 10 percent of students in each experimental group reported using solar lanterns to study (fig. 1). This suggests that a small minority of students had access to such lights in Zimba District from sources outside this research. The gift of a free solar lantern by the research team did *not* make a child more likely to report using it to study.[19] The relationships between the types of lights used for studies, other study patterns, and test scores is further explored in S5 in the supplementary online appendix; one notable finding from that analysis is that a student's self-reported *use* of a solar lantern (regardless of whether or not they received one through this experiment) was not predictive of their test scores. This suggests that even if more children in the solar treatment group had used the lanterns they were given to study, there might nevertheless not have been an additional impact on academic performance.

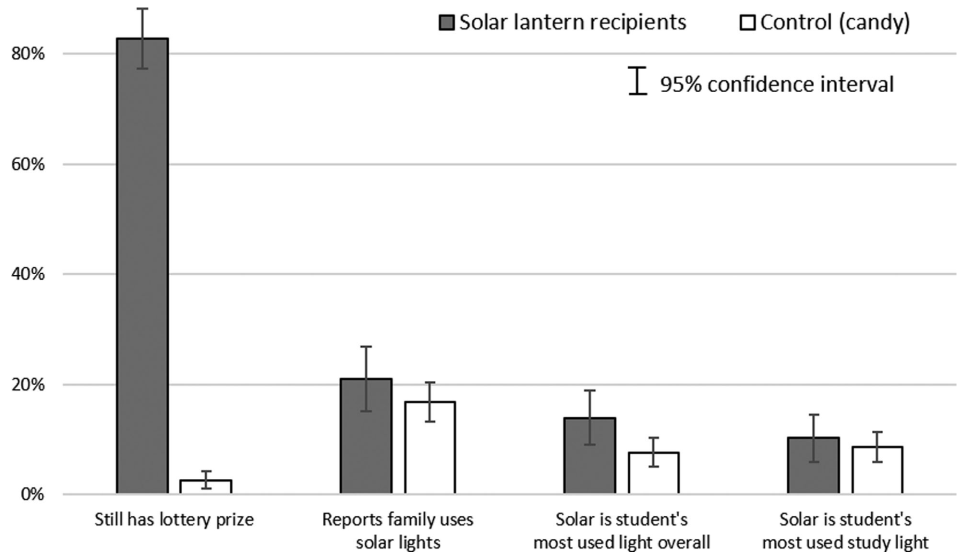
Not only did the children in the solar treatment group fail to use the lights to study, but it also appears that provision of solar lights failed to have a material impact on overall household lighting patterns more

17 Although 54 percent of the control group reported flashlights to be their primary study lights in the endline survey, an even larger proportion of the solar treatment group (62 percent) also reported flashlights to be their main lights. This 8 percentage point estimated impact of the solar lights on flashlight use is precisely estimated.

18 Students treated with a clock in this study also reported higher rates (62 percent) of flashlight use for studies, but a theory was not developed for why this might be the case. So it is possible that the observed increase in flashlight use rates among two of the treatment groups was by chance rather than through any impact that the gift of a solar lantern or alarm clock might have triggered.

19 Despite attempts to encourage them to do so, only 10 percent of the children that were given lanterns reported solar as their most often used lighting for studying in the dark.

Figure 2. Solar Lantern Use in Solar Treatment and Control Groups (endline survey)



Source: Authors' analysis based on survey data collected in the field.
Note: Children in the solar lantern treatment group reported still owning their lights at endline, but the reported lantern use rates were very low. As a result, even though children reported greater use of solar lights in their family and for their personal use relative to the control group, these differences do not appear to be practically meaningful.

generally. Students to whom solar lanterns were given did report greater rates of lantern use in their households and for their own personal use (though not necessarily for studying) relative to the control. These differences between the groups are precisely estimated, so it could be argued that the receipt of a solar light caused children to be more likely to report that they or someone in their family used solar lanterns for something. However, this outcome does not appear to be practically meaningful, given that the solar lantern use rates in all experimental groups were so low in absolute terms (fig. 2).

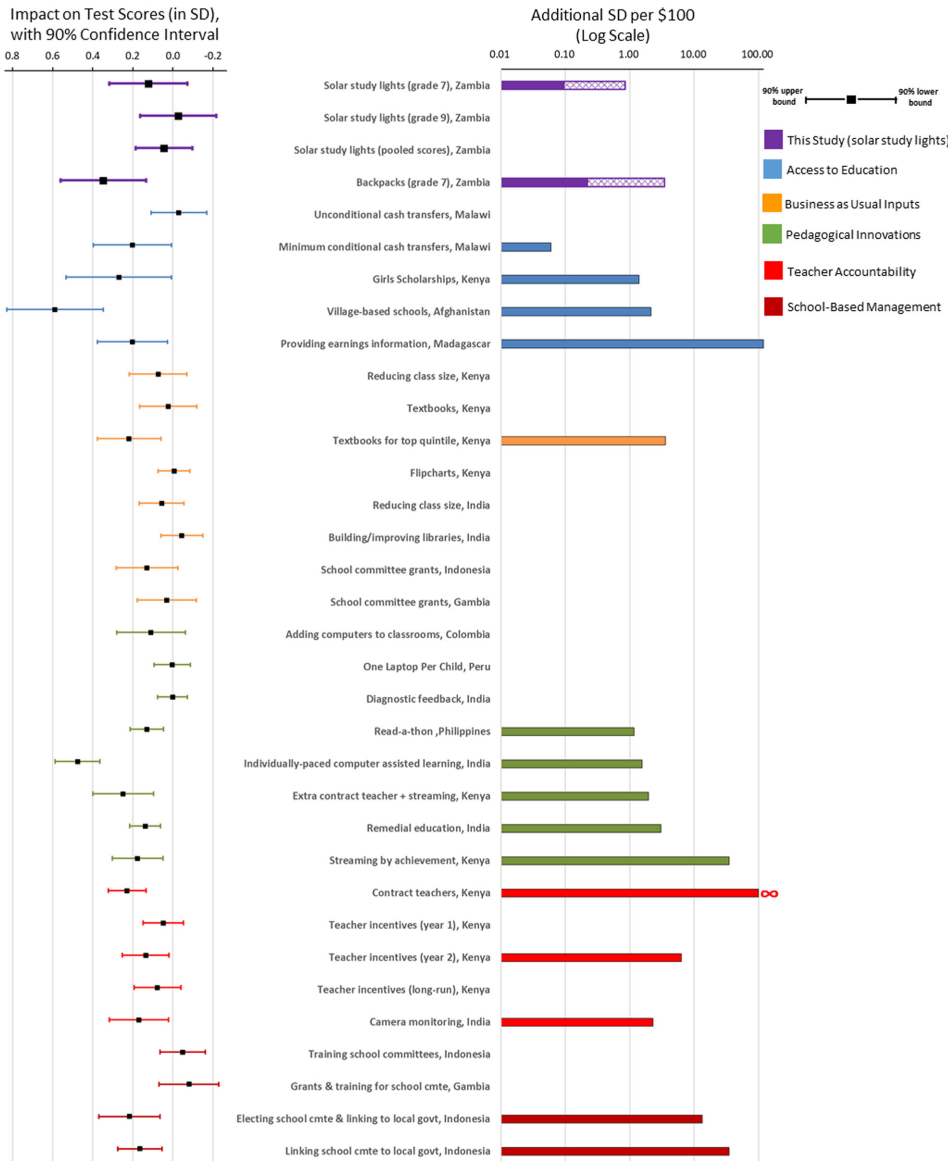
One potential explanation for the surprisingly low rates of solar lantern use by the treatment group is that, within the research sample, the vast majority of children reported (during both the baseline and endline surveys) that flashlights were their family's primary lights.[20] At baseline, only 12 percent reported that kerosene lamps, candles, or a fire – all of which are considered to be poor quality lighting sources and harmful to health, and from which a shift to solar seems to provide obvious benefit – were their family's most-used lights. Like solar lamps, flashlights also offer modern, LED-based lighting, so students and their families may not have perceived any additional benefits to using the solar lanterns compared to the flashlights they already had.

5.4 Comparison with Other Education-Oriented RCTs and Cost-Effectiveness Analysis (CEA)

In order to place the results of this RCT in context with other education-motivated interventions in the developing world, this study follows the framework and methodology of Kremer, Brannen, and Glennerster (2013) in their CEA across 27 RCTs that aimed to improve test scores in developing countries. Figure 3 is a reproduction the central results of Kremer, Brannen, and Glennerster (2013); the underlying data are available from J-PAL (2019). Their results are supplemented with the estimated impacts and cost-effectiveness of solar lights and (for grade 7) backpacks from this study, shown at the top of the figure.

20 Figure S3.2 in the supplemental online appendix shows a picture of the kinds of flashlights often used in Zimba District.

Figure 3. Impacts on Test Scores from RCTs in Primary Schools in the Developing World



Source: Kremer, Brannen, and Glennerster 2013 and J-PAL 2019, supplemented with the authors' results on solar lights and backpacks from this paper (shown at very top).

Note: **Left column:** Point estimates and confidence intervals show that, like many other education RCTs in developing countries, this study fails to detect meaningful impacts of solar lights on test scores. The confidence interval for the specification with pooled scores is close to the median confidence interval length of the other RCTs shown. Estimated impacts of backpacks in grade 7 are much more promising.

Right column: Solid purple bars estimate a lower bound for the cost-effectiveness of solar lights and backpacks in grade 7, calculated using the actual spending for this study and the methodology of Kremer, Brannen, and Glennerster 2013. Neither intervention compares favorably to the 15 other RCTs estimated to have positive impacts on test scores. The striped purple bars show an upper bound on cost-effectiveness under much more favorable assumptions for the costs of lights and backpacks. Even in this scenario, the lights do not compare well to the other programs; however, the backpack intervention appears more promising, even relative to some of the other interventions.

The left part of fig. 3 shows that the results of this RCT are generally consistent with other interventions in the developing-country education literature. Specifically, the point estimates for most educational interventions' impacts are increases in test scores of less than 0.2 standard deviations. The majority of studies do not detect impacts on test scores, even with a generous 10 percent significance level (as shown graphically by the 90 percent confidence intervals). The confidence intervals for the estimated impacts of solar lights in this study are well within the range of widths of the confidence intervals for other educational interventions in developing countries. When the specification that pools the grade 7 and grade 9 test scores is considered, the confidence interval from this study is only slightly wider than the median confidence interval width of the 27 RCTs in Kremer, Brannen, and Glennerster (2013).

With respect to the CEA shown in the right portion of fig. 3, this study makes the same assumptions and calculations that Kremer, Brannen, and Glennerster (2013) did. (The data and calculations are available to download from J-PAL (2019), to which the costs and results from this RCT are added.[21]) This enables an estimate of the total standard deviation increase in test scores that would be expected per $100 spent on distributing solar lights and backpacks to students in grade 7 in Zambia's Zimba District.[22] Although Kremer, Brannen, and Glennerster (2013) would have excluded solar lights for grade 7 students from their CEA, because no impacts were detected at a 10 percent significance level, this study includes it in the present analysis for two reasons. First, the point estimate in this study could be viewed as being promising but imprecise enough to argue in favor of undertaking the analysis in order to protect against the risk that the failure to detect impacts was due to the study being statistically underpowered (for example, due to a sample size that was too small). Second, because solar lights are the focus of this study, the CEA provides a sense of the magnitude of impacts that would be needed (regardless of whether they were actually detected) in order for the impacts of solar lights to be meaningful relative to other policies that education-focused stakeholders may wish to pursue to boost test scores.

The CEA suggests that giving students solar lanterns is not a cost-effective way to improve test scores in developing countries. There is an estimated improvement of only 0.1 standard deviations for each $100 invested in distributing solar lanterns (with a 95 percent confidence interval for the cost-effectiveness metric of –0.08 to 0.28). This is far worse than all but 1 of the educational RCTs considered by Kremer, Brannen, and Glennerster (2013). This calculation was made using the costs this study actually incurred. However, that is likely a lower bound on cost-effectiveness because the research staff could have distributed more solar lights (or backpacks) than the numbers that were actually given away in the lotteries without incurring additional fixed costs.[23]

An upper bound on cost-effectiveness is one where the market price for solar lights and backpacks is the only cost included in the CEA calculation. Since these items could, in theory, be bought in shops near

21 This includes selecting the appropriate costs of the intervention to include in the calculations, as well as the process for converting everything to a set of "common units" through consistent adjustments for inflation, exchange rates, and calendar year of implementation. While any CEA is sensitive to such assumptions, this study's sensitivity to exchange rates and inflation was lessened due to the short time-frame of the experiment and low inflation during the study and the years since in both Zambia and the United States. The costs included were $16 (in 2011 USD) price per solar light for the 85 lights that were distributed to students in grade 7 plus $9,557 (in 2011 USD) in staffing, transportation, shipping and other overhead costs actually incurred to implement this intervention.

22 Following Kremer, Brannen, and Glennerster (2013), the grade 9 results are excluded from the CEA because an impact could not be detected.

23 Realistically, the research team could have given away up to 500 lights or backpacks for the same fixed costs, although total costs would increase due to the per-unit costs. If this is taken into account and it is further assumed that the estimated impacts would hold if 500 lights or backpacks were to be given out, then the cost-effectiveness of solar lights for grade 7 students would increase to 0.35 standard deviations (with a 95 percent confidence interval of –0.31 to 1) per $100 invested. They would still not be a cost-effective intervention relative to the other programs. However, the backpacks look more promising, with an estimated cost-effectiveness metric of 1.4 standard deviations per $100 (albeit a wide 95 percent confidence interval of 0.38 to 2.41).

Zimba, the purchase price could be argued to include all the costs related to the treatment of distributing a solar light or backpack. This assumption is probably safer for backpacks than for solar lights, because solar lights tend to break down and require after-purchase support that incurs financial and time costs. Lights also require proper-use training, daily charging, and maintenance. Such time costs would normally be included in a CEA, but they are excluded here because treatment is defined as the distribution rather than the use of the lights. Even under this optimistic assumption that only considers purchase price, the estimated cost-effectiveness for solar lights would still be only a 0.75 gain in standard deviations per $100 invested (95 percent confidence interval of –0.66 to 2.17). This remains well below all but one of the other RCTs in fig. 3. On the other hand, the backpacks would become a potentially attractive option, as the estimated 3.22 standard deviations gained per $100 (and 95 percent confidence interval of 0.87 to 5.57) compares favorably to many of the other interventions in Kremer, Brannen, and Glennerster (2013).

As discussed in "Defining and Evaluating Economically Meaningful Impacts" in section 4, the average treatment effect of the solar lights would need to be a 0.37 standard deviation improvement (even under the optimistic assumption that only purchase costs should be considered in the CEA) before the cost-effectiveness metric would rise to the median 2.28 standard deviations per $100 of the other education RCTs of fig. 3. Regardless of the model specification used, the point estimates and associated confidence intervals suggest it is highly unlikely that this study's intervention resulted in impacts close to that magnitude. In the setting of this study, therefore, providing solar lights would not be cost-effective relative to other interventions available to policymakers.

6. Conclusion

Despite the notable success of vendors selling millions of solar lanterns as devices that will help children study, there remains scant evidence that the lights improve educational outcomes. This study's experiment in rural Zambia failed to detect impacts on standardized examination scores or on study habits, with the latter being a potential intermediary outcome through which improved lighting could translate into better academic performance.

Solar lanterns did not seem to have much appeal for the children who participated in this study; they did not use the lights for studying or for other activities, and their families also did not appear to put the lights to use.[24] In this respect, the results of this study are markedly different from the prior literature on solar lanterns (Furukawa 2014; Hassan and Lucchino 2016; Kudo, Shonchoy, and Takahashi 2017; Rom, Günther, and Harrison 2017), which reported extensive use of the lanterns even as they similarly failed to find convincing evidence of improved test scores. The attention in this research design to blinding participants to the study's focus on solar lanterns could be one reason behind the low reported rates of solar lantern use.

Another key difference is that prior examinations of solar lanterns and education, as well as nearly all other studies of the off-grid solar space, have taken place in settings where kerosene was the incumbent lighting fuel. By contrast, Zimba District is a location where flashlights are the dominant lights. This high penetration rate of battery-powered flashlights may be common in much of rural Sub-Saharan Africa (see Bensch, Peters, and Sievert (2017), who report similar trends in seven more countries).[25] Although

24 It is therefore not surprising that a treatment of disseminating lights, by itself and without subsequent widespread use, did not trigger economically meaningful impacts.

25 It is possible that the passage of just a few years between the data collection for prior published research on solar lanterns and the fieldwork for this study in 2016 explains why, unlike prior studies, this study encountered a population that had already largely stopped relying on traditional lighting. It may also be the case that rural populations in Zambia and other countries in Sub-Saharan Africa have historically used kerosene much less than Kenya and Uganda, which have been the setting for most of the prior published research on off-grid solar PV (see, e.g., Stojanovski, Thurber, and Wolak 2017). In such settings, the key question is not whether a solar lantern is preferable to traditional options, as has

there appears to be a strong demand by rural populations to move away from kerosene lamps, it is less clear that solar lanterns are a similarly attractive alternative to populations that do not rely on kerosene. An important area for further assessment by impact-oriented organizations is the extent to which even relatively low-quality LED flashlights might meet the lighting needs of prospective solar lantern adopters. At the very least, the common assumption that the social benefit of LED lighting from cheap flashlights is inferior to that of solar lanterns should be critically examined (Bensch, Peters, and Sievert 2017).[26]

Even if solar lanterns were to be widely and successfully adopted, it is not clear whether a longer-lasting, brighter, and more comfortable lighting option would make much of a difference on test scores in places like Zimba. Children in the research sample did not report studying in the dark as a major challenge, regardless of the type of study light they used. In addition, the types of lights that they reported studying with during the baseline and endline surveys were not predictive of their national examination scores (see S5 in the supplementary online appendix). Instead, the major schooling challenges reported by the children in the sample were an inability to pay school fees, the lack of school supplies, and being overwhelmed with too many responsibilities beyond school. Put simply, poverty was a far greater barrier to education than inadequate lighting. Recent studies of other energy access initiatives suggest that easing energy poverty does little to improve overall poverty (Lee, Miguel, and Wolfram (2018); Burlig and Preonas (2016)). Seen in this light, Zimba District could simply be a location where the financial barriers to schooling are so great that they render insufficient lighting a relatively unimportant educational input, which would be in line with the conclusion of Kudo, Shonchoy, and Takahashi (2017) in their examination of solar lanterns in rural Bangladesh.

In settings like Zambia's Zimba District, introducing better ambient lighting may be a worthwhile development goal in itself, but it appears unlikely to improve educational outcomes. For those focused on boosting educational performance in rural areas, there appear to be other more cost-effective opportunities. The results suggest, for example, that providing backpacks – or more books and school supplies – could benefit some students.

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been previously studied, but rather whether solar lanterns offer better lighting than the more modern bulbs found in flashlights or telephones.

26 The research team's experience during this and previous research has been that flashlights and phones are generally perceived by the solar industry's proponents as inferior options to solar lanterns (Mills et al. 2014; Grimm et al. 2016; Kudo et al. 2017). The flashlights sold in rural African areas, in particular, are often talked of as cheap, low quality, and/or inferior lighting sources that are unreliable, environmentally hazardous (because of the improper disposal of dry-cell batteries that power them), and that spoil the market for higher-quality solar products (Mills et al. 2014). Telephones, meanwhile, tend to have fairly dim and small LED lights and require a potentially inconvenient recharging outside the home, usually at a charging shop.

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