Decreasing Emissions by Increasing Energy Access? Evidence from a Randomized Field Experiment on Off-Grid Solar

Adina Rom, Isabel Günther

August 21, 2019

Abstract: Human-driven climate disruption and widespread energy poverty are among the most pressing challenges of our times. Over 1 billion people still lack access to energy, many of which use kerosene for lighting, which has high operational costs and contributes to global warming and indoor air pollution. Prices for solar have fallen dramatically and policy makers, entrepreneurs, and investors are enthusiastic about the potential of solar lighting to reduce harmful emissions while improving access to better energy services. However, rigorous empirical evidence on their private returns as well as the impact of solar lighting on emissions reductions and health outcomes is scarce. Applying a randomized field experiment in rural Kenya, we find that access to a solar light leads to a reduction in kerosene consumption of 1.47 liters per month, curbing emissions at a cost of less than US \$7 per ton of CO_2 equivalent. Children's symptoms related to dry eye disease reduce by about a fourth standard deviation and respiratory illnesses by about a third standard deviation. In addition, households reduce their monthly cash expenditure by 2-3%. Decreasing transaction costs can increase demand at current market price of US \$9 from 19% to 44%, but price subsidies of over 55% are needed to increase adoption rates to 70%. Sensor data reveal that subsidies do not affect usage. Environmental and health effects combined with price sensitivity of demand and no detected sunk-cost or selection effects may justify using public resources to increase adoption of solar lighting to replace kerosene.

1 Introduction

In this century the global community faces two critical challenges: human-driven climate disruption and widespread energy poverty (Alstone, 2015; SEAll, 2017). Acknowledging these challenges, the UN Sustainable Development Goals has called upon the international community to "ensure access to affordable, reliable, sustainable and modern energy for all." Nevertheless an estimated 1.1 billion people remain without access to modern energy, most of whom rely on biomass and fossil fuels for lighting, cooking and heating with harmful emissions for the environment and humans (SEAll, 2017; WHO, 2016).

There is a heated debate about how to improve energy access while ensuring environmental sustainability, and many believe that there are inevitable trade-offs. There are high hopes that new technologies will allow avoiding painful tradeoffs and create "win-win" situations, by simultaneously increasing energy access (or reduce energy cost) and reducing emissions. However recent studies, mostly from high-income countries, suggest that engineering projections often overestimate efficiency gains from novel technologies (such as more efficient air-conditioners and fridges or energy efficient home improvements) and studies evaluating their cost-effectiveness in a real world setting have found that their private returns and potential to reduce emissions are much more limited (Davis, Fuchs & Gertler, 2014; Fowlie, Greenstone & Wolfram, 2018; Allcott & Greenstone, 2012). Similarly, field experiments on the use of cookstoves in developing countries have shown that lab tests have overestimated their effects on health and environmental outcomes, and in many instances the improved cookstoves are hardly used (Hanna, Duflo & Greenstone 2016).

Projections based on lab tests might overestimate cost savings and environmental gains from novel technologies for a number of reasons. First, households might not invest the necessary time and effort to access them. Second, they might not use and maintain new technologies over time. Third, there could be rebound effects, whereby households use the more energy efficient solutions more, or increase the use of different energy services, as they are cheaper to use. The result is that overall spending on energy and emissions are not reduced as much as previously thought (Fowlie, Greenstone & Wolfram, 2018; Gillingham et al., 2013; Van den Bergh, 2011). Finally, projections might be simply overly optimistic about their economic returns as they overestimate the costs of current solutions or underestimate "hidden" costs of the new product (Fowlie, Greenstone & Wolfram, 2018). Therefore, there is a need for impact evaluations that study the effect of new technologies in a real world setting. While there are a number of studies about the cost- and environmental effectiveness of carbon reducing technologies for residential energy in developed countries, evidence from developing economies is still very scarce (Davis, Fuchs & Gertler, 2014; Davis, Martinez & Taboada, 2018). This is particularly problematic as the largest increase in energy demand will come from developing countries (DOE, 2017; Wolfram, Shelef & Gertler, 2012).

In recent years, prices for solar panels and batteries have decreased dramatically and made off-grid solar a seemingly cost-effective solution to provide poor households with cheap and clean energy (Bloomberg, 2016). This is particularly relevant as electrification, which is the most obvious alternative to off-grid solutions, might be more expensive and less transformational in some rural settings than previously thought. In fact recent (quasi-) experimental evidence suggests that, at least in the medium run, rural electrification in poor countries might not be cost-effective (Barron & Torero, 2017; Burlig & Preonas, 2016; Lee, Miguel & Wolfram, 2016b; Lenz et al., 2017; Peters & Sivert, 2016).

Emissions from kerosene lamps contribute to global warming and indoor air pollution (Lam et al., 2012a; Jacobson et al., 2013), which is a leading risk factor for disease (WHO, 2016). The hope is that solar lighting would replace the widespread use of kerosene for lighting, allow low-income households to significantly decrease their energy expenditure, and reduce the associated emissions and related health risks.

Our study provides experimental evidence on the impact of solar lights on kerosene use and the associated effects on CO_2emissions, indoor air pollution, and health of household members. Due to the novelty of affordable solar lighting solutions, there are only a handful of studies on the impact of this technology. Three studies have focused on whether access to solar improves children's schooling outcomes (Furukawa, 2013; Hassan & Lucchino, 2016; Kudo, Shonchoy & Takahashi, 2017) and two studies have looked at a broader range of outcomes at the household level (Grimm et al., 2016a; Aevarsdottir et al., 2017). Only one study has focused on the effect on children's health outcomes (Kudo, Shonchoy & Takahashi, 2018).

To our knowledge, no field experiment to date has evaluated the climate-related impact of solar lights. Such an assessment is highly dependent on an accurate estimate of the use of solar lights of household. Measuring the use of new technologies with surveys only is challenging, as respondents might be tempted to overreport usage, leading to social desirability bias in estimates (Wilson et al., 2016; Thomas et al., 2013). We therefore used sensors, specifically developed for this project, for accurate high-frequency measures of solar light use.[1]

However, even if the use of solar lighting reduced the negative effects of kerosene use on global warming and indoor air pollution, households might still not invest in solar lights as they do not fully internalize these benefits or might not be aware of them. There are a number of additional reasons why households might invest less in solar lights than what is socially optimal. First, they might underinvest due to present bias and inconsistent time preferences, which has been shown for different preventative health products before (Dupas, 2011; Dupas, 2014; Kremer & Miguel, 2007). Second, they might be overly risk averse and hesitant to invest in a technology with unknown return and lifespan. Third, households might be too credit-constraint to invest in the substantial up-front payment. Finally, there could be issues related to intra-household allocation: children might benefit particularly from the solar light as they can use improved light for their homework. The household's financial decision makers might underinvest as they do not fully internalize children's preferences. Hence, we also need to understand the private economic benefits of solar lights for households and, if limited, analyze whether subsidies would increase the adoption of this new technology without compromising its usage. Subsidies might affect use as paying a lower price for a good might decrease its perceived value and makes people less likely to use it (sunk-cost effect) or people who are less interested in the product might purchase it and use it less (selection effect). We address both questions in the second part of this study.

We conducted a randomized field experiment with over 1,400 households in the rural areas of Western Kenya, where less than 5% of the population were connected to the electricity grid at the time of the study. Households either received a free solar light, an offer to buy a solar light at a high discount (US \$4), a low discount (US \$7), the market price (US \$9), or they were randomly assigned to a control group and received no intervention. In addition to a household survey before and after the intervention, we installed sensors measuring the use of solar lights in a subset of households and collected children's test scores before and after the intervention.

We find that access to a solar light reduces kerosene use by 1.47 liters on average per month, leading to yearly emissions abatement of 828.47 kg of CO_2equivalent

---

[1] Results from sensor measurements are discussed in Chapter 3 in detail.

per household. If this was scaled to all households using kerosene in Kenya, this could decrease emissions by 2.17 mega tonnes of CO_2 equivalent, corresponding to 3.58% of Kenya's overall emissions in 2014 (CAIT, 2017). We estimate that the price per tonne of CO_2 equivalent averted is between US $5.87 and to US $9.69, which is lower than what is typically considered as the social cost of carbon (IWG, 2015) and also lower than clean energy investments in Europe or the US (Abrell et al., 2017). Access to solar lighting also decreases symptoms of dry eyes disease for both children and adults and symptoms for respiratory illness for children. The private returns are more modest, with households saving around 102.4 KES (US $1.02) per month corresponding to 2%-3% of total cash expenditure. We do not find any effects on children's test scores in school. Our results also suggest that demand for solar lighting is very price sensitive. At current market conditions and prices US $9 demand is modest with 19% of households owning a solar light. We find that decreasing transaction costs alone can increase demand to 44% but price reductions are needed to increase take-up further.

2 Background and Study Design

2.1 Context

Only 1.6% of the Kenyan population used solar as their main lighting source in 2005 (KIHBS, 2018). In 2008, Lighting Africa, an initiative led by the World Bank and IFC, selected Kenya together with Ghana as pilot countries to support the off-grid solar sector through a variety of measures, including product quality verification, costumer awareness campaigns, provision of market intelligence and technician trainings to provide after-sales maintenance support (Lighting Africa, 2016). In 2014, the Government of Kenya exempted solar products from the Value Added Tax of 16%, which reduced the price for end users (GoK, 2014). The share of household who use solar as their primary energy source for lighting has increased to 14.1% by 2015, but annual sales have stagnated since (GOOGLA, 2018;KIHBS, 2018).

The Government of Kenya has stated that it wants to eliminate kerosene for household energy consumption due to health and environmental concerns.[2]

---

[2] See for example Kenya's Climate Change Action Plan "When used in simple kerosene lamps, kerosene leads to high indoor air pollution as well as to an increased risk of burns, fires and poisonings" (GoK, NCCAP, 2012). Kenya's Energy Policy states that "Increased use of LPG shall be encouraged with a view to eliminate the use of kerosene, charcoal and firewood

Moreover, in response to the Paris Agreements, the Government of Kenya announced that it intends to reduce its CO_2 emissions by 30% compared to a "business as usual" scenario by 2030 (GoK, 2015) and developed a National Climate Change Response Strategy and Action Plan (GoK, NCCAP, 2012). As a result, there is an ongoing debate about the government's energy policy and how it should balance concerns over access with environmental sustainability. For example, the Government of Kenya currently discusses how much kerosene should be taxed; while some argue that environmental and health concerns justify taxes, other fear that poor households will be hit hard by increasing kerosene prices and won't be able to access sufficient lighting anymore (GoK 2012; Daily Nation, 2018).

At the same time the Government of Kenya has also heavily invested in rural electrification to increase access to energy for its population. The ambitious goal is universal access to electricity by 2020 (GoK, 2015). In 2013 the Rural Electrification Agency announced that 90% of the country's public facilities were electrified and thus a large share of the population lived within proximity of the grid. However, only 18-26% of households were electrified at the time. In 2015 the Kenyan government announced that they raised additional US $364 million for the "Last Mile Connectivity Project", mostly from the World Bank and the African Development Bank (Lee, Miguel & Wolfram, 2016b). This project provides large subsidies so that connections for those living close to the grid would only cost US $150 for the individual households (Lee, Miguel & Wolfram, 2016b; Kenya Power, 2017). According to the Kenya Power and Lighting Corporation (KPLC), this has led to almost 50% of households connected to the electricity grid in 2016. The program was still in its early stages during the time of our study in 2015 and the villages we worked in remained largely unaffected. Only 1.4 % of households in our sample were connected to the grid and only 13 households heard about an electrification project in their village. The costs for grid connection was still at 35,000 KES (US $350) during our study.

2.2 Intervention

While a number of different types of solar products are sold on the Kenyan market, we analyze the impact of low-cost solar lights — small portable lighting units. Our study partner was SolarAid, one of the largest local distributor of portable solar lights at the time of the study. From 2009-2015 our partner sold

---

in households" , GoK, NEPP (2015).

over 1.7 million solar lights through its subsidiary SunnyMoney, most of them in Tanzania, followed by Kenya (SolarAid, 2015). Two different types of lights were studied: the Sun King Eco and the Sun King Mobile, both manufactured by Greenlight Planet and quality assured by Lighting Global, a World Bank initiative. According to tests conducted by Lighting Global, the Sun King Eco provides light for 5.8 hours when used at its maximum brightness of 32 lumens, [3] and up to 30 hours when used at its least brightest mode of 4 lumens, according to the manufacturer (Greenlight Planet, 2016; Lighting Global, 2015). The Sun King Mobile can be used for 5.4 hours in its brightest mode (98 lumens) and 10.3 hours in its medium mode (51 lumens) (Lighting Global, 2015). The Sun King Mobile can also be used to charge a mobile phone.

For comparison, a simple kerosene tin lamp provides around 7.8 lumens and a kerosene lantern 45 lumens (Mills, 2003). A picture can be found in the Appendix (Figure A.1 and A.2). Both types of solar lights hence provide a stronger light than the tin lights, which are used as the primary lighting source by 27.7% of Kenyas rural population (KIHBS, 2018). In 2015, our partner organization was selling the Sun King Eco light for US $9 in Kenya, and the Sun King Mobile at US $24, corresponding to 12.3% and 32.8% of a household's average monthly cash expenditure.

2.3 Experimental Design

We conducted a randomized control trial (RCT) between June 2015 and March 2016 in Nambale and Teso South, two sub-counties located in the Busia County in Western Kenya. In a first step, we randomly selected 10 schools in each of the sub-counties out of a total of 97 eligible schools that met a pre-specified set of criteria.[4] Within each of these 20 schools, we identified all households that had at least one pupil in class five, six, or seven. Class eight was not included since these pupils would have left school by the time the endline survey was conducted. Students in lower classes (1-4) were not invited to participate in the study since it would have been harder for them to answer questions about

---

[3] Lumen measures the brightness of a lighting source (i.e. the amount of visible light is emitted). Watt on the other hand are used to indicate the amount of energy needed to power the product. A 3-5-watt compact fluorescent lamp corresponds to around 110 lumens.

[4] The local administration provided a list of all 127 public schools (50 in Nambale and 77 in Teso South). A number of schools were eliminated, such as schools with less than 100 pupils, schools with only girls or only boys, boarding schools, schools located in urban centers or that were too far from the research office to be reached within a field work day, and schools whose head teacher was not present at the term head teacher meeting, where our partner organization typically recruited head teachers for their solar program. From the remaining 97 schools, 20 were selected at random (10 in each sub-county).

homework, time use, light use, etc. In a second step, out of the 3,360 eligible households (with at least one child in class five, six, or seven in the 20 schools in our sample) a total of 1,410 households were randomly selected to be part of the study (Figure 1).[5]

Randomization into different treatments was then conducted at the household level and stratified at the school level, or in other words we randomly selected around 70 households per school, leading to 1,410[6]selected households across all 20 schools and randomly assigned them into one of several groups.

1. Control group: 20 households per school, 400 households total.
2. Free solar lights group: 20 households per school, 400 households total, received a free solar light, of which 200 received a solar light that also had a port to charge a mobile phone.
3. Voucher group: About 30 households per school, 610 households in total, received a voucher to purchase a solar light at one of the following prices:
    - Subsidized price of 400 KES /US $4 (N=209)
    - Subsidized price of 700 KES/US $7 (N=201)
    - Market price of 900 KES/US $9 (N=200)

In each household, we surveyed the selected child and the child's main caretaker. We designed a lottery based on text messages, to make it clear to respondents, that whether they won a prize was decided by random chance. The lottery worked in the following way: at the end of the baseline interview surveyors gave respondents a "lucky number" and invited them to participate in the lottery. The respondent then sent a text message with the "lucky number" to participate in a lottery and immediately received a text message back, announcing if they either won a free solar light, had the opportunity to purchase one at a given

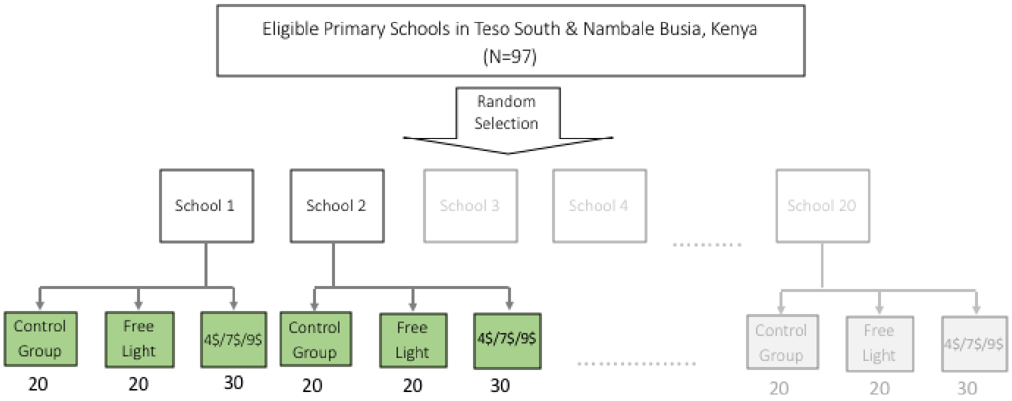
---

[5] Visits to schools were announced in advance and children were encouraged to come to school; however, if a selected pupil was absent that day s/he was replaced with another pupil who was drawn at random.

[6] Two of the schools did not have enough households that met the selection criteria. In these two schools, we reduced the number of vouchers distributed to 0 (Sango) and to 10 (Aburi) and increased the number of sampled students in larger schools instead. To keep field operations as simple as possible we increased participation to 75 (Opeduru, Olepito, Obekai, Kaliwa, Kamarinyang, Ong'aroi, Asinge, Ng'eechom) or 80 (Sianda, Khayo) in other schools.

price during the following weeks, or did not win anything (control group). This text message could then be redeemed to either receive a free solar light on the spot or a personalized voucher. As these types of text-message games are very common in Kenya, it was easy to understand for respondents and made it clear that the allocation of prizes was random.[7]

Figure 1: Research Design



Notes: We randomly selected 20 schools (10 in each sub-county) out of 97 eligible schools. Randomization into treatments was conducted at the household level and stratified at the school level.

In the end of the baseline interview, field staff showed the solar light to every guardian who received an offer to purchase one and read a script containing basic information (Appendix, Section E) about the solar light. All vouchers contained the respondent's name and were not transferable. We conducted audits to ensure that the respondents did not sell or trade their vouchers. Respondents could redeem their vouchers through the head teacher of the participating schools within 4-6 weeks.[8] This means that those who received an offer to purchase

---

[7] Cellphone providers frequently send subscribers codes that they can submit via text message to participate in a lottery. After developing this process with our local partners we tested it in several pilots, discussed it with beneficiaries, and made sure the lottery was well understood by our respondents. It turned out that this process had the advantage that respondents would intuitively understand that the allocation of prices was random and that what they answered in the survey would not have an impact on their chances of winning.

[8] This was how our partner SunnyMoney typically operated.

Table 1: Balance Table for Main Outcomes

Stats	(1) Control Mean (SD)	(2) Free Mean (SD)	(3) Diff. [P-Val]
Kerosene Used (l)	3.106	3.070	0.036
	(3.744)	(4.027)	[0.897]
Kerosene Spent (KES)	211.536	200.669	10.867
	(145.986)	(158.271)	[0.318]
Adults Dry Eyes 0-6	3.005	2.920	0.070
	(1.886)	(1.878)	[0.597]
Pupils Dry Eyes 0-6	4.178	4.000	0.170
	(3.429)	(3.603)	[0.498]
Adults Respi. 0-5	1.538	1.585	-0.055
	(1.551)	(1.590)	[0.620]
Pupils Respi. 0-5	0.703	0.673	0.032
	(0.457)	(0.470)	[0.331]
Nr of Kerosene Lights Used	2.545	2.583	-0.038
	(1.112)	(1.125)	[0.635]
Nr of Calls	16.469	14.639	1.829
	(18.619)	(18.858)	[0.271]
Times Phone Charged	1.485	1.447	0.038
	(1.249)	(1.207)	[0.665]
Homework Completion	0.674	0.652	0.022
	(0.470)	(0.477)	[0.559]
Homework Hours	2.198	2.208	-0.003
	(1.599)	(1.626)	[0.976]
Sleep Hours	7.276	7.352	-0.106
	(3.383)	(3.395)	[0.661]
Average Test Scores	-0.005	0.045	-0.053
	(0.999)	(1.020)	[0.486]
Observations:	398	398	796

Notes: Sample restricted to control group and free solar light group, since we only have few baseline measures for groups that received a voucher to buy a solar lantern. Number of observations is indicated for adult surveys. We had 793 pupil surveys (396 in the Control Group and 397 in the Free Group) but only 718 (355 in the Control Group and 363 in the Free Group) observations for test scores.

Table 2: Summary Statistics and Balance Table

Stats	(1) All Mean (SD)	(2) Control Mean (SD)	(3) 400 Diff. [P-Val]	(4) 700 Diff. [P-Val]	(5) 900 Diff. [P-Val]	(6) Free Diff. [P-Val]	(7) All Diff. [P-Val]
Iron Roof	0.646	0.666	0.060	0.045	0.036	-0.003	-0.028
	(0.478)	(0.472)	[0.143]	[0.278]	[0.381]	[0.940]	[0.331]
HH Head Female	0.303	0.309	0.016	0.022	0.040	-0.018	-0.008
	(0.460)	(0.463)	[0.689]	[0.587]	[0.315]	[0.595]	[0.757]
Household Size	6.688	6.784	0.178	0.143	-0.023	0.183	-0.134
	(2.141)	(2.177)	[0.345]	[0.456]	[0.902]	[0.218]	[0.293]
Main Income is Agriculture	0.683	0.688	-0.013	-0.004	-0.017	0.038	-0.008
	(0.466)	(0.464)	[0.733]	[0.924]	[0.670]	[0.259]	[0.770]
Business Ownership	0.294	0.332	0.014	0.111 ***	0.103 ***	0.018	-0.052 *
	(0.456)	(0.471)	[0.721]	[0.005]	[0.009]	[0.596]	[0.054]
Yrs of Schooling HH Head	6.386	6.599	0.549 *	0.334	0.069	0.251	-0.295
	(3.804)	(3.895)	[0.096]	[0.336]	[0.838]	[0.378]	[0.206]
Number of Mobile Phones	1.397	1.425	0.040	0.033	0.024	0.048	-0.038
	(0.794)	(0.802)	[0.550]	[0.634]	[0.733]	[0.411]	[0.414]
Solar Lantern Ownership	0.065	0.053	-0.029	-0.009	-0.018	-0.015	0.017
	(0.247)	(0.224)	[0.163]	[0.662]	[0.373]	[0.372]	[0.235]
Access to Electricity	0.014	0.013	-0.016	-0.003	0.002	0.003	0.002
	(0.119)	(0.112)	[0.154]	[0.780]	[0.798]	[0.738]	[0.726]
Total Expenditure	7,319.549	7,405.847	-	-	-	171.938	-
	(5,461.814)	(5,407.505)				[0.657]	
Land Owned	2.035	1.977	-	-	-	-0.114	-
	(1.455)	(1.793)				[0.388]	
Chickens Owned	6.043	6.156	-	-	-	0.226	-
	(5.138)	(6.396)				[0.598]	
Earth Floor	0.883	0.864	-	-	-	-0.038 *	-
	(0.608)	(0.343)				[0.098]	
Observations:	1396	398	208	195	197	398	1396

Notes: *** p<0.01, ** p<0.05, * p<0.1. Columns 3-6 show differences with mean of the control group (Column 2). Some are missing since as discussed in Section 2.4 we do not have all baseline variables for the voucher group. Column 7 shows difference of all groups with control group.

a solar light (including at market price) could buy the solar light in an easily accessible place (their child's school) without high transportation costs, whereas household from the control group could only purchase the solar light through local retailers. We learned through our surveys that solar lights where not always easily available, as only 7.52% of the sampled households said that they could be bought in their village and 43.41% in the closest market center.

2.4 Estimation Strategy

Our main specification for the analysis of impact is an instrumental variable (IV) approach to estimate the Local Average Treatment Effect (LATE). The LATE is the effect of having a functioning solar light (either having received a free one or having bought one through our program) on the various outcomes of interest.[9] We use the randomly allocated treatment group (either voucher to purchase a solar light for 400 KES, 700 KES or 900 KES or receiving a free Sun King Mobile or Sun King Eco light) as an instrument. The treatment status affects the probability of having a functioning solar light strongly and should not affect the outcomes of interest through any other channel than through having a functioning solar light. Using this identification, we combine the treatment effects of the different subsidies into one. In Section 3.4 we show that there is no significant difference in solar light usage for households that receive a free solar light in comparison to solar lights who have to pay US \$4, \$7 or \$9.
Formally we estimate the following set of regressions:

$$light_{ij} = \alpha_0 + \sum_{k=1}^{5} \alpha_k (offer_{ij}) + \beta X'_{ij} + \lambda_i + \epsilon_{ij} \tag{1}$$

$$y_{ij} = \alpha_0 + \alpha_1 (lig\hat{h}t_{ij}) + \beta X'_{ij} + \lambda_i + \epsilon_{ij} \tag{2}$$

$light_{ij}$ designates whether household i in school j had a functioning solar light at endline, $offer_{ij}$ designates the type of offer the household received, which was either a free Sun King Eco light, a free Sun King Mobile light or a voucher to purchase a Sun King Eco light (for 400 KES, 700 KES or 900 KES). X_j refers to a set of control variables namely electricity connection at baseline, business ownership and wether anyone in the household is employed as well as

---

[9] For simplicity, we use the following terms "effect of having access to a solar light " or the "effect of solar lights" etc. to describe the LATE.

household size. The regressions shown in the main paper are without controls, with the exception of gender of the respondent, if the relevant outcome is at the individual level and class fixed effects for children's outcomes. Regressions with the controls mentioned above are shown in the Appendix. The results do not change significantly. λ_i refers to school fixed effects (we stratified at the school level). ϵ_{ij} is an error term. y_{ij} designates the outcome of interest of household i in school j and α_1 captures the LATE.

Due to budget constraints, we do not have all baseline measures for all outcome variables of interest for the entire sample (only for the free solar light and the control group). Therefore we cannot control for baseline measures of our dependent variables. Table 1 shows that the sample is balanced between the free and the control group across all outcomes of interest, Table 2 shows that the sample was mostly balanced across a number of other household characteristics across all treatment groups.

For full transparency and as outlined in our pre-analysis plan we provide the Intention-To-Treat (ITT) measures of our main results in Table 12.

2.5 Data

Prior to commencing the full study, we conducted a number of in-depth interviews with solar light users and non-users, with teachers as well as field staff and executives from our study partner SunnyMoney. We also held five focus group discussions with users and non-users of solar lights. The information from the in-depth interviews and focus groups was used to design the survey instruments. In addition, we tested the random distribution of free lights, as well as the survey questions and the acceptability of the sensor technology before running the full baseline survey.

We surveyed the randomly selected pupils (see Section 2.3) as well as their primary guardian, which in most cases was the mother (50.2%) or the father (28.7%). Data were collected at baseline (July/August 2015) before the intervention and around seven months after baseline (February/March 2016). We created survey instruments based on previous studies conducted by leading researchers in the field of renewable energies in low-income countries, including Cattaneo et al. (2009), Furukawa (2013), Grimm et al. (2016a) and Lee, Miguel & Wolfram (2016b), as well as standardized scales to measure health and well-being (World Value Survey, European Community Respiratory Health Survey II and the Standard Dry Eyes Disease Questionnaire and CES-D).

The main outcomes of interests are different measures of kerosene used, energy spending, indices to measure health outcomes, light and phone use as well as homework completion and test scores, time children spent doing homework and other activities.

In addition to survey data, which, in most cases, are self-reported by respondents, we used sensors to measure light use. A random sub-sample of the solar lamps that were distributed free or purchased at 700 KES (US \$7) or 900 KES (US \$9)[10] were equipped with Bluetooth-enabled sensors developed by Bonsai Systems.[11] Respondents were informed before downloading the data about the sensor and asked for permission to access the data. No data were downloaded if the participant had any objections. Sensors tracked when the solar lights were used and for how long, by measuring the change in voltage across the device's light emitting diode (LED). Using smartphones enabled with Bluetooth and an iPhone application called "Lamplogger" (which was specially developed for this project), field officers visited households and wirelessly uploaded data from the sensor to the phone. These data are primarily used in Chapter 3.

To receive an additional and more objective measure of educational outcome, we also collected school-level test score information before the study started (March 2015), as well as after the study ended (March 2016). Test scores were collected for all tested subjects: Math, Swahili, Science, English, and Social Studies.

3 Results

3.1 Energy and Light Use at Baseline

At baseline, the average household in our sample had 6.7 members, with 4.3 children under the age of 18. The average household head attended school for 6.4 years (Table 2, Column 1). Most houses had earth floors (88.3%) and iron sheet roofs (64.6%) on their main building. The average household spent US \$73.2 in cash per month, or US \$10.93 per person and month. Expenditures captured here do not include items that households consume from their own farms, which constitutes a large fraction of overall consumption for many rural households. A typical household owned 2.0 acres of land, 1.3 cows, and 6.0 chickens (Table 2, Column 1). Slightly more than half (53.8%) of households owned a bicycle, but only 7.8% a motorbike. Almost all households (98.8%)

---

[10] However due to logistical difficulties not all lights sold at a price price were equipped with a sensor.

[11] http://www.bonsai-systems.com

conducted agricultural activities and for 68.3% of households this remains the main income source. About a third (29.4%) owned a business, however mostly without any employees, usually selling fish or other food items. Only 20.1% of the households had one member or more who were employed in the previous year (formally or informally). Hence, the households sampled in our study depend largely on agriculture, live in basic housing, and are poor - even when compared to the average in rural Kenya (KIHBS, 2018).[12]

In the beginning of our study only 4.2% of the sampled households had access to some form of electricity. To break this number down: 1.4 % of households were connected to the grid, 1.1% had access to a solar home system, 1.5 % had access to a car battery, which provides energy for the household, and 0.1% had access to a generator. Most of these households were using the respective electricity source for their radio (80.0%), for lighting (72.0%) or to charge their mobile phones (65.4%). Just less than a third (32.0%) used electricity to watch TV, and 20% for ironing. No one had a fridge and no one used the energy source for activities that are potentially income generating such as sewing, water pumping or irrigation.

The vast majority of the sampled households (98.4%) used an open fire for cooking. Charcoal, kerosene, LPG, and other stoves are not common. As opposed to other settings, where eating and cooking happens in the same room (see for example Kudo, Shonchoy & Takahashi, 2018), people in the region of our study cook in a separate building or outdoors (93.3%) and only 6.7% cook in the same house as they eat. The relative importance of lighting as a source of indoor air pollution is larger in settings where people cook in a different place (Lam et al., 2017).

Most households (88.4%) rely on small locally produced kerosene lights (tin lanterns) for lighting (Appendix, Figure A.1). Others use larger kerosene lanterns (5.3%) (Appendix, Figure A.2), solar lights (3.8%), and only 1.1% use electricity-powered lighting as their primary lighting source. On average, a household owns 2.1 tin lamps. Tin lanterns can be bought for US $0.25-$0.50, depending on the size and quality of the lamp. Kerosene lanterns cost between US $3-$6. They also use more kerosene per unit of time and are therefore more expensive to operate (Mills, 2003). Every household that uses grid electricity also uses at least one other source of lighting — probably a reaction to the frequent blackouts

---

[12] According to the 2015/6 Kenya Integrated Household Budget Survey 83.2% of the rural population had iron roofs and only 43.2% earth floors, meaning that they stay in better quality housing than the average in our sample.

in the study region. During baseline an average household spent around US $3.61 (360.9 KES) per month on energy, corresponding to 4.9% of the households' total cash expenditure.[13] Energy expenditures are mostly on lighting. For kerosene alone, households spent US $2.06 (206.1 KES) per month, which corresponds to 57.1% of the total energy expenditure and 2.8% of total cash expenditure. These numbers are similar to national representative surveys of Kenya (KIHBS, 2005/2006; Lighting Global, 2012) as well as what other studies find (Kudo, Shonchoy & Takahashi, 2017; Grimm et al., 2016a). Monthly household energy expenditures unrelated to light use include expenditure on mobile phone charging (US $0.42), charcoal (US $0.24), batteries not used for lighting (US $0.30), firewood (US $0.21), and electricity bills (US $0.18).

3.2 Reducing Emissions

The use of kerosene for lighting contributes to indoor air pollution and global warming. Emissions from one tin lamp can increase indoor small particles (PM 2.5)[14] concentrations around 10 times above WHO guideline levels (Apple et al., 2010). Some studies even suggest that particles generated by kerosene combustion might be more toxic than wood-smoke (Lam et al. 2012b; Pokhrel et al., 2009; Bates et al., 2013; Epstein et al., 2013). In addition, 95% of the PM2.5 that kerosene lights emit are black carbon (BC), which is estimated to be around 700 times more warming than CO_2 (Lam et al., 2012b). Kerosene lights also directly emit a small amount of CO_2. While the literature on the subject is still limited, Lam et al. (2012a) estimate that the combined emissions of kerosene used in households worldwide have the same warming effect as 4.5% of total United States' CO_2 emissions and is therefore non-negligible.

Access to a solar light leads to a significant reduction in kerosene use of households and associated emissions (Table 3). A typical household keeps using kerosene as it would replace one of their two kerosene lights with a solar light (Table 3, Column 1). Some households also stopped using kerosene once they got access to a solar light. In fact, having access to a solar light reduced chances of using a kerosene-based products the previous evening by 29.5 percentage-points

---

[13] To provide a reference for comparison, European households spend on average around 4% of their total expenditure on electricity, gas, and other fuels used by the household in 2011 (Eurostat, 2011 retrieved from http://ec.europa.eu/eurostat/statisticsexplained/index.php/Archive:Household_consumption_expenditure_-_national_accounts)

[14] PM 2.5 are fine particulate matter fine of inhalable particles, with diameters that are 2.5 micrometers and smaller.

(Table 3, Column 2). On average, households reduce their kerosene use by 1.47 liters[15] per month (Table 3, Column 5).

Table 3: Impact on Kerosene Use and Emissions

VARIABLES	(1) Nr of Kerosene Lights	(2) Used Ker Yest.	(3) Tins Kerosene Use (l)	(4) Lantern Kerosene Use (l)	(5) All Kerosene Use (l)	(6) Monthly PM 2.5 (g)	(7) Monthly BC (g)	(8) Monthly CO2eq (kg)
Solar Works	-1.028***	-0.295***	-1.207***	-1.814***	-1.471***	-97.582***	-93.887***	-69.039***
	(0.109)	(0.038)	(0.314)	(0.411)	(0.259)	(18.495)	(17.891)	(13.080)
Lower Bound	-0.814	-0.220	-0.592	-1.008	-0.963	-61.332	-47.729	-43.402
Upper Bound	-1.242	-0.369	-1.823	-2.620	-1.978	-133.831	-133.8	-94.676
Observations	1,313	1,313	957	342	1,299	1,291	1,291	1,291
R-squared	0.130	0.186	0.054	0.248	0.075	0.070	0.070	0.070
School FE	YES	YES	YES	YES	YES	YES	YES	YES
Controls	NO	NO	NO	NO	NO	NO	NO	NO
Control Mean	2.234	0.837	2.502	2.265	2.445	164.9	158.8	116.7

Notes: Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Solar ownership is instrumented with price discounts. Column 3 shows the reduction for households that only use tin lights, Column 4 for those using kerosene lanterns only and Column 4 for everyone else. Columns 6-8 show information for both types of households. In Column 6-8 we used the following factors: if a household uses tin lanterns only 90g of BC/kg of Kerosene, 93g of PM2.5/kg of Kerosene and 2770g of CO2eq/kg of Kerosene. If the household only uses kerosene lanterns 9g of BC/kg of Kerosene, 13g of PM2.57kg of Kerosene and 3080 g of CO2eq7kg of Kerosene. All factors are based on Lam et al. (2012). The 13.79% of households that use both types of lanterns we use a simple average of both values. For 8 households we do not know the types of lanterns they use, hence they are missing on Columns 2-4.

We used information from a study that was conducted in Uganda, where PM2.5 as well as BC emissions of tin lamps and kerosene lamps were measured (Lam et al., 2012), to estimate how reductions in kerosene use translate into emissions reductions. The relationship between fuel burned and emissions is linear. To estimate emissions reductions, the decrease in kerosene use per households can therefore be scaled by the relevant factor of PM2.5 and BC emissions per liter kerosene burned. Note that these factors are much larger when the kerosene is

---

[15] This is based on survey answers about the amount of kerosene purchased previous week.

burned with a tin light as opposed to a larger kerosene lantern. In our sample, 73.65% only used tin lamps during the past month[16], 13.79% used both, tin lights and kerosene lanterns and 2.13% only kerosene lanterns. The remaining 10.43% did not use any kerosene based lighting products in the past one month. For households that used both kerosene and tin lights, we used a simple average of the factors for tin and kerosene lights. When we convert BC into CO_2 equivalents, we also add the small amount of CO_2, which additionally gets emitted by kerosene combustion (calculations are conducted at the household level and conversion rates are based on Lam et al., 2012b). We find that a typical household reduces its emissions by 97.58 g of PM2.5 and 93.89 g of BC and 69.04 kg of CO_2 equivalents per month (Table 3, Columns 6-8).

Based on the estimates in Table 3, assumption of a cost of US $9 per solar light, a lifetime of two years, and 48 kg of CO_2 embedded in the light from the production (based on Alstone et al., 2014)[17] as well as a 3% yearly discount rate for CO_2 emissions (based on IWG, 2015) and a failure rate of 1.15% per month (based on our study), we estimate an abatement cost of US $5.87 per ton of CO_2 equivalent (Appendix, Table A.2). While we do not have detailed program cost estimate, we assume that US $9 per household is a conservative estimate as this is the price at which quality solar lights could be purchased on the private market at the time of the study. However the price has further reduced since (Bloomberg, 2016; IFC, 2018). This only reflects the reduction in CO_2 equivalents and does not consider any other benefits such as health effects and households savings, which we will discuss later. However, this estimate is sensitive to the share of the targeted population that uses kerosene based products for lighting in the first place, as well as the share of tin vs. kerosene lamps that are used. This is relevant because the latter's emissions are much smaller (Lam et al. 2012b). In our sample the share of tin light users was larger than in the country as a whole, as our respondents tended to be poorer. Note also that households in our study only got access to one solar light, which typically allowed them to replace one of their kerosene lights. However most households used two kerosene lanterns and replacing the second one would reduce their

---

[16] We asked what lighting sources were used in the past one month.

[17] The solar lights assessed by Alstone et al. 2014 are not exactly the same types as the ones used in this study. We used estimates that are most comparable with the ones we used in our study. Based on Dones et al. we then estimated that 27.78 kg of CO_2 are emitted per KwH of energy used to produce the solar lights. This is a rather conservative estimate as we assume that all parts of the lights are produced with coal energy in inefficient power plants in China. Using this back of the envelope approach we estimate stored 48 kg of CO_2 eq in total and hence less than 2kg of CO_2 equivalent per month (assuming a lifespan of two years).

emissions further. Another caveat, is that these calculations do not include CO_2 emissions and other environmental damages from recycling or disposing the solar light, as to our knowledge such assessments do not exist yet.

There are two differences between our sample and national averages that have important implications for these estimates. First, in our sample more households primarily use kerosene for lighting. While in our sample over 80% primarily rely on kerosene for lighting, it is only 35.0% of the country as a whole (KIHBS, 2018). Second, among households that rely on kerosene, more use tin lights as opposed to kerosene lanterns (KIHBS, 2018). In our sample 82.25% of households that used kerosene based lighting products in the past one month only used tin lamps, while 17.75% also used kerosene lanterns. For Kenya as a whole only 55.1% of households primarily use tin lamps, among those who use kerosene for lighting, and 44.9% kerosene lanterns.[18] Given that our sample is on average poorer and more rural and tin lights are cheaper to acquire and operate, this finding is not surprising. When we use the national averages instead of our data, we get to a cost of US \$9.69 per ton of CO_2 equivalent (Appendix, Table A.2). However, these estimates assume that solar lights can be targeted at households that would otherwise use kerosene based products, which might not be trivial.

Cost estimates of the reduction of a ton of CO_2 equivalents can be compared with the social cost of carbon (SCC). SCC estimates vary as they depend inter alia on the rate used to discount future damages. The most recent central estimates of the U.S. Interagency Working Group on the Social Cost of Greenhouse Gases was US \$50 per ton of CO_2 (Revesz et al., 2017; IWG, 2015). While the group was dismantled by the current U.S. administration Revesz et al. (2017) suggest that researchers and policy makers keep using this estimate until there are reliable up-dated estimates.

Our CO_2 abatement cost estimates of US \$5.87 and US \$9.69 can also be compared to the cost of other programs aiming to reduce CO_2 emissions. Abrell et al. (2017) estimates the cost for reducing one ton of CO_2 emissions through subsidies of solar in Europe between €500-1870 (US \$600-\$2244).[19] Gayer & Parker (2013) estimate the cost per ton of CO_2 averted in a subsidy program for electric cars between US \$300-\$1200. Davis, Fuchs & Gertler (2014) eval-

---

[18] KIHBS, 2018 households were asked about the lighting source they use primarily, whereby we used information about tin light and kerosene lantern use during the past month, hence the results are not exactly comparable.

[19] Using a conversion rate of 1 € =US \$1.20 US

uate a large scale appliances replacement program in Mexico and estimate the cost per ton of CO_2reduced to be over US $500. Our estimates are higher than what Jayachandran et al. (2017) project based on an evaluation of a program which offered households in Uganda money to conserve trees on land that they own. Assuming that the observed effects persist with a permanent program, the authors estimate that the net present cost per ton of abated CO_2would be less than US $3.

Back-of-the envelope calculations suggests that if all households that use kerosene in Kenya for lighting (35.0% according to the 2015/2016 Kenya Integrated Household Budget Survey) had access to one solar light[20] and assume their kerosene reduction would be the same as in our study, this would lead to a reduction of 2.17 mega tonnes of CO_2 per year. This is equal to around 3.58% of Kenya's total greenhouse gas emissions and 11.14% of Kenya's energy emissions in 2014[21](Appendix, Table A.2). Assumptions for calculations are listed in Appendix Table A.1.

Previous studies also find an association between kerosene smoke and adverse health effects (Lam et. al, 2012; Furukawa, 2014; Kudo, Shonchoy & Takahashi, 2018; Pokhrel et al., 2010), in particular with regard to respiratory diseases and eye irritations. While there is a broad consensus that indoor air pollution is the most important environmental health risk factor worldwide (WHO, 2016), it is still unclear to what extent indoor kerosene lighting, as opposed to indoor biomass burning for cooking, is a relevant factor. Moreover, it remains unknown to what extent access to a solar light improves health outcomes – even if it leads to a reduction of indoor kerosene combustion as shown in the previous section. We use standardized questions from the European Community Respiratory Health Survey II to understand possible effects on respiratory symptoms and create an index following Bates et al. (2015) ranging from 0-5, where higher numbers indicate that the respondent suffers from more symptoms. For the questions related to eye health we also created an index based on six questions about symptoms for dry eyes, also following Bates et al. (2015). The questions that were used to create the index can be found in Appendix D.

We find a reduction in symptoms related to dry eye disease of about 0.48 symptoms for adults and for children (corresponding to 0.24 and 0.26 standard de-

---

[20] Again, here we assume that they only one solar light and, emissions could be further reduced if they get access to two lights.

[21] We are using the estimations from CAIT, 2017, as well as the latest Kenya Integrated Household Budget Survey from 2015/6.

viations and 16.7% and 19.5% reduction in symptoms respectively) and the difference is significant at the 5% level (Table 4, Columns 1 and 2). Children also face 0.39 fewer symptoms related to respiratory difficulties (significant at the 1% level and corresponding to 0.29 standard deviations and 28% reduction of symptoms compared to the control mean), whereby adults' reduction of 0.24 symptoms is not statistically significant (Table 4, Columns 3 and 4). Since children are the main users of the solar lights (as discussed in the next Section), it seems plausible that they experience somewhat stronger health effects. We also observe that women and girls are overall more likely to experience symptoms related to respiratory illnesses. Again this is not surprising, given that they tend to spend more time cooking, and hence are more exposed to emissions from wood-smoke.[22]

Table 4: Impact on Health

VARIABLES	(1) Adults Dry Eyes 0-6	(2) Pupils Dry Eyes 0-6	(3) Adults Respi. 0-5	(4) Pupils Respi. 0-5
Solar Works	-0.478**	-0.482**	-0.236	-0.392***
	(0.205)	(0.192)	(0.151)	(0.142)
Female	0.184	0.117	0.384***	0.167**
	(0.119)	(0.105)	(0.083)	(0.077)
Observations	1,313	1,202	1,313	1,202
R-squared	0.037	0.020	0.038	0.034
School FE	YES	YES	YES	YES
Controls	NO	NO	NO	NO
Control Mean	2.864	2.475	1.431	1.402
Number of Schools	20	20	20	20

Notes: Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Solar ownership is instrumented with price discounts. Indices are created based on European Community Respiratory Health Survey II and Bates et al. (2015). Higher numbers indicate that the respondent suffers from more symptoms.

In summary, solar lights are relatively inexpensive and considerably reduce kerosene use among households that previously primarily used kerosene for light-

---

[22] Time use data from out survey data reveal that women and girls spend more time with household chores.

ing. They therefore have the potential to reduce warming emissions at a cost that is low compared with the social cost of carbon. Moreover, access to solar lights improves household members' health. In the next sections we discuss if, in addition to these environmental and health benefits, it also improves access to reliable energy services and allows households to lower energy expenditures.

3.3 Increasing Energy Access

Changes in Quantity and Quality of Light

Our survey data suggest that households with access to a functioning solar light used it frequently, namely for 6.1 out of 7 weekdays and for 3.51 hours the previous day on average. Sensor data confirm this finding. According to data from 220 sensors, 58.6% of households used the solar light on every day of the study; and on average households used the solar light for 4 hours per day. To calculate the number of hours that adults and children use lighting each day we also included questions about light use in the time use section of the survey. For every hour of the day, we asked respondents to report the primary activity they had engaged in. For every hour[23] without sunlight (6:00 pm to 7:00 am), we asked whether they used any lighting source, and if so, which one. From that information, we calculated the total number of hours per day that adults and children reported using any lighting source (i.e., total hours of lighting regardless of source used). Adults and children in the control households used an average of 3.3 and 3.2 hours of light per day (Table 5, Columns 1 and 2). Having a functioning solar light increases children's lighting hours by 0.38 hours (22.80 minutes) per day (Table 5, Column 1), corresponding to a 11.43 % increase in lighting hours. Solar lights do not have a statistically significant impact on lighting hours of adults (Table 5, Column 2).

In addition to more lighting hours, solar lights also increase the quality of light, in particular in comparison with tin lights (see Section 2.2). Solar lights also makes the supply of light more consistent. Respondents were 39.1 percentage-points less likely to sit in the dark over the last month and 64.9 percentage-points less likely to rely on a lighting source that is not their first choice because they ran out of kerosene or wick within the past month (Appendix, Table A.11).

---

[23] We asked for half-hour slots in the evening between 7pm and 10pm, where we expected most use based on answers from the pilot study.

Table 5: Impact on Light Use and Energy Expenditure

VARIABLES	(1) Lighting Hours Children	(2) Lighting Hours Adults	(3) All- Energy Exp (KSH)	(4) Energy Exp as Share of Total	(5) Energy Exp as Share of Total w/o Edu
Solar Works	0.375***	-0.196	-115.781***	-0.027***	-0.034***
	(0.130)	(0.139)	(25.045)	(0.004)	(0.005)
Lower Bound 95%	-	-	-66.694	-	-
Upper Bound 95%	-	-	-164.868	-	-
Female	0.400***	0.084			
	(0.070)	(0.082)			
Observations	1,202	1,313	1,313	1,313	1,313
R-squared	0.109	0.021	0.054	0.096	0.077
School FE	YES	YES	YES	YES	YES
Controls	NO	NO	NO	NO	NO
Control Mean	3.324	3.206	272.4	0.0510	0.0670
Number of Schools	20	20	20	20	20

Notes: Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Solar ownership is instrumented with price discounts. We excluded education expenditure from Column 5, as school fees were due just before endline and are a large share of that month's expenditure.

Energy Expenditure Savings

An average household in the control group spends 272.40 KES (US $2.72) per month on energy.[24] Having a solar light allows households to reduce energy expenditure on average by 115.78 KES (US $1.16) per month (Table 5, Column 3), corresponding to 42.5% of household's total spending on energy. This is not surprising given that lighting is a large fraction of energy expenditure and that households replace on average one out of two solar lights (see also Table 3,

---

[24] Spending on kerosene was lower than in the beginning of the study due to lower kerosene prices. Total expenditure on the other hand were higher due to school fees, which were due shortly before data collection and possibly also since the endline happened was right after harvest, while baseline was before harvest.

Column 1). The amount households save, however, only corresponds to 2.4-3.3% of total cash expenditure (Table 5, Columns 4-5), because energy expenditures account for only a small fraction of total cash expenditure (5.1%).

These findings are likely to be a lower bound as kerosene prices were at a historic low due to falling global oil prices during our endline data collection in February 2016. According to the Kenyan Energy Regulatory Commission, pump prices for kerosene were 42.83 KES (US $0.43) per liter, while at baseline they were 64.92 KES (US $0.65) per liter.[25] This baseline price (July/August 2015) is similar to the average kerosene price in the year before our study took place (July 2014 - July 2015).[26] In Kenya, as in other countries in sub-Saharan Africa, kerosene prices in rural and remote areas are much higher than at the pump stations in the city center due to high transportation costs and lower quantities being sold (Lighting Africa, 2012)

With a monthly interest rate of 7.5%, which is most common in Kenya,[27] monthly breakages of 1.15%, which we observed in our data[28] and assuming that the lights last a maximum of two years, we obtain a net present value (NPV) for the smaller solar light (Sun King Eco) of 246.42 KES (US $2.46). The amortization period (i.e. NPV=0) (with 7.5% interest rate, and 1.15% monthly breakages) is 14 months (Table 6, Row 1). According to our calculations, the investment in a solar light pays of over a period of two years if a household saves more than 86.20 KES (US $0.86) per month with a solar light, which is likely. Hence in addition to environmental and health impact, households save 2.7% of their monthly cash expenditure and the investment pays off after 14 months. However, breakage rates remain an issue and risk averse households might not want to invest into an appliance that breaks down with a likelihood of 7.8% within the first seven months. Table 6 Row 2 shows calculations with a lower interest rate of 4% per month, which is what is offered to households in rural Kenya that have a bank account.[29]

---

[25] http://www.erc.go.ke/index.php?option=com_content&view=article&id=162&Itemid=666 However, pump prices differ a lot from the prices people face in remote areas (see Lighting Africa (2012)).

[26] ERC (2015) provides information on three price points (July 14, Feb 15, and Jun 15). The average of these three points is 66.09 KES (Nairobi) and 69.54 KES if adjusted for Busia.

[27] This is the interest rate offered by the mobile money provider MPESA to households that do not have a bank account. More information can be found on www.safaricom.co.ke.

[28] We observed a total breakage rate of 7.78% and assume breakages are evenly distributed over time

[29] More information about interest rates for different credit products commonly used in the study region can be found on www.safaricom.co.ke.

Table 6: Net Present Value (NPV) and Amortization

Assumptions			NPV			Amortization		
	Breakages %	Interest Rate %	Mean KES	Lower Bound KES	Upper Bound KES	Mean Months	Lower Bound Months	Upper Bound Months
			115.78	66.69	164.86	115.71	66.69	164.86
1	1.15%	7.5%	246.42	-136.90	986.42	14	n/a	7
2	1.15%	4.0%	665.50	75.41	1’511.00	11	21	7

Notes: Our results are based on our point estimate and a 95% CI around as upper and lower bounds (Table 7, Column 1). Breakage rates of 1.15% are based on our data and we assume that breakage rates are distributed evenly across time. Interest rates of 7.5% are based on figures based on credits available for people without bank accounts (M-shwari) and 4% are for those with a bank account (KCB M-PESA). Interest rates are from 2018. We assumed the solar lights would last a maximum of two years, as this is the lenght of the warranty of the product.

As explained in Section 2.2, half of the group receiving a free solar light was given a Sun King Eco (SK Eco) and the other half a Sun King Mobile (SK Mobile) solar light. The SK Mobile has a larger and stronger light and the ability to charge a mobile phone. Households which received an SK Mobile reduce their mobile phone charging costs (19.90 KES or US $0.20) per month, which corresponds to an almost 100% reduction compared with the control group’s expenditure. Otherwise, however, they do not save more than households receiving a smaller light (regression results are available from the authors on request). Given the much higher purchasing price of 2’400 KES (US $24.00) the Net Present Value (NPV) is only -1’191.14 KES (- US $11.91), if we assume 7.5% monthly interest rate, 1.15% monthly breakage rate, and a maximum life-time of two years.

An additional possible private return is a reduction in travel time to purchase kerosene. However, we do not expect time use savings to be large, as most households still use kerosene once they get access to a solar light. They typically only purchase kerosene six times per month and most (89.7%) would undertake the trip to the market center/petrol station in any case for other reasons.

Educational Outcomes

There is a wide held belief among practitioners in the solar field that solar lights will improve children's school outcomes. Some companies even sell solar lights through head teachers of primary schools using that reason (SolarAid, 2013). The idea is that better quality lighting and additional lighting time will allow children to study more and/or under better conditions at home.

Children in all types of households received homework on 2.6 days during the previous week and completed the homework after dark most of the time. Having access to a functioning solar light increased the share of homework completed after dark by 10.0 percentage-points (Table 7, Column 2) and increased self-reported homework completion by 15.9 percentage-points (Table 7, Column 1). However, we do not find any changes in hours spent on homework or in school (Table 7, Columns 3 and 4) or test scores (Table 8, Columns 1-6). Moreover, we find that sleeping hours are reduced by 0.70 hours (or 42 minutes) (Table 7, Column 5), which could adversely affect children's school performance.

Previous literature also did not find effects of accessing solar on test scores (Furukawa, 2013; Kudo, Shonchoy & Takahashi, 2017). Hassan & Lucchino (2016) also did not find that test scores change at the individual level. The authors suggest, nevertheless, that there were effects at the class level. However this analysis was not part of their initial research plan and has, as the authors admit, some identification challenges. One might still be puzzled that children report increases in homework completion but we do not observe any changes in their test scores. Children's self-reported increase in homework completion might simply be driven by social desirability bias (which is likely given that they do not seem to spent more time on homework). Or, the increase in completion might be real but homework completion does not lead to better learning and/or test scores. It is also possible that we do not see any changes in test scores since not enough time has lapsed between the beginning and the end of the study. Finally, spillover effects with children from the control group benefitting from children who received or purchased a solar light might lead to null results, which will be discussed in Section 3.5.

Table 7: Impact on Homework Completion and Time Use

VARIABLES	(1) Home -work Com- pletion	(2) Share HW after Dark	(3) Home -work (hours)	(4) School (hours)	(5) Sleep (hours)
Solar Works	0.159***	0.100***	0.282	0.475	-0.702***
	(0.049)	(0.039)	(0.183)	(0.322)	(0.227)
Pupil Female	-0.028	0.010	-0.085	-0.062	-0.233*
	(0.027)	(0.022)	(0.098)	(0.178)	(0.120)
Observations	1,050	1,050	1,202	1,202	1,202
R-squared	-0.003	-0.002	0.044	0.010	0.019
School FE	YES	YES	YES	YES	YES
Controls	NO	NO	NO	NO	NO
Control Mean	0.692	0.780	2.458	4.508	8.077
Number of Schools	20	20	20	20	20

Notes: Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Solar ownership is instrumented with price discounts. Column 1 shows the share of times the pupil was able to complete the homework past week. Column 2 shows the share of times the homework was completed after dark. Columns 2-5 show data from the time use section. In this table we control for pupil's class and gender.

Table 8: Test Scores

VARIABLES	(1) Swahili	(2) Math	(3) English	(4) Science	(5) Average	(6) KCPE Average
Solar Works	-0.161	0.017	-0.047	-0.037	-0.088	-0.137
	(0.099)	(0.100)	(0.086)	(0.093)	(0.076)	(0.162)
Pupil Female	0.193***	-0.063	0.082*	-0.089*	0.043	0.002
	(0.049)	(0.052)	(0.044)	(0.048)	(0.039)	(0.080)
Observations	1,082	1,095	1,082	1,099	1,101	226
R-squared	0.355	0.286	0.467	0.372	0.616	0.507
School FE	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES
Control Mean	0	0	0	0	0	0
Number of Schools	20	20	20	20	20	20

Notes: Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Solar ownership is instrumented with price discounts. Test scores are from final yearly exam in March 2016 and standardized. We control for pupils' class and gender as well as baseline test scores from March 2015. The last column contains the average of class eight who attended KCPE exam, an exam held nationally in the end of primary school.

3.4 Effects of Subsidies on Demand and Use

Given that solar lights can reduce harmful and warming emissions at a low cost and have additional private benefits, increasing their adoption could be in the public interest. Therefore we are interested in learning about how further price reductions (either through subsidies or further technological progress) effects demand, and use, and whether and how other measures such as decreased transaction costs and information can increase take-up of solar lights, which was at 6.5% during baseline.

Effects of Subsidies on Demand

Demand responds strongly to price changes. We start by looking at the share of people who took up the offer we made to purchase or receive a solar light within our sample. While everyone in the free group took up the offer of a solar light as well as 68.8% of those who could purchase a solar light at 400 KES (US $4), take-up decreased to 37.4% when the offer was to purchase a light for 700

KES (US $7). At market price of 900 KES (US $9) 28.9% bought the solar light (Table 9, Column 1). This corresponds to an average price elasticity of demand of -1.07, meaning that a 1% increase in price leads to a 1.07% reduction in quantity that is purchased (Table 9, Column 4).

We also analyze the share of households that owned a solar light seven months after baseline, independently from whether they redeemed the voucher they received from us or purchased it in some other way (Table 9, Column 2). These measures are generally larger than the first column, as people could also purchase solar lights outside of our study and some households already owned one at baseline. Using this measure, there is no statistical difference between the highest (US $9) and the second highest price (US $7) (Table 9, Column 2 and 3). Our data suggest that breakages were common, particularly for solar lights with sensors. Breakage rates for solar lights without sensors were still at 7.78% after seven months.

Interestingly, whereas 44.6% of those who received an offer to purchase a solar light at market price owned a solar light at endline, only 19.1% in the control group owned one (Table 9, Column 2). This could be caused by a number of reasons, such as increased information about solar lights in our US $9 treatment group, as the field staff showed them the product and explained its basic features (see script in the Appendix). Moreover, the program reduced transaction costs, since the solar lights were available through the head teacher in their children's school, whereas in the control group respondents had to buy them elsewhere. In fact, 31.3% of respondents in the control group mentioned that they never saw a solar light before and only 8.5% said that solar lights could be bought in their own village. The remaining respondents mention that they either had to travel to the closest town or market center (45.8%) or even to a larger city to buy a solar light (14.4%).

Together these findings suggest that while reducing transaction costs and increasing information can increase take-up, further price reductions are needed to boost adoption above 50%. In fact, substantial price reductions are needed as a reduction to US $7 did not lead to higher ownership at endline (compared with the market price of US $9).

Table 9: Solar Light Ownership at Endline

VARIABLES	(1) Redeemed Voucher	(2) Solar Ownership	(3) Ownership (works)	(4) Log Quantity
Free	1.000	0.974***	0.834***	
	(0.000)	(0.008)	(0.019)	
Voucher 400 KES	0.688***	0.734***	0.683***	
	(0.032)	(0.031)	(0.033)	
Voucher 700 KES	0.374***	0.437***	0.383***	
	(0.035)	(0.037)	(0.036)	
Voucher 900 KES	0.294***	0.446***	0.397***	
	(0.033)	(0.037)	(0.036)	
Control	0.000	0.191***	0.172***	
	(0.000)	(0.021)	(0.020)	
Log Price				-1.071**
				(0.039)
Observations	1,396	1,313	1,313	
R-squared	0.805	0.738	0.643	0.997

Notes: Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Column 1 shows whether respondents purchased a solar light through our program. Column 2 shows solar light ownership at endline and Column 3 shows ownership of a functioning solar light at endline.

Effects of Subsidies on Use

In this section we study whether those receiving a free solar light use it less than those who paid for it.[30] There could be differential use of solar lights between buyers and those who received a solar light for free for two main reasons. First, there could be a selection effect: households that purchase a solar light might be different from households how decide not to. For example, lower lighting needs might make some households less likely to buy solar lights. Second, there might be a sunk cost effect, whereby the act of paying a price for a solar light makes households more likely to use it. While our research design does not enable us to differentiate between the selection and the sunk cost effect, we can test whether households, that purchase a solar light use it more than those who received it for free.

Table 10: Buyers vs. Non-Buyers

VARIABLES	(1) Hours Used Yesterday	(2) Energy Spending (KES)	(3) Lighting Hours Pupils	(4) Lighting Hours Adults	(5) Time Spent Homework (Hrs)
Buyer vs. Free	0.099	26.849	-0.021	0.140	-0.055
	(0.201)	(22.619)	(0.130)	(0.140)	(0.095)
Observations	423	424	388	424	388
R-squared	0.001	0.003	0.000	0.002	0.001
School FE	NO	NO	NO	NO	NO
Controls	NO	NO	NO	NO	NO
Free Mean	3.069	6.028	3.544	3.086	0.786

Notes: Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Sample restricted to owners of functioning Sun King Eco Light.

Using a similar approach to Dupas & Cohen (2010), we limit the sample to households that had a functioning solar light at endline,[31] and test whether households that bought a solar light use them more. We chose to combine the offers into one as our power to detect any differences would be very low otherwise. We find that households that received a free solar light use it as

---

[30] We chose to combine the offers into one, since sample sizes in each cell would become very small when reporting each price point. There is also no difference in use when looking at each offer individually (regression results are available from the authors on request).

[31] The main result does not change significantly if the sample is only restricted to those who still own a solar light at endline no matter if it still worked or not.

Table 11: Lee Bounds

	(1) Ker Use (l)	(2) Engery Exp. (KES)	(3) Dry Eyes Adults	(4) Dry Eyes Pupils	(5) Respiratory Pupils	(6) Light Hours Pupil	(7) Sleep Time Pupil	(8) HW Completion Pupil
Point estimate	-0.911***	-74.812***	-0.159**	-0.194**	-0.165*	0.237**	-0.392***	0.099***
Lower Bound	[-1.219	[-104.820	[-0.426	[-0.196	[-0.164	[0.179	[-0.475	[0.086
Upper Bound	-0.858]	-68.294]	-0.158]	-0.152]	-0.152]	0.262]	-0.276]	0.140]
Total Sample	800	800	800	800	800	800	800	800
Non-Missing	740	747	747	737	737	737	737	647

Notes: Lee bounds in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$.

frequent as households that purchased it (Table 10, Column 1). There is also no difference in reduction in energy expenditure (Table 10, Column 2), nor in lighting hours for adults or children (Table 10, Column 3-4), hence we do not find any evidence that price affect use of solar lights.

3.5 Robustness Checks

Attrition

Despite our efforts to keep attrition low, attrition was at 4.5% in the free group, 5.7% in the voucher group and 7.8% in the control group among the adult respondents. Attrition among pupils was higher at 10.5%, 7.2% and 8.5% respectively (Appendix, Table A.4). Attrition does not correlate with the observable characteristics we tested for (Appendix, Table A.5). However, attrition is still a concern as the attritors may be different from the non-attritors in some unobservable dimensions, which may correlate with our outcomes of interest. We address this concern using a bounding approach developed by Lee (2005) and commonly used since. We trim the outcome variable of interest in the free group (since this is the group with less attrition), either chopping off the observations with the highest or the lowest values, so that the number of observed individuals is the same in both groups. This means that we make extreme assumptions about the missing information. For all estimates, the lower and upper bounds do not change signs, which indicates that the results are robust to attrition (Table 11).

Multiple Hypothesis Testing

To further examine the robustness of our results, we adjust for the fact that we test for multiple hypothesis, using the false discovery rate adjusted q-values (analogue to the standard p-value). This approach limits the expected proportion of rejections that are false discoveries (or type I errors) (Benjamini, Krieger & Yekutieli, 2006; Anderson, 2008). In Table 12, Column 2 reports intention to treat (ITT) estimates of our main results alongside with adjusted q-values. We report ITT estimates, since this is what we pre-specified in our pre-analysis plan. As expected the ITT coefficients are smaller than the treatment effect on the treated (TOT) estimates. The false discovery rate adjusted q-values are robust to multiple hypothesis testing (Table 12, Column 5).

Spillovers

We could underestimate the impacts of having access to solar if households which receive a free solar light or purchase one share them with households in the control group of the same school. This could be the case if they lend the solar lights to other households, if the children bring it to school and share it there, or if individual household members from control households visit households with a solar light to enjoy their improved lighting. Finally, it could be that children in the control group benefit from the schooling progress of their peers who have access to a solar light. We look at spillovers in different ways. First, we report the answers we asked children and adults about borrowing, lending and sharing the solar light as well as if children brought them to school and shared it there. Second, we use an approach that is similar to Baird et al. (2014) and Kudo, Shonchoy & Takahashi (2017), whereby the treatment saturation can be used to estimate spillover effects on the non-treated population.

Only 14 households (2.2%) that received or purchased a solar light through our program shared the light with someone from the same school and they shared it only 1.4 times on average during the past month. It is therefore very unlikely that there are significant spillovers from borrowing or lending the solar light. We also asked children with whom the solar light was shared, when they used it most recently. While many shared it with other household members, only 11 pupils (2.3 %) shared it with someone from the same school. Hassan and Lucchino

Table 12: Intention to Treat and Adjustments for Multiple Hypothesis Testing

		Control [SD] (1)	ITT (SE) (2)	TOT (SE) (3)	P-Val (4)	FDR q-val (5)
(1)	Ker. Use (l)	2.445	-0.911***	-1.470***	0.000	0.001
		[2.868]	(0.177)	(0.259)		
(2)	Energy Exp.(KES)	272.354	-74.812***	-115.781***	0.000	0.001
		[279.328]	(13.747)	(25.045)		
(3)	Nr. Ker. lights used	2.234	-0.687***	-1.027***	0.000	0.001
		[1.094]	(0.075)	(0.109)		
(4)	Dry Eyes Pupils (0-6)	2.475	-0.355**	-0.482**	0.012	0.010
		[1.831]	(0.141)	(0.192)		
(5)	Dry Eyes Adults (0-6)	2.864	-0.323**	-0.478**	0.020	0.011
		[1.999]	(0.123)	(0.205)		
(6)	Respirat. Pupils (0-5)	1.402	-0.220*	-0.392***	0.006	0.007
		[1.363]	(0.127)	(0.142)		
(7)	Respirat Adults (0-5)	1.431	-0.131	-0.238	0.117	0.031
		[1.467]	(0.079)	(0.150)		
(8)	Light Use Pupil	3.323	0.263**	0.375***	0.004	0.006
		[1.325]	(0.088)	(0.130)		
(9)	Light Use Adult	3.206	-0.138	-0.196	0.159	0.039
		[1.439]	(0.110)	(0.139)		
(10)	Sleep Time Pupils (hrs)	8.077	-0.391**	-0.716***	0.001	0.003
		[2.046]	(0.137)	(0.209)		
(11)	HW Time Pupils (hrs)	2.458	0.181	0.278	0.115	0.031
		[1.670]	(0.129)	(0.176)		
(12)	HW Completion (%)	0.692	0.097***	0.160***	0.001	0.003
		[0.462]	(0.023)	(0.048)		
(13)	HW Completion (%)	0.780	0.059**	0.106***	0.006	0.007
	after Dark	[0.356]	(0.028)	(0.039)		

Notes: *** p<0.01, ** p<0.05, * p<0.1. Table includes main outcomes from the study. We controlled for school fixed effects and gender when we looked at individual outcomes. No other control variables are used. Column 1 reports the mean from the control group with SD in brackets. Column 2 reports ITT regression with robust standard errors in parentheses (sample is restricted to free group and control group). Column 3 reports IV estimates with robust standard errors in parentheses. Column 4 shows standard p-values for TOT estimates. Column 5 reports the FDR-adjusted q-values following Benjamini, Krieger & Yekutieli (2006) associated with the p-values in Column 4.

(2016) hypothesize that they find spillover effects, probably from sharing solar lights in schools. In our sample however, bringing the solar light to school was very rare as only 19 children had ever taken the solar light to school. Again, it does not seem plausible that this led to large spillover effects.

The number of people in one's neighborhood (radius of 500 m) who received a free solar light varies between the different households and we use this variation to see whether control households that happen to live close to a large number of households that received a free solar light are benefiting from these lights. As outcome variables we use hours energy spending, lighting hours for pupils and adults as well as time spent doing homework. We choose these variables since we consider them "first stage", meaning that it is unlikely that the other outcomes change if this outcome does not change. None of these outcomes of the control group changes for households that have a higher share of neighbors who received a free solar light (Table 13, Columns 1-4). From this additional analysis we conclude that while we can not rule out that spillover effects exist to some extent, it is unlikely they lead to a large underestimation of effects in our study.

Table 13: Spillover Use

VARIABLES	(1) Energy Spending (KES)	(2) Lighting Hours Pupils	(3) Lighting Hours Adults	(4) Time Spent Homework (Hrs)
# Neighbours (Free) within 500m	-10.087	-0.014	-0.056	-0.049
	(7.251)	(0.049)	(0.052)	(0.032)
# Neighbours within 500m	5.671	-0.001	0.005	0.015
	(4.010)	(0.021)	(0.015)	(0.016)
Observations	368	339	368	334
R-squared	0.005	0.003	0.009	0.013
School FE	YES	YES	YES	YES
Controls	NO	NO	NO	NO
Mean	272.1	3.324	3.207	0.670
Number of Schools	20	20	20	20

Notes: Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Sample restricted to control group.

4 Conclusion

There is a heated debate about how societies should increase energy access while maintaining environmental sustainability. This is particularly relevant in emerging economies where the largest increase in energy demand and in CO_2 emissions will come from. There are high hopes for novel technologies that increase energy efficiency and the use of renewable energies. The idea is that these technologies can create "win-win" cases where both society at large wins due to lower emissions and pollution and the consumer wins due to lower costs or better energy access. However recent impact evaluations, primarily from high-income countries, show that the potential for such "win-win" cases might be much more limited than previously thought (Davis, Martinez & Taboada, 2018; Hanna, Duflo & Greenstone, 2016, Davis, Fuchs & Gertler, 2014; Fowlie, Greenstone & Wolfram, 2018; Allcott & Greenstone, 2012).

We provide evidence for such a double win case in a developing country context. Solar lights are used as a substitute for kerosene and thus reduce kerosene related emissions, which has benefits that are, in part, external to the household. This finding has at least two important aspects. First, environmental externalities: kerosene combustion emits a high concentration of Black Carbon, which is around 700 times more warming than CO_2. Having a functioning solar light leads to a reduction in emissions equivalent to 828.47 kg of CO_2 per household yearly, and if scaled to the whole country, the reduction would correspond to 3.58% of Kenya's greenhouse gas emissions in 2014 at a cost of less than US \$10 per ton of CO_2. This cost is low compared with the estimated social cost of carbon of US \$50 per ton of CO_2 (Revesz et al., 2017; IWG, 2015) as well as when compared to other programs aiming to reduce emissions with increase efficiency or reliance on renewable energies in Mexico (Davis, Fuchs & Gertler, 2014), Europe and the US (Abrell et al., 2017). Second, accessing solar lights reduced symptoms related to asthma and dry eyes disease, especially for children, who are also the main users of the solar light. This is in line with a number of studies that find improvements in indoor air-quality and a reduction in symptoms related to eye and respiratory illnesses (Furukawa 2013; Barron & Torero, 2017; Grimm et al., 2016 a). It also corresponds to the findings of Kudo, Shonchoy & Takahashi (2018) with regard to eye irritation, however, they did not find any effects on respiratory symptoms.

Solar lights also provide access to better and more consistent light quality and allow households to reduce 2.7-3.4% of total monthly expenditure. There seems to be converge on these figures among different studies: Grimm et al. (2016a) discovered expenditure reduction of US $0.92 as a result of providing solar lights for free, corresponding to 3% of total expenditure in Rwanda. Kudo, Shonchoy & Takahashi (2017) in their study in Bangladesh, calculate expenditure savings of 3.2% of total expenditure,[32] Aevarsdottir et al. (2017) report that households in Tanzania were able to cut their lighting expenditure in half, which is also similar to what we find. From a typical households' perspective purchasing a small solar light pays off within the first 14 months from a purely financial perspective. However an average household cannot recoup the cost of the larger Sun King Mobile light as they would have to save more than US $2.30 per month. Even for the smaller light, the amortization periods are still relatively long at current prices. Given this fact, it is unsurprising that take-up increases sharply with price reductions, ranging from 29% at market prices (US $9) to 69% when sold at the lowest price (US $4). We do not observe that solar lights are used less when prices decrease.

Together these results suggest that price reductions are likely to increase product take-up and also use, reducing kerosene use and related emissions, which has health and environmental benefits that are larger than their social cost. Moreover it increases access to some sort of basic modern energy, which is an important policy goal for the United Nations as well as many national governments, and, at least in the medium run might be more cost-effective in this rural setting than grid extension (Lee et al 2016b).

Solar lighting is however not a panacea to address energy poverty and climate change. While they provide some improvement compared with kerosene, energy access is still limited to lighting and mobile phone charging in the case of the larger version of the light and does not allow households to power appliances like fans or irons. Solar lights will not be enough as living standards rise. Moreover, cookstoves, not kerosene lights, are the most important contributor to indoor air pollution, and a better cooking solutions must be found, to achieve substantial health gains (WHO, 2016). Also, while every reduction in warming emissions counts, the contribution of kerosene lights remains limited. Moreover, the positive externalities discussed in this paper rely on the fact that solar lights replace kerosene. However there is evidence that kerosene is increasingly being displaced by battery powered torches, at least in places where it is not subsidized (Bensch, Peters & Sievert, 2017). Hence the counterfactual might look different

---

[32] This is only significant at the 10% level. However, it is only 1.6% of total expenditure, which is not significant at the 10% when they do control for baseline.

in the future. Finally, maintenance and recycling of old solar lights, especially their batteries still remains a challenge and if not solved properly might create new environmental challenges.

First and foremost we hope that future research will rigorously field test and evaluate approaches that aim to improve energy access as well as energy efficiency and the use of renewable energies in developing countries. This will allow policy makers to compare the cost-effectiveness of different policy options in low-income settings. It is particularly relevant to study policy options in developing countries as this is where energy demand and CO_2 emissions are projected to grow most significantly in the coming years. With regard to solar lighting in particular, we hope that future studies will evaluate demand and impacts in environments where kerosene is not the counterfactual (anymore), as large shares of the population are electrified or use battery powered torches rather than kerosene lights. It would also be important to further analyze what drives and constraints different types of consumers' demand for such products and wether there are important market failures in contexts that are different from ours. Further, we hope that researchers will look at the problem of electronic waste in developing countries and how it can be addressed. Finally, for our findings with regard to indoor air pollution, it would be important to better understand how kerosene use interacts with cooking conditions and what combination of policies are best suited to improve indoor air quality.

Appendix

A. Information About Design, Intervention & Calculations

Table A.1: Assumptions and Sources for CO2eq Calculations

	Unit	Amount	Source
Total Emissions (2010)	MtCO2eq	60.53	CAIT, 2017
Energy Emissions	MtCO2eq	19.47	CAIT, 2017
Using Kerosene	%	35.0	2015/2016 Kenya
Of which using Tins	%	55.1	Integrated Household Budget Survey
Of which using Hurricanes	%	44.9	(KHBS 2015/6)
Tins CO2eq Kerosene/kg	kg	65.77	Lam et al. (2012b)
Hurricanes CO2eq Kerosene/kg	kg	9.38	
Total HH in Kenya	#	12’115’000	
Total Pop Kenya	#	48460000	World Bank 2016
People per HH in Kenya	#	4	KHBS 2015/16
CO2eq Discount Rate	%	3	Greenstone, Kopits, Wolverton (2011)
Embedded CO2 in Production	kg	48	Alstone et al. (2014)
Density of Kerosene	kg/l	0.8	total.co.ke (2018)
Tins CO2eq Kerosene Reduction per HH/month	kg	0.97	Our Data
Hurricanes CO2eq Kerosene Reduction per HH/month	kg	1.45	Our Data

Table A.2: Cost per Ton of CO2eq and Impact on National Emissions

Our Study					
	Unit	Amount	Lower Bound	Upper Bound	Notes
Reduction in CO2eq 2yrs per HH	kg	1’334.23	993.823	2’167.900	Discounted 3% per yr 1.15% breakages per month Share of Tins: 73.7 %
Cost per HH for 2yrs	$	9			Current market price
Cost per Ton of CO2eq	$	5.87	9.06	4.15	
Projections if Scaled Nationally					
Reduction in CO2eq 2yrs per HH	kg	929.23	492.53	1462.55	Discounted 3% per yr 1.15% breakages per month Share of Tins: 55.1 %
Cost per HH for 2yrs	$	9			Current market price
Cost per Ton of CO2eq	$	9.69	18.27	6.15	
Projections as % of Kenya’s Total Emissions in 2014					
Total CO2eq reduced year	Mt	2.17	1.09	3.25	
Share of Total Emissions in 2014	%	3.58	1.81	5.36	Total emissions 61.53 MtCO2eq CAIT, 2017
Share of Energy Emissions in 2014	%	11.14	5.61	16.67	Total emissions 19.47 MtCO2eq CAIT, 2017

Notes: Failure rate of 1.1% is based on a total failure rate of 7.78% in our sample across 7 months. We assume that failure rates remain the same for 24 months, after which none of the solar lights works anymore. All other assumptions are listed in A.1.

Table A.3: Sampled Households by School

School Name	Frequency
Malanga	70
Lwanyange	70
Emukhuyu	70
Esidende	70
Maolo	70
Sianda	80
Khayo	80
Sango	40
Opeduru	75
Mwangaza	70
Olepito	75
Obekai	75
Kaliwa	75
Kamarinyang’	75
Ong’aroi	75
Asing’e	75
Ng’elechom	75
Akites	70
Aburi	50
Odiyoi	70
Total	1,410

B. Additional Robustness Checks

Table A.4: Attrition

VARIABLES	(1) Attrition (Adults)	(2) Attrition (Pupils)
Free Solar Light	-0.033*	-0.013
	(0.017)	(0.019)
Voucher	-0.021	0.020
	(0.016)	(0.019)
Observations	1,396	1,396
R-squared	0.003	0.002
Control Mean	0.0780	0.0850

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table A.5: Correlation of Attrition with Observable HH Characteristics

VARIABLES	(1) Endline Completed	(2) Endline Completed	(3) Endline Completed	(4) Endline Completed	(5) Endline Completed	(6) Endline Completed	(7) Endline Completed	(8) Endline Completed.	(9) Endline Completed
Iron Roof	0.001 (0.013)								
HH Head Female		-0.002 (0.013)							
Household Size			0.005 (0.003)						
Main Income is Agriculture				0.015 (0.015)					
Business Ownership					0.014 (0.012)				
Yrs of Schooling HH Head						-0.000 (0.002)			
Number of Mobile Phones							0.002 (0.009)		
Solar Lantern Ownership								0.006 (0.019)	
Access to Electricity									0.011 (0.040)
Observations	1,396	1,396	1,396	1,396	1,396	1,332	1,395	1,396	1,396
R-squared	0.000	0.000	0.002	0.001	0.001	0.000	0.000	0.000	0.000
School FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Controls	NO	NO	NO	NO	NO	NO	NO	NO	NO
Control Mean	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917
Number of Schools	20	20	20	20	20	20	20	20	20

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table A.6: Impact on Kerosene Use and Emissions- With Controls

VARIABLES	(1) Nr of Kerosene Lights (kg)	(2) Used Ker Yest.	(3) Tins Kerosene Use (l)	(4) Lantern Kerosene Use (l)	(5) Monthly Kerosene Use (l)	(6) Monthly PM 2.5 (g)	(7) Monthly BC (g)	(8) Monthly CO2eq (kg)
Solar Works	-0.997***	-0.292***	-1.204***	-1.736***	-1.438***	-95.948***	-92.320***	-67.883***
	(0.104)	(0.037)	(0.312)	(0.398)	(0.256)	(18.278)	(17.681)	(12.927)
Observations	1,313	1,313	957	342	1,299	1,291	1,291	1,291
R-squared	0.188	0.205	0.062	0.272	0.087	0.080	0.080	0.080
School FE	YES	YES	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES	YES	YES
Control Mean	2.234	0.837	2.502	2.265	2.445	164.9	158.8	158.8
Number of Schools	20	20	20	20	20	20	20	20

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Notes: Robust standard errors in parentheses.*** p<0.01, ** p<0.05, * p<0.1. Solar ownership is instrumented with price discounts. Column 1 shows the reduction for households that only own tin lights, Column 2 for everyone else. Columns 3-8 show information for both types of households. In Column 3-6 we used the following factors: if HH used tin lanterns only 90g of BC/kg of Kerosene, 93g of PM2.5/kg of Kerosene and 2770g of CO2eq/kg of Kerosene. If the household only used kerosene lanterns 9g of BC/kg of Kerosene, 13g of PM2.57kg of Kerosene and 3080 g of CO2eq7kg of Kerosene. All factors are based on Lam et al. (2012). The 13.79

Table A.7: Impact on Health- With Controls

VARIABLES	(1) Adults Dry Eyes 0-6	(2) Pupils Dry Eyes 0-6	(3) Adults Respi. 0-5	(4) Pupils Respi. 0-5
Solar Works	-0.472**	-0.487**	-0.235	-0.393***
	(0.203)	(0.190)	(0.149)	(0.142)
Female	0.195	0.114	0.396***	0.168**
	(0.120)	(0.105)	(0.084)	(0.077)
Observations	1,313	1,202	1,313	1,202
R-squared	0.040	0.024	0.042	0.036
School FE	YES	YES	YES	YES
Controls	YES	YES	YES	YES
Control Mean	2.864	2.475	1.431	1.402
Number of Schools	20	20	20	20

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Solar ownership is instrumented with price discounts. Control variables include electricity connection at baseline, business ownership, whether anyone in the household was employed during the past 12 months and household size.

Table A.8: Impact on Light Use and Energy Expenditure - With Controls

VARIABLES	(1) Lighting Hours Children	(2) Lighting Hours Adults	(3) All- Energy Exp (KSH)	(4) Energy Exp as Share of Total	(5) Energy Exp as Share of Total w/o Edu
Solar Works	0.379***	-0.177	-113.671***	-0.028***	-0.034***
	(0.129)	(0.136)	(24.193)	(0.004)	(0.005)
Female	0.403***	0.102			
	(0.070)	(0.082)			
Observations	1,202	1,313	1,313	1,313	1,313
R-squared	0.113	0.048	0.093	0.102	0.078
School FE	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES
Control Mean	3.324	3.206	272.4	0.0510	0.0670
Number of Schools	20	20	20	20	20

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Solar ownership is instrumented with price discounts. Control variables include electricity connection at baseline, business ownership, whether anyone in the household was employed during the past 12 months and household size.

Table A.9: Impact on Homework Completion and Time Use- With Controls

VARIABLES	(1) Home -work Completion	(2) Share HW after Dark	(3) Home -work (hours)	(4) School (hours)	(5) Sleep (hours)
Solar Works	0.159***	0.099**	0.293	0.479	-0.709***
	(0.049)	(0.039)	(0.182)	(0.321)	(0.227)
Pupil Female	-0.029	0.009	-0.081	-0.063	-0.234*
	(0.027)	(0.022)	(0.098)	(0.178)	(0.120)
Observations	1,050	1,050	1,202	1,202	1,202
R-squared	-0.003	0.002	0.050	0.011	0.021
School FE	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES
Control Mean	0.692	0.780	2.458	4.508	8.077
Number of Schools	20	20	20	20	20

Notes: Robust standard errors in parentheses.*** $p<0.01$, ** $p<0.05$, * $p<0.1$. Solar ownership is instrumented with price discounts. Column 1 shows the share of times the pupil was able to complete the homework past week. Column 2 shows the share of times the homework was completed after dark. Columns 2-5 show data from the time use section. In this table we control for pupil's class and gender. In this table we control for pupil's class and gender in addition to standard controls, namely electricity connection at baseline, business ownership, whether anyone in the household was employed during the past 12 months and household size.

C. Additional Outcomes

Table A.10: Time Use Adults

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	Sleep	Chores	Recreation	Work	Ag Work	Non-Ag Work	Work after dark
Solar Works	0.200	0.110	0.838	-1.414**	-0.786	-0.567	-0.761**
	(0.460)	(0.354)	(0.563)	(0.698)	(0.541)	(0.671)	(0.324)
Solar Works * Female	-0.544	-0.551	-0.416	1.683**	0.787	0.897	1.079***
	(0.554)	(0.491)	(0.661)	(0.801)	(0.615)	(0.749)	(0.372)
Female	0.040	5.252***	-1.696***	-3.360***	-1.764***	-1.573***	-1.599***
	(0.318)	(0.284)	(0.380)	(0.465)	(0.368)	(0.440)	(0.216)
Observations	1,313	1,313	1,313	1,313	1,313	1,313	1,313
R-squared	0.001	0.471	0.088	0.090	0.045	0.026	0.066
School FE	YES	YES	YES	YES	YES	YES	YES
Controls	NO	NO	NO	NO	NO	NO	NO
Control Mean Male	6.909	1.273	4.746	6.064	3.735	2.307	2.587
Number of Schools	20	20	20	20	20	20	20

Notes: Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. Solar ownership is instrumented with price discounts.

Table A.11: Light Interruptions

VARIABLES	(1) Light Interruption Dummy	(2) Light Interruption	(3) Use Alternative Dummy	(4) Use Alternative
Solar Works	-0.391***	-1.219***	-0.357***	-0.649***
	(0.043)	(0.141)	(0.045)	(0.138)
Observations	1,286	1,286	1,286	1,285
R-squared	0.154	0.109	0.047	0.013
School FE	YES	YES	YES	YES
Controls	YES	YES	YES	YES
Control Mean	0.445	1.153	0.402	0.815
Number of Schools	20	20	20	20

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Solar ownership is instrumented with price discounts. Questions about light interruption and use of alternative lighting sources were asked for the past month.

Table A.12: Perceived Safety at Night

VARIABLES	(1) Feeling Safe at Night Home	(2) Feeling Safe at Night Outside	(3) Burns past 3 months
Solar Works	-0.041	-0.045	-0.006
	(0.050)	(0.047)	(0.013)
Female	-0.119***	-0.130***	0.005
	(0.029)	(0.028)	(0.007)
Observations	1,313	1,313	1,313
R-squared	0.053	0.041	0.010
School FE	YES	YES	YES
Controls	NO	NO	NO
Control Mean	0.512	0.357	0.0190
Number of Schools	20	20	20

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Solar ownership is instrumented with price discounts. Question asked: In the last 7 days how often did you feel safe at your house (outside of the house) at night? 1=always 0= usually, sometimes or never.

Table A.13: Impact on Psychological Outcomes

VARIABLES	(1) Future Better than Parents (0-3)	(2) Econ Sit Improved (0-4)	(3) Future holds good things (0-3)	(4) Happiness (0-3)	(5) Life-Satisfaction (0-10)	(6) Risk of Depression (0/1)
Solar Works	0.168**	0.282***	-0.020	0.061	-0.138	-0.059
	(0.083)	(0.103)	(0.066)	(0.058)	(0.244)	(0.049)
Female	-0.061	0.014	-0.019	0.005	-0.015	0.126***
	(0.049)	(0.059)	(0.040)	(0.033)	(0.141)	(0.029)
Observations	1,313	1,313	1,313	1,313	1,313	1,313
R-squared	0.045	0.032	0.016	0.029	0.028	0.060
School FE	YES	YES	YES	YES	YES	YES
Controls	NO	NO	NO	NO	NO	NO
Control Mean	2.253	1.248	1.248	2.196	5.005	18.05
Number of Schools	20	20	20	20	20	20

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Solar ownership is instrumented with price discounts. Column 1 and 3 options are: 0=strongly disagree, 1=disagree, 2=agree 3=srongly agree. Column 2: 0=got a lot worse, 1=got a bit worse, 2= stayed the same, 3=improved a bit, 4=improved a lot. Column 4 0=not happy at all, 1=not very happy, 2=quite happy, 3= very happy. Column 5 scale from 0-10. Column 6 risk of depressen dummy according to CES-D scale.

Table A.14: Knowledge about Solar Lights

VARIABLES	(1) Know Price	(2) Know Charging	(3) Know Battery Run Time	(4) Know Durabilit	(5) Nr Brands Know
Solar Works	-0.056	0.519***	0.483***	0.107**	0.464***
	(0.048)	(0.048)	(0.046)	(0.049)	(0.083)
Female	0.019	-0.005	-0.069***	-0.002	-0.130***
	(0.028)	(0.028)	(0.027)	(0.028)	(0.047)
Observations	1,313	1,313	1,313	1,313	1,313
R-squared	0.070	0.080	0.163	0.070	0.120
School FE	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES
Control Mean	0.406	0.234	0.436	0.490	0.597
Number of Schools	20	20	20	20	20

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1. Solar ownership is instrumented with price discounts.

D. Survey Questions Used for Indices

Question for Index of Symptoms of Respiratory Infections

Based on Bates et al. 2015 we asked the following 5 questions (yes/no answers). We aggregated all the symptoms and created a score ranging from 0-5.

- In the last 3 months have you ever had wheezing or whistling in your chest?
- In the last 3 months have you ever woken up with a feeling of tightness in your chest?
- In the last 3 months have you ever experienced an attack of shortness of breath that came on during the day when you were at rest?
- In the last 3 months have you ever been woken up at night by an attack of shortness of breath?
- In the last 3 months have you ever been woken up at night by an attack of coughing?

Questions for Index of Symptoms of Dry Eyes

As for the questions about symptoms of dry eyes we asked the following 5 questions (Options: every day, most days, some days, rarely, never, coded as dummy, where 1= all choices except "never"). We aggregated all the symptoms and created a score ranging from 0-5.
Do you experience any of the following and if so, how frequently?

- a feeling of dryness in your eyes?
- a feeling of grittiness (having sand) in your eyes?
- a burning feeling in your eyes?
- redness in your eyes?
- crusting with yellow discharge in your eyes?
- sticking together of your eyelids when you wake up in the morning?

E. Script with Information about Solar Light

Now I will show you a solar light called SUN KING ECO and we will give you the opportunity to play a game where you can win this product or a similar one. Show the product:

- The lantern comes with a separate panel that you can put outside to charge in the sun.
- There are three different modes to use this lantern (SHOW THEM). In the first least bright you can use it for 30 hours, in the middle one for 6 and in the brightest one for 4 hours.
- The product comes with a warranty of 2 years and a battery that can last up to 5 years.

F. Pictures

Figure A.1: Tin Light

Figure A.2: Kerosene Lantern