Adoption and Impact of Solar Lighting : A Randomized Field Experiment in Rural Kenya

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Abstract

Over 1 billion people lack access to electricity worldwide. They typically use kerosene for lighting, which provides low-quality light at a high cost and contributes to indoor air pollution and global warming. Prices for solar have fallen dramatically and policy makers are enthusiastic about solar as a cleaner and more cost-effective alternative. However, there is still little empirical evidence on the demand for solar lights as well as their impacts on poor rural households and the environment. In a randomized field experiment with 1,400 households in rural Kenya we find that take-up is price-sensitive ranging from 100% with free distribution, to 69% when sold at 4 USD to only 29% when sold at market price of 9 USD. Breakage rates of over 10% as well as relatively modest private returns might explain the relative low take-up rates at market price. Households use the solar light for 3.5 hours per day on average and recipients of a free light do not use it less than those who purchased it. Access to a solar light leads to a reduction in kerosene consumption of 1.4 liter per month, curbing harmful particulate matter and black carbon emissions. In terms of health outcomes, we find that symptoms related to eye illnesses reduce by 0.25 standard deviations for both adults and children and symptoms related to respiratory illnesses reduce by 0.17 and 0.27 standard deviations respectively. Children's homework completion increases, however there are are no increases in test scores. Price sensitivity and limited adoption rate at market price, combined with environmental and health externalities and the fact that lower prices do not lead to lower use, suggest that policy makers who aim for universal adoption of solar lights should consider subsidies.

1 Introduction

The global community is facing two crucial challenges in this century: human-driven climate disruption and widespread energy poverty (Alstone 2015; SEAll 2017). Acknowledging these challenges, the UN Sustainable Development Goals call upon the international community to "ensure access to affordable, reliable, sustainable and modern energy for all." There has been a major push to increase energy access as well as to transition away from fossil fuels and increase the use of renewable energy sources to limit negative externalities such as air pollution and global warming (SEAll 2017). Nevertheless, an estimated 1.1 billion people remain unelectrified, most of which rely on kerosene for lighting (SEAll 2017; WHO 2016). Kerosene lights typically provide low quality lighting at a high cost. Many policy makers and practitioners hope that access to better lighting sources with lower operational costs allows adults to use their time more productively and children to improve their schooling outcomes (Grimm et al., 2016a; Mills, 2003). In addition, emissions from kerosene use contribute to global warming and indoor air pollution (Lam et al., 2012a; Jacobson et al., 2013), which is a leading risk factor for global disease burden (Lim et al., 2013; WHO 2016). Concerned about the negative health effects the WHO discourages the use of kerosene for lighting and at the same time asks for more research on the issue (World Health Organization 2016). Moreover a number of governments made the elimination of kerosene use for lighting an explicit policy goal (GoK 2012; Grimm et al. 2016).

In recent years, prices for solar panels and batteries decreased dramatically and made solar a promising alternative to kerosene (Bloomberg 2016). Solar can be used in many forms ranging from large infrastructure feeding into national grids, to mini-grids, home systems, and small portable solar lanterns. In this paper, we focus on small off-grid solar lights, which are particularly attractive for poor households since they require only a small up-front investment, are easy to deploy, and require limited maintenance. Moreover, unlike mini-grids, they do not pose the management and distribution problems typically associated with public goods. However, these solar lights provide minimal access to energy and cannot satisfy energy needs beyond simple lighting and, in some cases, mobile phone charging.

Studying the demand for and impact off off-grid solar lighting in Kenya seems particularly relevant, as there is a heated debate about how to address energy poverty in its rural areas. On the one hand the Government of Kenya (GoK) secured a massive loan from the world bank to expand the electricity grid and has set a very ambitions goal to achieve universal electricity access by 2030. On the other hand it has one of the most advanced markets of off-grid solar in Sub-Saharan Africa and just decide to invest more public money in off-grid solar (GoK World Bank 2017; GoK, NCCAP, 2013). Understanding the demand for electricity as well as off-grid products as well as their financial returns and impact on rural households and possible externalities is crucial to make sound policy decisions. This study is contributes to the small but growing literature that experimentally studies the demand for and impact of different products and infrastructure that aim to provide access to modern energy including electrification (Lee, Miguel & Wolfram, 2016b; Barron & Torero 2015; Dinkelman 2011; Lipscomb, Mobarak, and Barham 2013; Burlig & Preonas 2016; Chakravorty, Emerick, and Ravago 2016), mini-grids (Bensch et al. 2011), solar home systems (Samad et al. 2013) and solar lights (Furukawa 2013a; Kudo, Shonchoy & Takahashi 2016; Grimm et al. 2016a and 2015b).

We conducted a randomized field experiment was conducted with over 1,400 households in the rural areas surrounding the town of Busia in Western Kenya, where less than 5% of the population were connected to the electricity grid at the time of the study. Households were sampled through schools and the randomization was conducted at the household level. We surveyed one school-aged child and its primary care-taker in each household at baseline and conducted an endline seven months later. In addition, we installed sensors measuring the use of solar and kerosene lights in a subset of households and collected children's test scores before and after the intervention. Respondents received either a free solar light, an offer to buy a solar light at a high, a low discount, or the market price, or they received no intervention (control group). We used two different types of solar lights for the free distribution, a small one (Sun King Eco), which provides light for 4-30 hours, depending on which brightness setting is used and a larger one (Sun King Mobile), that can also charge a mobile phone and that provides light for 3-18 hours.

The goal of this study is to provide more evidence on the demand for and impact of solar lights for governments, financiers, international organizations, enterprises and NGOs who are looking for solutions to address widespread energy poverty and climate change. We first examine the demand for solar lights as well as their direct financial returns. Results from the take-up experiments suggest that suggest that demand is very price elastic and that at market price less than 45% of households decide to purchase a solar light (this includes households who purchase outside of the program). These relatively low take-up rates make sense when one considers the relatively high investment of 900 KES (US $ 9) corresponding to around 12% of a typical households monthly expenses as well as the risk of over 10% that the solar light will break during the next 7 months and the relative modest monthly savings of 111.2 KES (US $1.11) on average. The average net present value of the small solar light (Sun King Eco) is slightly positive if we assume risk neutral consumers and an interest rate of 7.5% per month. Larger solar lights, that also allow to charge mobile phones lead to slightly higher monthly savings, however their market price is much higher 2400 KES (US $ 24), and their net present value is highly negative (-1300 KES/-US $ 13) for the average household. Note however that the returns to the investment depend largely how much household reduce their kerosene use and are very heterogenous. We find no evidence that households who receive a free solar light use the product less. In line with what Hoffman 2009 found in the case of bed nets, pupils also benefit more from the solar light in households where they were distributed for free. Pupils are 8.7%-points more likely to be considered the "main user" of the solar light in households who received a free solar light (as opposed to one that paid for it). Moreover, they are 6.2%-points more likely to have used the solar light for their homework the previous day. These results suggest that the financial returns alone do not necessarily justify the investment in solar even if the consumer has neutral risk preferences. The observed take-up rates suggest that market based solutions alone are not likely to lead to universal adoption of solar lights in this context in the near future and thus policy makers who aim for the universal adoption of solar should consider subsidies.

In the second part of the study we look at the externalities and non-financial returns to solar lights. We first examine if indeed households use the solar lights and the extent to which they replace kerosene and thus reduce harmful emissions and quantify the reduction. Then we look if this reduction is reflected in better health outcomes. Moreover we test if accessing solar lighting allows children to spend more time on their homework and to improve their schooling outcomes. We find that most households who purchase or receive a solar light use it daily for of 3.5 hours per day on average. Children use 22 minutes more light per day as a consequence of having a solar light at home, but light use for adults does not change. Children in households with access to a solar light almost unanimously report using them for homework and they also report an increase in homework completion rates. However we only find a marginally significant increase in the time boys spend studying and no gains for girls. We also don't observe an increase in test scores for boys or girls. The only clear effect on children's time use is that a significant decrease (48 minutes) in sleep time for both girls and boys. Finally, we find that adults also do not shift their time use towards more productive activities. Households reduce kerosene consumption per month by 1.4 liters on average, leading to an estimated yearly emissions reduction corresponding to 720 kg of CO2 equivalent per household. Moreover, access to solar lighting decreases symptoms of eye and respiratory illness for both children and adults. These benefits, are at least partially external to the household and for the most part external to the financial decision maker.

Due to the novelty of the product, there are only a handful of studies that have looked at the impact of solar lighting on rural households before. Two studies have focused on whether access to solar improves children's schooling outcomes and found modest increase in study time, but no increase in test scores (Furukawa, 2013a; Kudo, Shonchoy & Takahashi, 2016). Only one study has been published which looked at a broader range of outcomes (Grimm et al., 2016a). To our knowledge there is no published work on the demand of solar lights. However there are a few working papers that aim to elicit household's willingness to pay, (Youn et al. 2014; Grimm et al. 2016b; Niccolò et al. unpublished). In all cases, the research team played an auction game and found relatively low willingness to pay for solar lights. Instead, we randomized prices for solar lights at the household level, which is easier to understand than bidding games and many argue also closer to reality. In addition this design allows us to see whether households who pay for a solar light are more likely to use it compared to those who received one for free. This could be the case if paying for a good increases its perceived value and makes people more likely to use it (sunk-cost effect), or if households, which have particularly high returns to solar, are more likely to purchase a solar light (selection effect). Furthermore, we hope to complement the existing work on the impact of solar lights with a larger sample size, which allows us to detect smaller effects. Moreover, we use novel sensor technology, specifically developed for this project, to get precise high-frequency measure of solar and kerosene light use that is not susceptible to social desirability bias (households might over-report solar use and under-report kerosene use since they think this is what is expected from them). Studies on cookstoves revealed that social desirability biases can be substantial (Wilson et al. 2016; Thomas et al. 2013). In addition, we look at additional outcomes such as the reduction in harmful kerosene emissions, which to our knowledge has not been done before.

This paper proceeds as follows: section 2 explains the background and research design, section 3 describes the data and empirical strategy, section 4 presents the results, and section 5 concludes. We prepared a pre-analysis plan (PAP) that can be found here. All hypotheses outlined in the PAP are tested and explained either in the main part or the Appendix of the paper.

2 Background and Experimental Design

The study was conducted in Busia County in Western Kenya. Busia is one of the more densely populated and poorer counties of Kenya's 47 counties: it is below the national average when it comes to urban population, literacy, and share of population with a secondary education. Moreover, fewer people are electrified and fewer paved roads exist in Busia than the Kenyan national average.

2.1 Background

Across Sub-Saharan Africa there are still 600 million people who do not have access to electricity. Achieving universal access to modern energy has become a policy priority for many governments throughout the continent (IEA 2014). In Kenya, rural electrification has been discussed since the 1970s and the Government of Kenya (GoK) set an ambitious goal of universal access by 2020 (GoK 2015). However progress was slow until recent years, when the government of Kenya launched a big push to connect public facilities throughout the country. Many households live now within proximity of the grid and in 2015 the Kenyan government announced that it raised $364 million, mostly from the World Bank and the African Development Bank, to connect such households to the grid (Lee et al. 2016). According to the Kenya Power and Lighting Corporation (KPLC) the so called Last Mile Connectivity Project led to an impressive increase of electricity connections in Kenya: while only 23% of its population were connected to in 2009 almost 50% where connected in 2016. The program was still in its early stages during the time of our study and the villages we worked in remained largely unaffected. In fact, only 13 households in our sample heard about an electrification project in their village and during our study the costs for grid connection were still at 35,000 KES (US $350) in the study area. Since the average monthly expenditure in our sample was only between US $73-US $89, and hence a grid connection would be as much as what an average household would spend in 4 to 5 months. In our sample around a third did not know how much a grid connection would cost, the remaining responses were a large range with a median of 30,000 KES (US $300), which is a bit lower than than the price at the time.

In addition to massive grid expansion, sales of solar products have been increasing rapidly in Kenya and the county became the leading markets for pico solar products in Africa. Sales of quality verified solar lights have increased from 57'000 products in 2010 to 970'000 in 2014 (Bloomberg 2016). Note that these estimates only include branded products, which are verified by Lighting Africa and do not include sales from non-verified products. While no one really knows how many non-verified products have been sold, experts estimate that they are more than 50% of total sales (Bloomberg 2016; World Bank 2017). Already in 2008, Lighting Africa, a initiative led by the World Bank and IFC, has selected Kenya as one of its two pilot countries. Since then Lighting Africa supports the private market for off-grid solar sector through a variety of measures including: product quality verification, costumer awareness campaigns, the provision of market intelligence and training of technicians to provide after-sales maintenance support (Lighting Africa 2016). The GoK exempted solar products from the Value Added Tax in 2014, which led to further reductions in prices of solar lights for end users (GoK 2014). To further increases access to solar lighting in its less densely populated North and Northeastern Provinces, the GoK secured a World Bank loan of US $150 million. The goal is to connect around 277,000 households (close to 1.3 million people), 1,097 community facilities, and 380 boreholes to off-grid solar in these regions. The GoK also intends to sell 150,000 efficient cookstoves as part of the program (World Bank 2017).

Like many governments in Sub-Saharan Africa the government of Kenya needs to decide what policy-mix to use to address the energy needs of its rural population. Assessments of people's willingness to pay for different energy solutions as well as their impact on rural households and possible externalities seems therefore politically highly relevant.

2.2 Intervention and Experimental Design

While there are a number of different types of solar products on the market, we analyze the impact of low-cost solar lights — small portable lighting units, which are the focus of our partner SunnyMoney's business. When we started this research project in 2015 our partner sold over 1.7 million products in Africa most of them in Tanzania, followed by Kenya (Solar Aid 2015). Two different types of lights were used in this study: the Sun King Eco and the Sun King Mobile, both manufactured by Greenlight Planet and quality assured by Lighting Global, a joint initiative of the World Bank and the International Finance Cooperation. In 2015, SunnyMoney was selling the Sun King Eco light (Figure 2.2) for US $9 in Kenya, corresponding to 12.3% of a household's average monthly cash expenditure during baseline. That model provides light for 4-30 hours, depending on which brightness setting is used and a maximum of 32 Lumen (Lighting Global 2015; Greenlight Planet 2016). During the same time period, SunnyMoney was selling the Sun King Mobile light (Figure 2.3) for US $24. According to the manufacturer, the model can charge a mobile phone and provide light for 3-18 hours, depending on which brightness mode is used and a maximum of 98 Lumen (Lighting Global 2016a). Half of the 400 households who received a solar light free got a Sun King Eco light (200 households) and half received a Sun King Mobile light (200 households). The discount vouchers were for the Sun King Eco model.

For comparison, a simple tin lamp provides around 7.8 lumens and a kerosene lantern provides 45 lumens (Mills, 2003). As opposed to grid connection and some larger off-grid solutions, these portable solar lights cannot be used to power larger appliances such as TVs, fans, or refrigerators. These products are, however, less expensive than larger home systems and typically require no installation and little maintenance. They currently cost between US $7.5–US $35, depending on the size and functionality of the unit. The price for a solar light is low compared to the original cost of around US $400 for a household grid connection and the highly subsidized price of US $150 under the ongoing “last mile project” (wiring the house or usage costs are not included in these figures) in Busia, Kenya (Lee, Miguel & Wolfram, 2016b; Kenya Power 2017).

That said, a solar light is still a considerable investment, given that 58.9% of the rural population in Kenya lives on less than US PPP $3.10 per capita per day (World Bank, 2005).

Sales of solar lights were handled through the head teacher of the schools that children attended, the same way SunnyMoney typically works. The subsample that received an offer to buy could redeem the vouchers during a period of 4-6 weeks.

We conducted an RCT between June 2015 and March 2016 in Busia County in Western Kenya. Within this region we selected 20 public, primary schools for the study out of a total of 97 eligible schools (see Section 2.3 for more details). In each of these schools, about 70 households with at least one child in class five, six, or seven were randomly selected. The randomization was conducted at the household level and stratified at the school level. Sampled households were assigned to one of the following 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[1] per school, 611 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=201)

We randomly selected 10 schools in each of the sub-counties which corresponded to a pre-specified set of criteria. [2]

Within each of these 20 schools, we drew a random sample of households that had at least one pupil in class five, six, or seven. [3] Out of 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 1,411 households were selected to be surveyed for the first time in July and August 2015 (baseline) and seven months thereafter (endline). [4] In each household, we surveyed the selected child and one of the pupils' guardians, in most cases the mother (50.2%) or the father (28.7%). Nine guardians preferred not to participate in the study, leaving 1,401 households that were willing to participate in the study. We were able to interview all pupils at baseline and 1,285 (91.7%) at endline. Most of the pupils that we were not able to be tracked had moved to different schools. At endline we were able to interview 1,313 (93.7%) of the adult respondents.

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[1] 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.

[2] Schools with fewer than 100 pupils, schools with only girls or only boys, boarding schools, schools located in urban areas or too far from the research office to be easily reached, and schools whose head teacher was not present at the term head teacher meeting were excluded.

[3] Standard 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 included since it would have been harder for them to answer questions about homework, time use, light use, etc.

[4] 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.

3 Data and Empirical Strategy

3.1 Survey Data

Prior to commencing the full study, we conducted a number of in-depth interviews with solar light users and non-users, as well as with teachers. 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.

We surveyed the randomly selected pupils (see Section 2.2) as well as their primary guardian, which in most cases (78.8%) was the mother or the father of the child. Data was 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, including Grimm et al. (2016a), Cattaneo et al. (2009), Furukawa (2013, 2014), and Lee, Miguel & Wolfram (2016a), as well as standardized scales (World Value Survey, European Community Respiratory Health Survey II, the Standard Dry Eyes Disease Questionnaire and CES-D) and our partners internal research tools. The advantage of building the questionnaire on other researchers' work is that we can learn from previous experience and compare our results.

3.2 Sensor Data

In addition to survey data, which, in most cases, is self-reported by respondents, we used sensors to measure light use. A sub-sample (300) of the solar lamps that were distributed free or purchased were equipped with Bluetooth-enabled sensors developed by Bonsai Systems[5]. At endline, 187 sensors (62.2%) were still operating, while the remaining 37.8% were experiencing some form of technical malfunction; from these, no data could be retrieved. Sensors tracked when the solar lights were used and for how long. The solar light sensor determines when the lamp is in use by measuring the change in voltage across the device's light emitting diode (LED). The solar light sensor was installed by soldering three wires from the sensor to the board inside the light (voltage, ground, side of the LED). The sensor draws a very small amount of power from the lamp battery. Hence, the solar sensor remains functional as long as the lamp battery is charged (and assuming it does not break for another reason). The sensor records an event when one presses a button to turn the light on and records an event when one turns the light off. Using smartphones enabled with Bluetooth and an iPhone application called "Lamplogger" (which was specially developed for this project), field officers visited households at endline and wirelessly uploaded data directly from the sensor to the phone. Field staff explained how the sensor worked and what data it recorded to study participants and asked them for permission before downloading any data. No data was downloaded if the participant had any objections.

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

3.3 Empirical Strategy

Analysis of Take-Up

When looking at take-up rates, the sample is restricted to the 601 households who received a voucher to purchase a solar light. We use the following equation to estimate price elasticity of demand:

$$Purchase_{ji} = \alpha_0 + \sum_{k=1}^{2} \alpha_k(price_j) + X_j'\beta + \lambda_i + \epsilon_{ji}$$

Whereby $Purchase_{ji}$ designates whether a household j in school i purchased a solar light. α_0 indicates the take-up price at the reference price of 900 KES (market price). α_k shows the effect of a discounted price (400 KES or 700 KES) in relation to the market price of 900 KES on the take-up of solar lanterns. $price_j$ is a set of dummies for the price level at which a household received a voucher to purchase a solar light (400 KES or 700 KES). X_j refers to other independent variables associated with the individual, such as levels of education, wealth, etc. λ_i refers to school fixed effects and ϵ_{ji} is an error term.

Analysis of Impact

As explained in the PAP, we apply two measures for the analysis of impact: the intention to treat (ITT) effect and the treatment effect on the treated (ToT). For simplicity, we typically report ToT measures, indicating the effect of having a functioning solar light on the outcome of interest. To ensure full transparency, however, we provide the results for all ITT measures in the Appendix.

Intention to Treat Effect The ITT compares averages between the treatment and the control group.

$$y_{ji} = \alpha_0 + \alpha_1(treat)_j + X_j'\beta + \lambda_i + \epsilon_{ji}$$

Whereby y_{ji}designates the outcome of interest of household j in school i at endline, $treat_j$ is a dummy variable indicating the treatment assignment of the respective household. $\alpha_1$captures the average treatment effect. X_j refers to a set of control variables at the individual level. λ_i refers to school fixed effects. ϵ_{ji} is an error term.

Whenever possible, regressions were run with and without controlling for baseline (outcome) levels as well as other control variables to check for the robustness of the estimated effects. It was not always possible to control for baseline levels, as we do not have baseline data for all measures.

Treatment Effect on the Treated The ToT is the effect of having a functioning solar light (either having received a free one or having bought one from the “offer to buy” intervention). We use an instrumental variable (IV) approach to calculate the ToT.

First stage: $light_{ji} = \alpha_0 + \sum_{k=1}^{4} \alpha_k(offer_j) + X_j'\beta + \lambda_i + \epsilon_{ji}$

Second stage: $y_{ji} = \alpha_0 + \alpha_1(light_j) + X_j'\beta + \lambda_i + \epsilon_{ji}$

$light_{ji}$ designates whether household j in school i had a functioning solar light at endline, $offer_j$ 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 KES 400, KES 700 or KES 900). y_{ji} designates the outcome of interest of household j in school i and $\alpha_1$captures the treatment effect on the treated (ToT). The other variables are the same as described in the previous paragraph on ITT. Note that using this identification we combine the different treatment effects of the different subsidies into one. In section 4.2.2 we use an approach that is similar to Dupas & Cohen 2010 to test whether there are significant difference in use among the different treatment groups and find no significant difference.

4 Results

We will first describe the sample, then look at the demand for solar lights and the private financial returns to the investment. Then we discuss the use of the solar light discuss wether households who pay for the solar light use it differently from households who did not. In the last part we present our findings on environmental and health externalities as well as educational outcomes.

4.1 Sample Description

The average household in our sample has 6.7 members, with 4.3 children under the age of 18. Most houses have earth floors (85.5%) and iron sheet roofs (64.6%) on their main building. A typical household has four separate rooms. The average household head attended school for 6.4 years (see Table 1 column1).

At baseline, the average household spent US $73.3 in cash per month. However, expenditure is seasonal and the average household expenditure was higher (US $79.3) during endline, which was conducted at the end of harvest time and shortly after school fees were due. The average household owns 1.9 acres of land, 1.3 cows, and 5.8 chickens. More than half of the households (53.8%) own at least one radio, 53.8% own a bicycle, and 7.8% own a motorbike. Almost all households (98.8%) conduct agricultural activities and a bit fewer than third (29.4%) own at least one business, most of them selling fish or other food items. Most of these businesses have no employees. Only 20.1% of households have at least one member who was employed in the previous year (formally or informally). The self-reported main income source for the largest share of households is agriculture (68.5%), followed by casual (informal) labour (14.8%), own business income (11.1%), formal employment (3.7%), and remittances and transfers (1.6%).

Overall, the sample is balanced with the exception of business ownership. We therefore run all the regressions with and without controlling for business ownership. None of the results changed significantly.

Energy and Light Use at Baseline

Access to modern energy sources are limited as only 8.3% of households have access to some form of electricity. To break this number down: 2.7% of households are connected to the grid, 3.1% have access to a solar home system, 2.2% have access to a car battery, which provides energy for the household, and 0.3% have access to a generator. The vast majority of the sampled households use an open fire (98.4%) or charcoal stoves (1.0%) for cooking. Kerosene, LPG, and other stoves are much less common (0.6% combined). An average household spends around US $3.66 (KES 366) per month on energy, corresponding

Table 1: Summary Statistics and Balance Table

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	All	Control	400	700	900	Free	All
Stats	Mean	Mean	Diff.	Diff.	Diff.	Diff.	Diff.
	(SD)	(SD)	[P-Val]	[P-Val]	[P-Val]	[P-Val]	[P-Val]
Iron Roof	0.646	0.666	0.063	0.045	0.031	-0.003	-0.027
	(0.478)	(0.472)	[0.124]	[0.278]	[0.450]	[0.940]	[0.338]
HH Head Female	0.303	0.309	0.012	0.022	0.045	-0.018	-0.009
	(0.460)	(0.463)	[0.753]	[0.587]	[0.257]	[0.595]	[0.748]
Household Size	6.689	6.784	0.167	0.143	-0.013	0.183	-0.133
	(2.141)	(2.177)	[0.376]	[0.456]	[0.945]	[0.218]	[0.294]
Main Income is Agriculture	0.683	0.688	-0.015	-0.004	-0.017	0.038	-0.008
	(0.466)	(0.464)	[0.706]	[0.924]	[0.670]	[0.259]	[0.779]
Business Ownership	0.294	0.332	0.016	0.111 ***	0.103 ***	0.018	-0.052 *
	(0.456)	(0.471)	[0.693]	[0.005]	[0.009]	[0.596]	[0.053]
Yrs of Schooling HH Head	6.386	6.599	0.544 *	0.334	0.069	0.251	-0.294
	(3.802)	(3.895)	[0.097]	[0.336]	[0.838]	[0.378]	[0.207]
Number of Mobile Phones	1.398	1.425	0.042	0.033	0.019	0.048	-0.038
	(0.794)	(0.802)	[0.531]	[0.634]	[0.789]	[0.411]	[0.421]
Solar Lantern Ownership	0.065	0.053	-0.029	-0.009	-0.018	-0.015	0.017
	(0.247)	(0.224)	[0.168]	[0.662]	[0.373]	[0.372]	[0.237]
Access to Electricity	0.014	0.013	-0.016	-0.003	0.002	0.003	0.002
	(0.119)	(0.112)	[0.157]	[0.780]	[0.798]	[0.738]	[0.728]
Observations:	1397	398	209	195	197	398	1397

to 6.2% of the households' total cash expenditure — US $73.3 per household per month (current US $). Note that expenditures captured here only include cash spending and do not include items that households consume from their own farms, which constitute a large fraction of overall consumption for many rural households. The seasonality of expenditure, as mentioned earlier, also influences these estimates.

Most households (88.4%) primarily rely on small locally produced kerosene lights (tin lanterns) for lighting. Others use larger kerosene lanterns (5.3%), 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 produce an open flame that provides a weak light (around 7.8 lumens according to Mills, 2003) and can be bought for US $0.25-$0.50, depending on the size and quality of the lamp. Kerosene lanterns, on the other hand, are larger and provide a much stronger light (around 45 lumens according to Mills, 2003). Kerosene lanterns cost between US $3-$6, depending on the size and quality. They also use more kerosene per unit of time and, for that reason, are more expensive to operate (Mills, 2003). Every household which uses grid electricity also uses at least one other source of lighting — possibly a reaction to the frequent blackouts in the study region as well as the desire for portability of lighting outside the home. For lighting alone, households spend US $2.19 (KES 219) per month, which corresponds to 59.7% of the total energy expenditure and 3.1% of total cash expenditure. Kerosene accounts for 94.5% of the US $2.19 per month used on lighting. 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). Energy expenditure as a fraction of total expenditure is similar to national representative surveys of Kenya (2005/2006 KIHBS; Lighting Global, 2012) as well as other studies (Kudo, Shonchoy & Takahashi 2015; Grimm et al. 2016a).

4.2 Demand for Solar Lights

First we look at households demand for solar lights at different prices, by reporting the share of households who took up our offer, meaning that they redeemed the voucher they received in the beginning of the study. Everyone in the free group took up the offer as well as 68.9% of those who could purchase a solar light at 400 KES (US $4). Take-up then decreases to 37.4% when prices are increased to 700 KES (US $7). At market price of 900 KES (US $9) only 28.9% took-up the product (see table 2 column 1). On average an increase in 100 KES (US $1) in price reduced take-up by 8%-points (not shown). This corresponds to an average price elasticity of demand of -1.09, meaning that a 1% increase in price leads to a 1.09% reduction in quantity (table 2 column 3).

Second, we looked at the share of households who 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. In this measure we only consider ownership of solar lights that still function. Due to a number of breakages we observe that only 83.4% of the households who received a free solar light still owned a functioning one (Table 2 column 2). The reported failure rate was significantly higher for solar lights with a sensor, however it was still 11.7% for solar lights without sensors, suggesting that product improvements are still necessary. [6]

Table 2 column 2 further shows that two thirds of households (68.5%) who received an offer to purchase a solar light at 400 KES (US $4) owned a functioning light at endline, and 39.3% of those who could purchase one at 700 KES (US $7) with almost no difference to those who got an offer for 900 KES (US $9). In the control group 17.2% owned a functioning solar light at endline. We are using this measure, namely whether households have a functioning light (table 2 column 2) in our main specification. This is since we are primarily interested in the "treatment effect on the treated" i.e. the impact of having a functioning light on various outcomes rather than the effect or receiving a voucher or a free light. As explained in section 3 we report the "intention to treat effect" in the appendix.

These results suggest that households respond strongly to price increases. Second we note that households who received an offer to purchase at market price had a significantly higher take-up rate than the control group. This could be caused by a number of reasons such as: increased information, as the field staff showed them the product and explained the basic features. In addition the program reduced transaction costs, as the solar lights were available to them through the head teacher in their children's school and hence they did not have to travel far to purchase a solar light (see section 2.3 for more details). In fact availability of solar lights still seems to be an issue, as 31.3% mentioned that they never saw a solar light before and only 8.5% of respondents mentioned that solar lights could be bought in their own village. The remaining respondents mentioned that you either had to travel to the closest town or market center (45.8%) or even to a larger city or town to buy one (14.4%).

However, even with additional information and reduction of transaction costs, only 39.3% (44.3% if we include broken lights) owned a solar light during endline and the majority of households did not choose to purchase a solar light at these conditions. This is and indication that the elimination of kerosene, which is an explicit policy goal of the Kenyan government, can probably not be achieved in the near future with current prices. Households could not adopt this technology due to a lack of information about its benefits, behavioral mechanisms such as present bias or self-control problems, credit constraints, or it could simply be a rational decision due to low financial returns, which we will discuss in the next section.

4.3 Financial Returns

During our endline data collection an average household in the control group spent KES 282 (US $2.82) per month on energy, corresponding to 5.3% of total expenditure. 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. Lighting alone accounts for US $1.61 (KES 161), or 56.5% of energy expenditure – and almost all of this (90.7%) is spent on kerosene.

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[6] This is the failure rates among solar lights without sensors. Technical challenges with the sensors led to a higher failure rate of those solar lights (21.35%). Since sensors were allocated randomly and technical failures are not related to use, we are not worried that these differential technical failures biased results. See section 3.2 for a more detailed discussion.

Table 2: Solar Light Ownership at Endline

VARIABLES	(1) Redeemed Voucher	(2) Solar Ownership	(3) Log Quantity
Free	1	0.834***	
	(0)	(0.0191)	
Voucher 400 KES	0.689***	0.685***	
	(0.0321)	(0.0329)	
Voucher 700 KES	0.374***	0.383***	
	(0.0347)	(0.0360)	
Voucher 900 KES	0.289***	0.393***	
	(0.0324)	(0.0362)	
Control	0	0.172***	
	(0)	(0.0197)	
Log Price			-1.092**
			(0.0284)
Observations	1,397	1,313	3
R-squared	0.805	0.644	0.999

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

Having a solar light allows households to reduce energy expenditure on average by KES 111.2 (US $ 1.11) per month, corresponding to a large share (51.4%) of household's total energy expenditure, which is expected given that lighting is a large fraction of energy expenditure. They are, however, saving only 2.9-3.5% of total cash expenditure (see Table 7), since energy accounts for only a small fraction of total cash expenditure (5.3%).

As explained in section 2.4, half of the group receiving a free light was given a Sun King Eco (SK Eco) and the other half a Sun King Mobile (SK Mobile) solar light. The difference between the two lights is that the SK Mobile has a larger and stronger light than SK Eco and has the ability to charge a mobile phone. Those households which received an SK Mobile incur lower mobile phone charging costs (KES 18.9 or US $0.18) per month, which corresponds to an almost 100% reduction compared with the control group's expenditure of KES 22.4 (US $0.22) (see table 7).

The monthly savings lead to an amortization period of 9.3 months for the SK Eco and 22.8 months for the SK Mobile.[7] The amortization period for the SK Mobile is much longer due to its higher cost (US $24 vs. US $9 of the SK Eco). Note that here we assume that the lanterns do not break and that interest rates are zero. As we saw in section 4.1, around 11.7% of lanterns had been broken by seven months after baseline. Given that the warranty only lasts two years, these amortization periods seem rather long, especially for the SK Mobile.

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[7] Here we only focused on those who received a solar light for free and estimated ToT effects on savings separately for the SK Eco (KES 96.9 or US $0.97) from the SK mobile (KES 104.8 or US $ 1.05) and used their respective market price of KES 900 and KES 2400 respectively).

Table 3: Savings

VARIABLES	(1) Monthly Energy Exp (KSH)	(2) Monthly Phone Charging Exp(KSH)	(3) Energy Exp as Share of Total	(4) Energy Exp as Share of Total w/o Edu
Solar Ownership	-111.243***	-18.858***	-0.029***	-0.035***
	(25.348)	(2.299)	(0.005)	(0.006)
Observations	1,301	551	1,301	1,301
R-squared	0.127	0.119	0.110	0.089
School FE	YES	YES	YES	YES
Controls	YES	YES	YES	YES
Control Mean	282.4	22.40	0.0520	0.0690
Number of Schools	20	20	20	20

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

4.4 Light Use

Households, that use kerosene for lighting they pay for every additional hour of light, when they switch to solar, they can consume an additional hour of light at not additional cost. Some of the benefits that policy makers and practitioners hope for, rely on the assumption that the quantity of light households will consume increases. For example, many hope that children with access to solar are able to study more hours, since the marginal cost of an additional hour of light is zero. If indeed the impact on households works through the channel of more lighting hours, we would expect to see an increase in the number of hours that adults and children use light as a consequence of having access to a solar light.

To calculate the number of hours that adults and children use lighting each day we 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 without sunlight (18:00 to 7:00), we also asked respondents whether they used any lighting source. If they did use a lighting source, we asked them 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). Both adults and pupils in the control households used an average of 3.2 hours of light per day. Women and girls tend to use 0.4 and 0.3 hours more lighting, respectively. Having a functioning solar light increases children's lighting hours by 0.36 hours (21.6 minutes) per day. This difference is significant at the 1% level (see table 3) and corresponds to a 10.9% increase in lighting hours. There is no significant difference for adults.

Table 4: Impact on Light Use

VARIABLES	(1) Lighting Hours Children	(2) Lighting Hours Adults
Solar Ownership	0.356***	-0.187
	(0.129)	(0.136)
Female	0.390***	0.143*
	(0.070)	(0.082)
Observations	1,260	1,301
R-squared	0.055	0.058
School FE	YES	YES
Controls	YES	YES
Control Mean	3.324	3.206
Number of Schools	20	20

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

Solar Light Users and Activities

In almost all households that use a solar light, school-aged children use it and almost always to do their homework. When we asked respondents in the free solar light group which household members used the solar light the previous evening, 51.8% of households reported that, both adults and children used it, whereas in 27.6% only children use it and in 2.1% only adults use it. Finally, 18.4% of households reported that no one had used the solar light, however, this includes the 12.1% of households that no longer had a functioning light.

We also asked both children and adults in the survey to indicate the main purpose for which the different household members had used the solar light the previous evening (one answer only).[8] Almost all children (96%) reported using the solar light primarily for homework. Only 4% mentioned other activities, such as talking (2%), cooking (1%), and reading (1%). Adults reported using the light for a much more diverse set of main activities. The most frequently reported activities were eating (28%), talking (24%), and cooking (19%).

Usage difference between buyers and recipients of free solar lights

There could be differential use between buyers and those who received a solar light for free for two reasons. First, there could be a selection effect as those who decide to purchase a solar light might be different types of households and have different energy needs and budget constraints for example. Second there might be sunk cost effect, whereby the act of paying a price for a solar light might make households more likely to use it. While our research design does not enable us to differentiate between these two different effects, we can test whether households who purchase a solar light use it differently from those who

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[8] If they had used the solar light for more than one activity, they were asked to choose the one that had taken the most time

received it for free. Along similar lines it could be that guardians who know that they will use the solar light self-select to purchase one and/or that the act of purchasing it with their money makes them feel more entitled to use it. Both mechanisms could lead to a situations where buying households pupils are less likely to be given priority to use the solar light compared with recipients of free lights (Hoffmann, 2009). Using a similar approach than Dupas & Cohen 2010, we limit the sample to households who had a functioning solar light at endline,[9] and test whether buyers and free recipients use them differently[10].

We find that households who receive a free solar light use it as frequent as household who purchased it and that there is also no difference in the reduction in kerosene use, which is important to know for the later discussion on externalities (table 5 column 1,2 and 3). Interestingly, pupils who live in households that purchased a solar light are 8.7%-points less likely to be considered the main user of the light by the guardian. They are also 6.2%-points less likely to have used the solar light the evening before the survey. This information from the guardians survey also matches with what children report.

Table 5: Buyers vs. Non-Buyers

	(1)	(2)	(3)	(4)	(5)
VARIABLES	Kerosene Use (l)	Hours used yestd	Days used past 7	Pupils is main user	Used Solar for Homework yestd.
Buyer vs. Free	0.259	0.113	0.023	-0.087**	-0.062**
	(0.195)	(0.197)	(0.238)	(0.044)	(0.029)
Observations	420	384	424	385	330
R-squared	0.004	0.001	0.000	0.009	0.010
School FE	NO	NO	NO	NO	NO
Controls	NO	NO	NO	NO	NO
Free Mean	1.093	3.389	6.028	0.818	0.954
Number of Schools	20	20	20	20	20

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

4.5 Environmental and Health Externalities

There are negative externalities associated with the use of kerosene as they contribute to indoor air pollution and global warming. In fact, emissions from one tin lamp can increase indoor PM2.5 concentrations several times above WHO guideline levels (Apple et al. 2010, Lam et al. 2012b) and some studies suggest that particles generated by kerosene combustion may be more toxic than

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

[10] 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.

woodsmoke (Lam et al. 2012b; Pokhrel et al. 2009; Bates et al., 2013; Epstein et al., 2013). In addition, 95% of the small particles (PM2.5) that kerosene lights emit are Black Carbon (BC), which is estimated to be around 700 times more warming than CO2 (Lam et al. 2012b).[11] While the literature on the subject is still limited, Lam et al. (2012) estimate that the combined emissions of kerosene used in households have the same warming effect as 12% of India's CO2 emissions (Lam et al. 2012a; Jacobson et al. 2013).

To establish environmental and health impacts of solar lights we first test to what extent solar lights reduce the use of kerosene. Then we use that information to estimate the related reduction in PM2.5, BC and CO2 equivalents and provide some rough estimates of the effects that solar light access could have at scale. Finally, we test whether solar lighting leads to a reduction in symptoms of respiratory and eye illnesses, which is frequently caused by indoor air pollution.

Access to solar lights led to a significant reduction in kerosene use. Notably, 100% of control group respondents reported using kerosene-based products the previous evening. Whereas, having a functioning solar light led 25.0% of households not to use any kerosene-based products the evening before the interview. On average, households reduce their kerosene use by 1.4 liters per month (table 4). Using the results from a series of experiments from Uganda, where PM2.5 as well as BC emissions were measured (Lam et al. 2012), we estimate how this translates into emissions reductions. As the relationship between fuel burned and emissions is linear, we simply scale the amount burned by the relevant factors.[12] In addition, we convert the reduction of BC into CO2 equivalent and add the small direct CO2 reduction to that estimate (all conversion rates are based on Lam et al. 2012b). We find that a typical household reduces its emissions by 84.8 g of PM2.5 and 81.5 g of BC, and 60.0 kg of CO2 equivalents per month (table 6).

Impact on the Environment

If all households who used kerosene in Kenya had access to one solar light [13], this would lead to a reduction of 3.01 mega tonnes of CO2 per year, corresponding to around 4.9% of Kenya's total green house gas emissions. This calculations is based on a number of assumptions: First, that the reduction in kerosene use would be similar in other parts of the country and that the share of tins vs. kerosene lanterns used is similar, as well. Second, data used to scale these effects is from the last household census which was in 2009 and it is likely that the share of households using kerosene has reduced in the meantime. In addition, these calculations do not include the emissions caused by the production and transport of the solar light nor by their disposal. Still, estimates of CO2 emissions from the production of the solar lights reveal that stored emissions are offset relatively quickly (Alstone et al. 2014). However the absolute value and in particular the estimate, which is relative the Kenya's total emissions are upper bounds.

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[11] That is over a time period of 100 years and depends on geographic location (Lam et al. 2012b)

[12] Based on Lam et al. 2012 we used the following factors: for tin lanterns 90 for BC, 93 for PM2.5 and 2770 for CO2. For kerosene lanterns: 9 for BC, 13 for PM2.5 and 3080 for CO2. Households that use both types of lamps we used a simpel average of both values.

[13] We are using the most recent available data on kerosene use and Kenya's global emissions from GoK, NCCAP, 2012 as well as the latest census data from KNBS, 2009.

(Question: how to deal with the fact that available data is from 2009/12? Much must have changed since? How can I improve this measure?).

[14]If we assume a distribution price of $11 per solar light, a lifetime of two years, and 48 kg of CO2 embedded in the light from the production, we get to an abatement cost of $7.9 per ton of CO2 equivalent, which is very low compared with subsidizing solar in developed countries (Abrell et al. 2017).

Table 6: Kerosene Emissions

VARIABLES	(1) Monthly Kerosene Use (l)	(2) Monthly PM 2.5 (g)	(3) Monthly BC (g)	(4) Monthly CO2eq (kg)
Solar Works	-1.402*** (0.210)	-84.824*** (15.621)	-81.558*** (15.098)	-60.015*** (11.048)
Observations	1,267	1,131	1,131	1,131
R-squared	0.096	0.056	0.055	0.056
School FE	YES	YES	YES	YES
Controls	YES	YES	YES	YES
Control Mean	2.159	151.6	145.8	145.8
Number of Schools	20	20	20	20

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

Impact on Health

Previous studies found an association between kerosene smoke and adverse health effects (Lam et. al 2012; Furukawa 2014; Pokhrel et al 2010), in particular with regard to respiratory and eye irritations and illnesses. While it is clear that indoor air pollution causes huge health problems, it is still unclear to what extent lighting, as opposed to cooking, is a relevant factor.

We used standardized questions from the European Community Respiratory Health Survey II to understand possible effects on asthma symptoms and created an index following Bates et al. (2015) ranging from 0-5, where higher numbers indicate that the respondent suffers form more symptoms. [15]For the questions

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[14] The solar lights assessed by Alestone 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 of 100MJ per solar light. Based on Dones et al. we then estimated that 27.78 kg of CO2 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 CO2 eq in total and hence less than 2kg of CO2 equivalent per month (assuming a lifespan of 2 years).

[15] Based on Bates et al. 2015 we asked the following 5 questions (yes/no answers) for the past 3 months: a) wheezing or whistling in the chest b) woken up a feeling of tightness in the chest c) experienced an attack of shortness of breath during the day, when at rest d) woken up at night by an attack of shortness of breath e) woken up at night by an attack of coughing. We aggregated all the symptoms and created a score ranging from 0-5.

related to eye health we also created an index based on six questions about symptoms for dry eyes, also following Bates et al. (2015).

Table 7: Health Effects

VARIABLES	(1) Adults Dry Eyes 0-6	(2) Pupils Dry Eyes 0-6	(3) Adults Respi. 0-5	(4) Pupils Respi. 0-5
Solar Ownership	-0.502**	-0.481**	-0.260*	-0.404***
	(0.206)	(0.187)	(0.151)	(0.138)
Female	0.190	0.106	0.393***	0.153**
	(0.121)	(0.103)	(0.085)	(0.075)
Observations	1,301	1,260	1,301	1,260
R-squared	0.040	0.020	0.041	0.032
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

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

We find a reduction in symptoms related to dry eye disease of about 0.50 symptoms for adults and 0.48 for children (corresponding to 0.26 and 0.25 standard deviations respectively) and the difference is significant at the 5% level. Children also face 0.40 fewer symptoms related to asthma (significant at the 1% level and corresponding to 0.27 standard deviations), whereby adults reduction of 0.26 symptoms is only significant at the 10% level (corresponding to 1.7 standard deviations). As children are the main users of the solar lights (see section 4.4) it seems plausible that they experience stronger health effects. We also observe that women and girls are overall more likely to experience symptoms related to respiratory illnesses, which makes sense given that they tend to spend more time cooking, and hence are more exposed to indoor air pollution than men. We do not observe differential effects from solar lights on female and male members of the household (regression not shown). While self-reported information about health outcomes are not a perfect measure, and ideally should be complemented by more objective measures or tests, the consistency of the results between adults and children as well as the fact that women indicate more problems, seem to make it plausible that there is an improvement in the subjective well being of respondents.

4.6 Impact on Education

To understand whether solar lighting has an impact on children's education, we first look at their self-reported homework completion, then at the time children spend on homework and on other activities and finally at their test scores. The idea is that better lighting and additional lighting time might allow children to work more and/or under better conditions at home. However there is no consensus about the effect on homework on educational outcomes.

The pupils in all groups reported that they had received homework on 2.6 days in the past week. On average, 30.8% of the children who had received homework during the past week reported that they were not able to complete it once or more. Access to a functioning solar light increased self-reported homework completion by 14.5%-points (this difference is significant at the 1% level). There is no statistically significant difference between boys and girls (table 8). Note, however, that this is purely self-reported information and these results might suffer from social desirability bias.

Table 8: Homework Completion and Time Use

VARIABLES	(1) Home -work Completion	(2) Home -work Completion	(3) Home -work (hours)	(4) Home -work (hours)	(5) School (hours)	(6) School (hours)	(7) Sleep (hours)	(8) Sleep (hours)
Solar Ownership	0.145***	0.156**	0.242	0.438*	0.219	0.383	-0.549***	-0.823***
	(0.049)	(0.071)	(0.173)	(0.259)	(0.168)	(0.257)	(0.195)	(0.307)
Solar Works * Female		-0.021		-0.381		-0.330		0.540
		(0.099)		(0.345)		(0.340)		(0.395)
Pupil Female	-0.021	-0.011	-0.106	0.081	-0.079	0.082	-0.195*	-0.460**
	(0.033)	(0.064)	(0.096)	(0.188)	(0.099)	(0.198)	(0.106)	(0.214)
Observations	643	643	1,173	1,173	1,173	1,173	1,173	1,173
R-squared	0.098	0.098	0.135	0.132	0.707	0.707	0.277	0.278
School FE	YES	YES	YES	YES	YES	YES	YES	YES
Controls	YES	YES			YES	YES	YES	YES
Control Mean	0.692	0.692	2.458	2.458	4.508	4.508	8.077	8.077
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
xxx

Children in all types of households completed the homework after dark most of time. In the control households, children completed their homework after dark 77.9% of the times. Having access to a functioning solar light increased the share of homework completed after dark by 7.7% (significant at the 5% level). Looking at children's time use, the largest effect is on sleeping hours, which reduced by 0.82 hours (or 48.7 minutes). This reduction is significant at the 1% level. There is also a marginally significant increase of 0.44 hours (25.4 minutes) in time boys spent on homework, but the effect disappears once we combine boys with girls (see table 8).

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 during the study and after the study ended (March 2016). Test scores were collected for all tested subjects, namely Math, Swahili, Science, English, and Social Studies. Scores range from 0-100. We were able to receive the test scores for 1,265 pupils for the first term exam held in March 2015 (baseline) and for 1,307 for the last term in 2015 (December). As for the first term in 2016, the field team was only able to collect exam results from 1,072 pupils since 9.7% transferred to other schools and it was often not possible to collect the test scores from these schools. We normalized test scores using the distribution from the control group and report results in standard deviations. We do not see any statistically significant changes in test score for boys or for girls (see table in Appendix). This finding is in line with the previous literature (Furukawa, 2013a; Kudo, Shonchoy & Takahashi, 2016). However, it is 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 or that there are spillovers.

5 Conclusion

Our most important result is that solar lights are used as a substitute for kerosene and thus, reduce kerosene use and related emissions, which has benefits that are, in part, external to the household. This finding is in line with previous studies (Grimm et al. 2016a; Kudo et al. 2016) and has at least two important consequences. First, environmental externalities: kerosene combustion emits a high concentration of Black Carbon, which is around 700 times more warming than CO2. Having a functioning solar light led to a reduction in emissions equivalent to 720 kg of CO2 per household yearly, and if scaled to the whole country could reduce 4.9% of Kenya's CO2 emissions at a cost of less than US $8 per ton of CO2. If scaled globally to all 500 million households who currently use kerosene for lighting (Lam et al. 2013), it would correspond to a decrease of 360,000,000 tons of CO2 equivalent per year, which has a warming effect on the planet that is equivalent to 14.6 % of India's CO2 emissions in 2015. .[16] These benefits are external to the household and hence might justify subsidies. Second, accessing solar lights reduced symptoms related to asthma and dry eyes, 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 infections (Furukawa 2013b; Barron & Torero 2015; Grimm et al. 2016 a). It also corresponds to the findings of Kudo et al. (2017) with regard to eye irritation, however, Kudo et al. (2017) did not find any effects on respiratory symptoms. This discrepancy might come from the fact that households in their sample in Bangladesh typically only have one room, where all activities, including cooking, happen and air quality is so poor that the additional emissions from lighting do not make much of a difference. In our context, in contrast, cooking typically does not happen in the same room as eating, homework, and other activities. In our study, health benefits are most pronounced for children and households might underinvest in solar as children are usually not the financial decision makers in the household (Hoffmann, 2009). In addition to those intra-household allocation issues, households might underinvest in solar due to constraints around information and present biases typically associated with preventative health products (Cohen & Dupas 2010; Dupas 2011).

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[16] Calculations based on information about India's CO2 emissions from Netherlands Environmental Assessment Agency 2016 and are in line with estimates provided by Lam et al. 2013.

Further we show that households who received subsidies do not use the solar lantern less than households who receive them for free and we do not see evidence of a sunk cost or a screening effect.

Another important finding is that the investment in solar lanterns is not as financially beneficial for the consumers as many policy makers and practitioners believe. The amortization period in the absence of subsides is relatively long (9-22 months) and given high interest rates and breakages of over 10%, the investment does not always pay back. In fact, the results of different studies seem to converge on this topic: 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 and an amortization period of purchasing a solar light of around 18 months. Kudo et al. (2016), in their study in Bangladesh, calculate expenditure savings of 3.2% [17], and a pay-back period of 21 months.[18] Given these results, it might not be surprising that take-up is highly sensitive to price changes and does not increase over 45% even when transaction costs are lowered and information about the product is increased.

Together these results suggest that subsidies are likely to increase product take-up and product use, and that they are likely to reduce kerosene use and related emissions, which has health and environmental externalities. Moreover it increase access to some sort of basic modern energy, which for many governments across is an important policy goal. Solar lighting is however also not a panacea to address energy poverty and climate change. Policy makers need to keep in mind that, 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. These small solar products do not allow you to power a sewing machine or a fridge and will not be enough as living standards rise. While children seem to benefit from the light across the board, their impact on educational outcomes are limited and there are way more cost effective policies to improve educational outcomes. Finally, kerosene is also not the only contributor to indoor air pollution, and cookstoves are typically a much more important contributor and while every reduction in warming emissions counts, kerosene lights are only a tiny fraction of what causes human caused climate disruption.

In resource-constrained settings like Kenya, the cost-effectiveness of any policy intervention should be compared to the cost-effectiveness of alternatives to achieve the same (combination of) policy goals. For example, if the goal is to reduce households' kerosene consumption, policy makers in Kenya should also consider abolishing kerosene subsidies or taxing it. If the focus is on providing some access to modern energy, our findings should be compared with studies looking at the impacts of access to other forms of modern energy access. Finally, if it is about indoor air pollution and health, then it should be compared with other policies aimed at the same goal. We hope that future research will explore how these different policy options compare with each other. Moreover, we hope that future studies will look more into health benefits of kerosene reduction by directly measuring indoor air quality and using medical tests rather than self-reporting to measure health outcomes. Ideally, such a study would also include

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

[18] Author's calculation based on information in the paper that products costs 37 USD and average yearly savings are around 21 USD.

cooking, which is typically the most important source of indoor air pollution. Finally, we believe it is important to gain a more nuanced understanding of the effects of prices on use and thus, it would be interesting to design a study similar to Karlan and Zinnman (2009) that allows differentiation between the screening effect and the sunk-cost effect. It would also be interesting to better understand the intra-household dynamics that led children to be more likely to be given priority to use the solar light if it was given out for free.

6 Appendix

7 Bibliography

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