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A First Step up the Energy Ladder?

Low Cost Solar Kits and Household's Welfare in Rural Rwanda

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Abstract

More than 1.1 billion people in developing countries are lacking access to electricity. Based on the assumption that electricity is a prerequisite for human development, the United Nations has proclaimed the goal of providing electricity to all by 2030. In recent years, Pico-Photovoltaic kits have become a low-cost alternative to investment intensive grid electrification. Using a randomized controlled trial, the paper examines uptake and impacts of a simple Pico-Photovoltaic kit that barely exceeds the modern energy benchmark defined by the United Nations. The authors find significant positive effects on household energy expenditures and some indication for effects on health, domestic productivity, and on the environment. Since only parts of these effects are internalized, underinvestment into the technology is likely. In addition, our data show that adoption will be impeded by affordability, suggesting that policy would have to consider more direct promotion strategies such as subsidies or financing schemes to reach the UN goal.

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More than 1.1 billion people in developing countries lack access to electricity. Some 590 million of them live in Africa, where the rural electrification rate is only 14 percent (SE4All 2015). Providing access to electricity is an explicit goal of the sustainable development goals (SDGs) and frequently considered a precondition for economic and social development (UN 2005). Based on such assumptions, the United Nations aims for universal access to electricity by 2030 via its initiative Sustainable Energy for All (SE4All; see also UN 2010). The investment requirements to achieve this target are enormous, estimated by the International Energy Agency (IEA) (2011) to be about 640 billion US Dollars.

In recent years, so-called Pico-Photovoltaic (Pico-PV) kits have become a low-cost alternative to existing electrification technologies thanks to a substantial cost decrease of photovoltaic and battery systems as well as energy saving LED lamps. Different Pico-PV kits exist that provide basic energy services like lighting, mobile phone charging, and radio usage. In the SE4All initiative's multi-tier definition of what is considered as modern energy, the Pico-PV technology constitutes the Tier 1 and thus the first step on the metaphoric energy ladder. Investment costs for Pico-PV kits are far lower than for the provision of on-grid electricity or higher tier PV systems.

This paper investigates usage behavior and the changes in people's living conditions when households make this first step toward modern energy based on a randomized controlled trial (RCT) that we implemented in rural Rwanda. The kit, which we randomly assigned free of charge to 150 out of 300 households in 15 remote villages, consists of a 1 Watt solar panel, a 40 lumen lamp, a telephone charger, and a radio—

and thereby just barely reaches the benchmark of what qualifies as modern energy access in the SE4All framework. The market price of the full Pico-PV kit is at around 30 USD. Our study population is the main target group of the Pico-PV technology, that is, the bottom-of-the-pyramid living in a country's periphery who will not be reached by the electricity grid in the years to come and who will have problems to afford higher tier PV systems.

We investigate the adoption of the Pico-PV kit at both the extensive and the intensive margin. At the extensive margin, we examine whether households actually use the Pico-PV kit. This is not obvious given that we distribute the kit for free and the technology is new for the households. There is an intense debate in the development community about usage intensity of freely distributed goods (see, e.g., Dupas 2014). At the intensive margin, so conditional on households using the kit, we examine the effects of Pico-PV usage on three types of outcomes: energy expenditures, health and environment, and productivity in domestic work. The amplitude of effects heavily depends on usage behavior: is the kit used in addition or as a substitute to traditional lighting sources like kerosene? Which household member uses the kit and for which purposes? Do households expand their activities that require lighting into evening hours, or do they just shift activities from daytime to nighttime? Does the total time awake of household members change? Nonelectrified rural households in Africa are increasingly using LED lamps that run on dry-cell batteries. Since these batteries are not disposed of appropriately and potentially harm the local environment, Pico-PV usage might also induce environmental benefits. We also analyze whether potential

productivity gains in domestic work release time that can now be dedicated to income generating activities.

Our paper complements the seminal work of Furukawa (2014) who studies the effects of Pico-PV lamps on children's learning outcomes in rural Uganda. We extend the scope by examining the effects of Pico-PV kits on various in-house activities of all household members, not only those of school children. We find that households use the kits intensively in spite of the zero price and the novelty of the product. Furthermore, the kit considerably reduces consumption of kerosene, candles, and dry-cell batteries and, in consequence, energy expenditures. The reduction of kerosene improves household air quality and the reduction of dry-cell battery consumption plausibly leads to environmental benefits. Moreover, we find that children shift part of their homework into the evening hours. Primary school boys even increase their total study time. While parts of these effects are clearly internalized benefits, other parts are important externalities, which may provide the cause for public subsidies, in particular if it turns out that households are simply too poor to raise the upfront costs alone.

The role of public policy in the promotion of Pico-PV technology is not defined so far. The expectation of the World Bank's Lighting Global program, for example, as well as other donors is that Pico-PV kits make inroads to African households via commercial markets, implying that end users pay cost-covering prices (see Lighting Global 2016). This might in fact work out for the relatively well-off strata in rural areas but is much more uncertain for the rural poor. In fact, the major target group of Pico-PV kits within

the SE4All endeavor is located beyond the reach of the grid in remoter areas. These households are short on cash, credit constrained, and might have more essential priorities to spend their money on. If these groups in the periphery of the developing world shall be reached by the SE4All initiative, direct subsidies or even a free distribution might be required. This is indeed the policy intervention we mimic in our study. From a welfare economics point of view this would be justified if the usage of Pico-PV kits generates private and social returns that outweigh the investment cost. Our paper provides empirical substance to this debate.

So far, only very little evidence exists on the take-up and impacts of Pico-PV lamps. To our knowledge, the only published study is Furukawa (2014), who concentrates on educational outcomes alone. Furukawa randomized Pico-PV lamps among 155 primary school students in Uganda who at baseline used kerosene wick lamps as the main lighting source at home. Although Furukawa (2014) finds that children's study hours clearly increased among Pico-PV lamp owners, he curiously observes decreasing test scores. Furukawa tests different explanations of this "unexpected result". Without having the data at hand to obtain a robust answer, he hypothesizes that the low power of the lamps and the inadequate recharging behavior could have led to flickering light, which eventually worsened studying conditions. Based on this experience, we will therefore carefully check the lighting quality and users' satisfaction in our experiment.

Much more evidence exists on the socioeconomic effects of classical rural electrification programs using higher tier technologies, mostly the extension of the

electricity grid. These interventions differ from our randomized solar kit to the extent that much higher effect sizes can be expected, but also much higher costs are incurred. Nonetheless, this literature constitutes an important background of our work, in particular those studies that explore the effects of electricity usage on similar outcomes. Van de Walle et al. (2016) for instance find that in rural India electrification led to a significant increase in households' expenditures. For the case of a grid extension program in El Salvador, Barron and Torero (2014, 2015) find reductions in kerosene consumption, in particulate matter exposure, and respiratory disease prevalence as well as an increase in study hours among children. The latter finding is confirmed in a grid extension program in Bangladesh (Khandker et al. 2012) but not in a previous study in Rwanda on the effects of mini-grid electrification (Bensch et al. 2011). For South Africa and Nicaragua, respectively, Dinkelman (2011) and Grogan and Sadanand (2013) provide evidence that the use of electricity saves women's time in household chores and leads to increased labor supply of women.[1]

In SE4All's multi-tier framework solar home systems are the intermediate step between Pico-PV and grid electricity. Samad et al. (2013) evaluate a solar home system program in Bangladesh and find increases in evening study hours of school children, TV usage, and female decision-making power. They also find reduced kerosene consumption and some moderate evidence for positive health effects. Bensch et al.

[1] Further studies exist that examine whether on-grid rural electrification programs can spur income generation and economic growth (see, e.g., Bensch et al. 2011; Dinkelman 2011; Bernard 2012; Khandker et al. 2012, 2013; Grogan and Sadanand 2013; Lipscom et al. 2013; Barron and Torero 2014; Lenz et al. 2016; Peters and Sievert 2016). As discussed above, we do not expect the Pico-PV systems to affect such outcomes.

(2013) confirm positive effects of solar home system usage on children's studying hours in Senegal.

It is the aim of our paper to extend the scope of this literature to the bottom step of the energy ladder. Hence, these findings are important to classify our observations, although of course the cost-related and technological differences between on-grid electricity, 50 Watt solar home systems and our 1 Watt Pico-PV kit have to be borne in mind.

The remainder of the paper is organized as follows: Section I gives the policy and country background. Section II provides theoretical considerations that will guide our empirical analysis. Section III presents our experimental design. Section IV discusses all results, and Section V concludes.

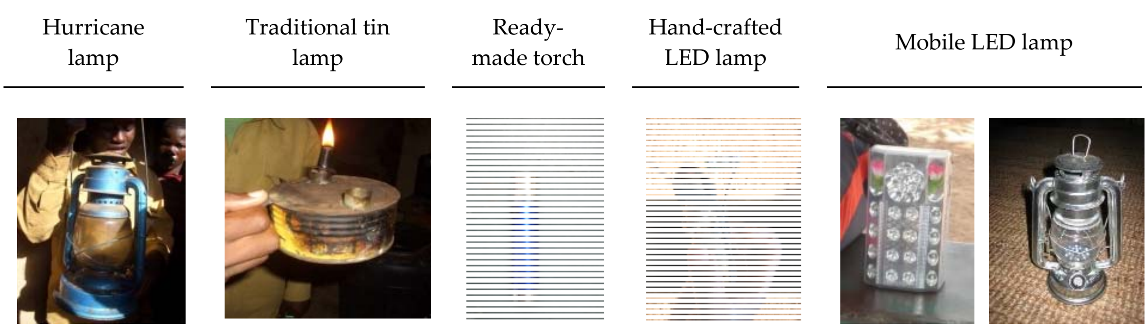
Background

Policy Background

In the absence of electricity, people in rural Sub-Saharan Africa light their homes using traditional lighting sources—candles or kerosene driven wick lamps and hurricane lamps. In recent years, dry-cell battery driven LED-lamps have become available in almost every rural shop and are increasingly used (see Bensch et al. 2015). The most common ones are small LED-torches and mobile LED-lamps that exist in various versions (see Figure 1). In addition, many rural households use hand-crafted LED lamps, that is, LED-lamps that are removed from torches and installed somewhere in

the house or on a stick that can be carried around. For rural households in Africa, expenditures for both traditional lighting sources and dry-cell batteries constitute a considerable part of their total expenditures. In very remote and poor areas, people who are cash constrained generally use very little artificial lighting and sometimes even only resort to the lighting that the cooking fire emits. For this stratum, the day inevitably ends after sunset.

Figure 1: Traditional lighting devices



Source: Own illustration

Obviously, this lighting constraint restricts people in many regards. Activities after nightfall are literally expensive but also difficult and tiring because of the low quality of the lighting (see Section II for more information on lighting quality). At the same time, it becomes evident that modern energy is not a binary situation. Rather, there are several steps between a candle and an incandescent light bulb.

This continuum has sometimes been referred to as the *energy ladder*. In fact, SE4All has defined different tiers of modern energy access within its Global Tracking Framework (SE4All 2013) according to the electricity supply that is made available. For example,

a regular connection to the national grid qualifies as Tier 3, because it allows for using general lighting, a television, and a fan the whole day. A solar home system would qualify for Tier 1 or 2 (depending on its capacity). Tier 1 requires having access to a peak capacity of at least 1 Watt and basic energy services comprising a task light and a radio or a phone charger for four hours per day. The spread between the service qualities of the different tiers is also reflected in the required investment costs: the retail price of the Pico-PV kit used in this study is at around 30 USD. The World Bank (2009) estimates a cost range for on-grid electrification in rural areas of 730 to 1450 USD per connection.[2]

The promotion of Pico-PV kits is most prominently pursued by the World Bank program *Lighting Global.* Based on the assumption that the market for Pico-PV systems is threatened by a lack of information and information asymmetries, it provides technical assistance to governments, conducts market research, facilitates access to finance to market players, and has introduced a quality certificate for Pico-PV systems. The objective of Lighting Global's initiative in the region, *Lighting Africa*, is to provide access to certificated Pico-PV kits to 250 million people by 2030. The Pico-PV lantern and the panel used for the present study were certified by Lighting Africa.[3]

[2] The investment requirements calculated by IEA (2011) of additional 640 billion USD to achieve universal access to electricity are based on electricity connections that provide a minimum level of electricity of 250 kWh per year. This roughly corresponds to a Tier 2 electricity source.

[3] At the point of the Pico-PV kit's certification, Lighting Africa did not yet issue certificates for mobile phone charging and other services.

Country Background

Rwanda's energy sector is undergoing an extensive transition with access to electricity playing a dominating role. The Government of Rwanda's goal is to increase the electrification rate to 70 percent of the population by 2017/2018 and to full coverage by 2020. The key policy instrument clearly is the huge Electricity Access Roll-Out Program (EARP) that since 2009 quintuplicated the national connection rate to 24 percent country wide. Three further programs exist that have not been implemented so far, though. First, the Government plans to establish a mechanism to provide the poorest households (categorized as Ubudehe 1 according to the national poverty scale) with a basic solar system corresponding to Tier 1 electricity access. Second, a risk mitigation facility shall be established to encourage the private sector to increase sales of solar products and services. Third, mini-grids shall be developed by the private sector (MININFRA 2016). These programs are complemented by the so-called *Bye Bye Agatadowa* initiative that aims at eliminating kerosene lamps completely from the country.

In the absence of public promotion schemes, few private firms that sell Lighting Africa verified Pico-PV kits were active in the country at the time of the study implementation. They operate mostly in the Rwandan capital Kigali and other cities. In rural areas, Pico-PV kits are sometimes available, but their retail price is much higher compared to lower quality dry-cell battery driven LED-lamps that can be bought in rural shops all over the country. These devices are not quality verified, but

cost only between 500 FRW (0.82 USD[4]) for hand-crafted LED lamps and 3000 FRW (4.95 USD) for an LED hurricane lamp. The battery costs to run an LED hurricane lamp for one hour are around 0.01 USD. This is cheaper than running a kerosene driven wick lamp (around 0.03 USD per hour) and the lighting quality is slightly better, which is why many households are now using such ready-made or hand-crafted LED-lamps. Compared to both battery-driven LED lamps and kerosene lamps, Pico-PV kits provide higher quality lighting (depending on the number of LED diodes) at zero operating costs. Assuming that a household uses the lamp for four hours per day, the investment into the Pico-PV lamp used for this study amortizes after 10 months if a ready-made LED lamp is replaced and after less than 5 months if it replaces a kerosene wick lamp.

Theoretical Considerations

Based on the literature on rural electrification presented in the Introduction, we assume that the Pico-PV treatment affects three dimensions of living conditions: First, the *budget effect* which arises because households with access to a Pico-PV kit experience a change in the price of energy, while no (substantial) investment costs occur as long as we assume that the Pico-PV treatment is subsidized or distributed for free. Second, *health and environmental effects* occur whenever Pico-PV kits replace kerosene lamps, candles, and dry-cell batteries. A decrease in kerosene and candles

[4] Exchange rate as of November 2011: 1 USD = 607 FRW.

consumption reduces household air pollution with potential effects on health (see Lam et al. 2012; WHO 2016). Environmental benefits arise due to inappropriate dry-cell battery disposal (see Bensch et. al 2015) that is reduced if dry-cell battery consumption goes down. Third, we analyze the productivity of domestic production, that is, production not intended to be traded on competitive markets. This we refer to as *domestic productivity* effect in what follows. The reason for only focusing on domestic production is that income in such remote rural areas is virtually only generated by subsistence agriculture. The Pico-PV kit, in turn, is too small to affect agricultural production. For non-agricultural products, access to markets is very limited and, hence, local nonagricultural labor markets are nonexistent. At baseline, only seven percent of head of household's main occupation and one percent of spouse's main occupation was a non-agricultural activity. Yet, since in theory the Pico-PV kit could liberate time from domestic labor and extend the time awake of household members, we examine at least the time dedicated to any income generating activity (agricultural and nonagricultural activities). Labor demand in such rural regions is too low, though, to absorb increases in labor supply, and therefore measurable effects on nonagricultural income cannot be expected.

The mechanism leading to the budget and health and environmental effects are quite intuitive, whereas the transmission channel for the domestic productivity effect might be less obvious. Productive activities at home include cooking, cleaning, and making and repairing of household goods as well as studying and charging a cell phone. Since the visual performance of humans strongly increases with the lighting level (Brainard

et al. 2001), we assume that the productivity in performing these activities increases with the quantity and quality of light. Productivity in fine assembly work for instance has been shown to increase by 28 percent as the lighting level increases from 500 to 1500 lumen (lm) (Lange 1999). But even increasing the lighting level from much lower levels comes with significant productivity effects. Evidence comes for instance from weaving mills (Lange 1999).[5] The literature attributes good quality lighting to devices that provide sufficient, nonglaring, nonflickering and uniform light, balanced luminous distribution throughout the room, good color rendering and appropriate light color (Lange 1999). Along all these criteria, the Pico-PV kits perform better than other traditional lighting devices such as kerosene lamps and candles, but also compared to smaller hand-crafted LED lamps. Our Pico-PV lamp emits 40 lm, while a candle only emits around 12 lm, a hurricane lamp used at full capacity around 32 lm and large mobile LED lamps can reach levels around 100 lm (O'Sullivan and Barnes 2006). The LED lamps used in poor and remote areas are less luminous, though. Lumen levels emitted by hand-crafted LED lamps vary substantially depending on the number and quality of diodes and batteries used. Two to three diode-lamps connected to a battery package emit about 10 lm.[6]

[5] More evidence exists also on softer impacts such as a positive linkage between lighting and work mood (Kuller and Wetterberg 1993; Boyce et al. 1997; Partonen and Lönnqvist 2000), fatigue (Daurat et al. 1993; Grunberger et al. 1993; Begemann et al. 1997), and eye strain and headache (Wilkins et al. 1989, Kuller and Laike 1998) that can be assumed to improve working performance. For a detailed presentation of the evidence for productivity effects associated with light, see the supplemental appendix.

[6] Since lumen numbers for these hand-crafted lamps do not exist, we tested the two most widely used structures (a two diode-lamp and a three diode-lamp structure) in a laboratory at University of Ulm, Germany, using standard lumen emission test procedures. According to these tests, the level of emitted lumens by hand-crafted LED lamps is at around 10 lm.

One additional effect associated with a possible increase in radio usage is better access to information, which in turn may have productivity effects if the information relates to market data or can affect norms, such as gender norms for instance, and preferences (Bertrand et al. 2006; Jensen and Oster 2009; La Ferrara et al. 2012; Sievert 2015). Although we analyze whether radios are used with the Pico-PV kit and display radio ownership and usage in the supplemental appendix (see Appendix S5), we do not further investigate any of these effects as most households use the Pico-PV kit only for lighting.

Research Approach and Data

Our identification strategy relies on the randomized assignment of Pico-PV kits after the baseline survey. The intention-to-treat effect (ITT) in our case is almost identical to the average treatment effect on the treated (ATT) because of the high compliance rate in the treatment group and no treatment contamination in the control group. Since all results are robust with regard to both ways of estimating impacts, we show only the more conservative ITT results.

Treatment

The randomized kits include a 1 Watt panel, a rechargeable 4-LED-diodes lamp (40 lumen maximum) including an installed battery, a mobile phone charger, a radio including a charger, and a back-up battery package (see Figure 2)**Error! Reference**

source not found..[7] There are different options to use the panel. First, it can be used to directly charge the lamp's battery. After one day of solar charging it is fully charged. The lamp can be used in three dimming levels and—fully charged—provides lighting for between 6 and 30 hours depending on the chosen intensity level. Second, the kit can be connected directly to the mobile phone connector plug and the radio connector to charge mobile phones or the radio. Third, the kit can be used to charge the back-up battery package that can then be used to charge the other devices without sunlight. The complete kit costs around 30 USD, the smallest version with only the solar panel and an LED lamp including an installed battery costs around 16.50 USD.

Figure 2: The Pico-PV kit

Source: Own illustration

Impact Indicators

As a precondition for the three effects on budget, health, and environment, and domestic productivity the households' usage behavior is our first matter of interest. We look at usage and charging patterns of the Pico-PV kit and analyze which of the

[7] The kit used in our experiment provides more energy services than the solar lantern used by Furukawa (2014), but the panel is also twice as large (1 Watt compared to 0.5 Watt).

different energy services—lighting, radio operation, and mobile phone charging—households use most. Since the kit is mostly used for lighting (see below), we focus in particular on this service.

For budget effects, we first look at changes in the price of the energy service. We calculate the *price per lighting hour* and *price per lumen hour* the households effectively pay. Second, we analyze whether price effects translate into a change in lighting consumption. Here, we look at the average amount of *lighting hours consumed per day* and *lumen hours consumed per day*. Lighting hours are calculated as the sum of usage time of all lamps used during a typical day (including candles and ready-made torches). The price per lighting hour is calculated by dividing expenditures on lighting fuels by the number of lighting hours consumed. For calculating lumen hours, we multiply the lamp specific lighting hours with the amount of lumen emitted per lamp.

Finally, we look at changes in *total energy expenditures* and in the expenditures for the different energy sources kerosene, batteries, and candles.

For health and environmental effects, we first explore reductions in kerosene and candle consumption and to what extent this leads to a perceived improvement of *air quality*, measured by the subjective assessment of the respondents. Also for measuring the household members' health status, we rely on self-reported information on whether any household member suffers from *respiratory diseases* and *eye problems*. We distinguish between male and female adults as well as primary, and secondary school children. We did not measure air quality or undertake any medical exams. For environmental effects, we analyze reductions in *dry-cell battery consumption* and the

way how households *dispose of dry-cell batteries.*

In order to investigate domestic productivity effects, we look at the main users' domestic labor activities exercised when using the Pico-PV lamp. The main domestic labor activity for adults is housework; children use the lamp mainly for studying. We assess the increase of domestic productivity by analyzing the *lighting source used* for these respective activities. Based on the evidence from the literature presented in Section II and the supplemental appendix, we assume that households become more productive when they switch from a lower quality lighting source or no artificial lighting to the Pico-PV lamp. This seems reasonable since even at day time, the typical dwelling in rural Rwanda is quite dark. Windows are small in order to keep the rain and the heat out of the inner of the dwelling. To analyze lamp switching, we enumerated all lamps in each household interview and asked respondents to name all users for each lamp and the respective purpose of using it. The information on time spent on different activities was elicited in the interviews through an activity profile for each household member. If a certain activity pursued by the household is not associated with one of the employed lamps, we assume that no specific lighting device is used for this activity, and it is either exercised using daylight, or using indirect lighting from the fireplace or lamps used for other household tasks.

In order to analyze whether the higher productivity also leads to an increase in total domestic labor input, we analyze the total amount of *time dedicated to domestic labor per day*. We furthermore examine whether *total time household members are awake* changes due to increased lighting availability and whether *time dedicated to income generating*

activities changes as a result of time savings in domestic production.

RCT Implementation

The key facts of the implementation are presented in Table 1. A detailed description of the implementation including a map of the survey area and a figure illustrating the participant flow can be found in the supplemental appendix. A discussion of the external validity of our results is also presented in the supplemental appendix.

Table 1. Key Facts on RCT Implementation

Baseline survey	November 2011
Delivery of Pico-PV kits	December 2011
Follow-up survey	June 2012
Study population	15 nonadjoined communities in four rural districts of Rwanda located in the Northern, Western and Southern Province.
	No Pico-PV kits available on the market
	~5.5 hours of sunlight per day (which is similar to country average)
Sample	300 randomly sampled households
Randomization	Stratified randomization and additional re-randomization using minmax t-stat method at the household level; random assignment of 150 Pico-PV kits
Stratification criteria	Consumed lighting hours per day, usage of mobile phones (binary), radio usage (binary), and district
Re-randomization	Balancing criteria are marked in The surveyed households are mainly subsistence farmers that live in very modest conditions. The educational level of the head of household is low and households own

only a few durable consumption goods. The households in our sample have cash expenditures of on average 0.45 USD (1.12 USD PPP) a day per person with the lower 25%-stratum having only 0.07 USD (0.18 USD PPP). Even the upper quartile has cash expenditures of 1.14 USD (2.86 USD PPP) only. By any standard, the sampled households qualify as extremely poor.

Also energy consumption patterns illustrate the precarious situation of most households (see

Table 3). They consume on average only around three hours of artificial lighting per day which is mainly provided through kerosene wick lamps or battery-driven small hand-crafted LED lamps. Around 11 percent of households even do not use any artificial lighting devices and rely only on lighting from the fireplace after nightfall. For the baseline values, we calculate lighting hours as the sum of lighting usage per day across all used lamps, excluding candles and torches, for which we did not elicit usage hours at the baseline stage. Almost 65 percent of the household own a radio, around 40 percent have a cell phone.

Table 2 and

Table 3

Compensation for control households	One bottle of palm oil and a 5 kg sack of rice worth around 7 USD
Attrition rate	< 1%
Compliance rate	87% (18 households declared their Pico-PV kit to be sold, lost or stolen; One household received kit only during follow-up)

Source: Household data set 2011/2012.

Results

Balance of Socioeconomic Characteristics of Participating Households

This section examines the balancing between treatment and control group and, at the same time, portrays the socioeconomic conditions in the study areas. Baseline values of the households' socioeconomic characteristics show that the randomization process was successful in producing two balanced groups (see The surveyed households are mainly subsistence farmers that live in very modest conditions. The educational level of the head of household is low and households own only a few durable consumption goods. The households in our sample have cash expenditures of on average 0.45 USD (1.12 USD PPP) a day per person with the lower 25%-stratum having only 0.07 USD (0.18 USD PPP). Even the upper quartile has cash expenditures of 1.14 USD (2.86 USD PPP) only. By any standard, the sampled households qualify as extremely poor.

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Table 2. Balance of Socioeconomic Characteristics between Treatment and Control Group (Baseline Values)

	Treatment		Control	*t*-test/chi-2-test (total treated vs. control *p*-values)
	total (SD)	noncompliant (SD)	total (SD)	
Household size [1]	4.85 (2.0)	5.5 (1.5)	5.0 (2.0)	.491
HH's composition (%)				
Share children 0–15 years	39 (24)	51 (16)	38 (23)	.680
Share elderly 65+	7 (20)	2 (6)	5 (16)	.389
HH's head male (%)	76	84	76	.892
Age of the HH's head	47 (15)	45 (17)	48 (15)	.795
Education of HH head (%) [1]				
None	35	53	35	.857
Primary education	61	42	60	
Secondary education and more	4	5	5	
Cultivation of arable land (%) [1]	99	100	98	.314
Ownership of arable land (%) [1]	95	90	95	.791
Ownership of cows (%) [1]				
No cow	63	84	69	.542
One cow	22	11	19	
More than one cow	15	5	12	
Ownership of goats (%) [1]				
No goat	68	79	74	.476
One goat	16	5	12	
More than one goat	16	16	11	
Material of the walls (%) [1]				
Higher value than wood, mud, or clay	14	11	14	1.000
Material of the floor (%) [1]				
Higher value than earth or dung	12	5	11	.854
District (%) [2]				
Gicumbi	19	16	20	.997
Gisagara	26	32	27	
Huye	28	26	27	
Rusizi	27	26	26	

Number of observations	148	19	148	

Note: [1] Used for re-randomization; [2] used for stratification.

Source: Household data set 2011.

If we look at the small group of non-compliers, who declared their kit to be sold, lost or stolen, we see that they are generally poorer than complying households: They have more children, own less land, have less cows and goats, and have less radios and cell phones.

Table 3. Balance of Outcome Related Characteristic between Treatment and Control Group (Baseline Values)

	Treatment		Control	*t*-test/chi-2-test
	total (SD)	non-compliant (SD)	total (SD)	(total treated vs. control *p*-values)
Lighting hours, categorized (%) [2]				
No lamps or candles	19	26	19	
Less or equal 3h/day	51	42	51	
More than 3h/day	30	32	30	1.000
Lighting hours per day, continuous[1]	3.1	2.7	3.2	.910
Usage of hand-crafted LED[1] (%)	37	26	35	.628
Usage of mobile LED[1] (%)	4	5	3	.520
Consumption of candles[1] (pieces per month)	1.25	2.32	1.76	.356
Usage of wick lamps (%)	49	47	47	.727
Usage of no artificial lighting (%)	12	16	11	.715
Consumption of kerosene for lighting [1] (in liter per month)	.46	.35	.54	.372
Radio ownership [2] (%)	64	32	64	1.000
Mobile phone ownership [2] (%)	36	32	36	1.000
Number of mobile phones [1]	.49	.21	.47	.876
Number of observations	148	19	148	

Note: [1] used for re-randomization; [2] used for stratification.

Source: Household data set 2011.

Impact Assessment

Take-Up and Lighting Usage

Among the 131 households that still have a Pico-PV kit when interviewed in the follow-up survey, usage rates are very high (see Table 4). In sum, 86 percent use the kit at least once per day, primarily for lighting. Radio and especially cell phone charging usage rates are rather low. Most households report that both the radio and the cell phone charger were very difficult to use with the kit, which was confirmed by technical inspectors involved in testing the kit for Lighting Africa. The major reason for this seems to be the low capacity of the panel, which only allows for charging all devices completely within one day if the daily sunlight is exploited at a maximum. In practice, households used the charging capacities mainly for the lighting device. Given this preference for lighting, too little capacity is left for the other two services. For cell phone charging, noncompatibility of the solar charger with some of the widely used cell phone types in rural Rwanda posed additional problems. In line with these technical deficiencies and the households' expressed priorities for lighting, charging patterns are dominated by the lamp: most of the time, the kit is used to charge the lamp (26 hours per week), followed by operating the radio (20 hours). It is hardly used to charge a cell phone (only two hours[8]).

Due to the technical drawbacks of the Pico-PV kit, we will concentrate in the following on effects related to the usage of improved lighting service. Virtually all kit owning

[8] The share of households using the kit for cell phone charging is very low at less than ten percent. Those households that do charge their phone with the kit charge it 19 hours per week.

households predominantly use it for lighting.[9] Some details on radio usage, preferred programs and other information sources are shown in the supplemental appendix.[10] The Pico-PV lamps are mainly used by female adults, followed by male adults (see Table 4). Children use the lamps less frequently.

Traditional lamp usage goes down substantially, with 47 percent of the treatment group using exclusively the Pico-PV lamp for lighting purposes.[11] While treatment group households use on average 0.8 traditional lamps (any type, including candles), control group households use 1.4 traditional lamps implying that the Pico-PV lamps have replaced half of the traditional lighting sources. Treatment households use above all significantly less wick lamps and hand-crafted LED lamps, but also less ready-made torches, hurricane lamps, and mobile LED lamps. The share of households that do not use any artificial lighting source, amounting to nine percent in the control group, still reaches five percent among treatment households. They either belong to the group of non-compliers or to the households with technical problems with the Pico-PV lamp.

Table 4. Usage of Pico-PV Kits (Share of Treatment Households in Percent)

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[9] The only exceptions are four households that reported to have technical problems with the lamp and cannot use it for this reason.

[10] It can be seen that radio usage significantly increased in the treatment group, on average and across all types of household members. Adults listen above all to news on the radio, while children listen to music. Consequently, radio is substantially more often the main source of information for treatment households. In the control group community gatherings constitute typically a more important source of information.

[11] Table S6.1 in the supplemental appendix shows a comprehensive presentation of lamp usage in the treatment and the control group.

Share of treatment households… (in parentheses: only compliant households)	%	**Pico-PV lamp is mainly used by…**	%
using the kit at least once a day	86 (95)	Female adult >17 years old	49
…using the kit for lighting	85 (97)	Male adult >17 years old	23
…using the kit for listening to the radio	68 (79)	Female between 12 and 17 years old	10
…using the kit for charging mobile phones	10 (11)	Male between 12 and 17 years old	7
…use the battery pack	65 (71)	Collectively used by whole family	6
		Children between six and 11 years old	5

Source: Household data set 2012.

Most lamp users are satisfied with the lighting quality of the lamp. More than 70 percent of all lamp users report they are "always" or "often" satisfied with the lighting quality. Only 22 percent report to be satisfied only seldom and six percent are never satisfied. Satisfaction levels with traditional lamps are substantially lower. For wick lamps and hand-crafted LED lamps, 94 percent and 91 percent, respectively, report to be satisfied seldom or never.

Since both treatment and control households are located within the same communities, spill-over effects might occur. Especially children often meet and play with friends and there might be positive spill-over effects on other households' children. If among these 'other' households are households from our control group, it may even downward bias our impact estimates. Yet we did not find any evidence for spill-overs. For instance, in the control group the share of children studying outside their home did not increase and is negligible at less than one percent. More generally, the qualitative interviews we conducted did not provide any indication for joint activities using the kits and hence spill-overs of that sort.

Budget Effects and Kerosene Consumption

Looking at the *price per consumed lighting hour* and the *price per consumed lumen hour* (Table 5), households in the control group pay approximately five times as much per lighting hour as households in the treatment group (950 FRW vs. 180 FRW; 1.56 USD vs. 0.30 USD). The difference is obviously even more pronounced for the price per lumen hour: A household in the control group pays seven times more per lumen hour than a household in the treatment group (70 FRW vs. 9 FRW; 0.12 USD vs. 0.02 USD).

This reduction in lighting costs effectively translates into a strong increase in the amount of *lumen hours consumed per day* in treated households, which is more than two times as high as in control-group households (see Table 5)—reflecting the very poor lighting quality of traditional lighting sources. Yet, also without accounting for the improved quality of lighting, the Pico-PV kit leads to an increase in lighting consumption. The amount of *lighting hours consumed per day* is significantly higher in the treatment group after having received the Pico-PV lamp.

Table 5. Price and Consumption of Lighting Energy

	Treatment	Control	*ITT*	*p*-value
Cost per lighting hour (in FRW per 100 hours)	176	950	*-702*	.000
Cost per lumen hour (in FRW per 100 hours)	9	70	*-57*	.000
Lighting hours consumed per day	4.43	3.85	*0.59*	.074
Lumen hours consumed per day	142	61	*78*	.000

Note: The ITT depicts the difference in means at the follow-up stage between the whole treatment and control group, including also non-complying households. We control for all stratification and re-randomization characteristics.

Detailed estimation results can be found in the supplemental appendix. Exchange rate as of November 2011: 1 USD = 607 FRW.

Source: Household data set 2011/2012.

Looking at *total energy expenditure* (Table 6. Expenditures per Month per Category (in FRW)

	Treatment	Control	*ITT*	*p*-value
Candles	42	109	*-20*	.339
Kerosene for lighting	155	609	*-418*	.000
Big batteries (Type D)	358	352	*-9*	.750
Small batteries (Type AA)	30	72	*-43*	.003
Mobile phone charging	407	520	*-68*	.407
Total traditional energy sources (without cooking energy)	993	1,662	*-557*	.000
Total expenditures	37,971	31,334	*7,249*	.276
Share of energy expenditure on total expenditures	0.04	0.07	*-0.03*	.001

Note: The ITT depicts the difference in means at the follow-up stage between the whole treatment and control group, including also non-complying households. We control for all stratification and re-randomization characteristics. Detailed estimation results can be found in the supplemental appendix. Exchange rate as of November 2011: 1 USD = 607 FRW).

Source: Household data set 2011/2012.

As a consequence, we observe a significant reduction in expenditures for small batteries, but not for the larger batteries since households use their Pico-PV kit predominantly for lighting but only very seldom to run their radio. The consumption of candles is also significantly reduced. In addition, we find a moderate reduction in expenditures on cell phone charging, although the difference is not significant. Estimating an ATT only among mobile phone users by employing the random treatment assignment as an instrument shows a statistically significant reduction of costs for phone charging of 1,662 FRW (2.74 USD). The average household that pays

for charging the mobile phone pays 1,400 FRW per month (2.31 USD).

In total, energy expenditures without cooking energy are 557 FRW (0.92 USD PPP) lower in the treatment group. This difference is statistically significant. If we compare this to the total household expenditures it shows the importance of energy expenditures for the household budget: The share of energy expenditures without cooking decreases by three percentage points from seven percent to four percent.

), we observe that households spend around five percent of their overall expenditures on kerosene, candles, and dry-cell batteries. In treated households we expect a significant decrease of expenditures for kerosene, candles and dry-cell batteries. In fact, we observe a significant and considerable drop of kerosene expenditures by almost 70 percent. Two types of dry-cell batteries are used in our sample, big (Type D) and small (Type AA) batteries. While more than 90 percent of small batteries are used for lighting, more than three-fourths of big batteries are used for radios.

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[12] This difference seems not to be driven by the treatment. The (nonsignificant) difference in total expenditures had already existed at baseline. Moreover, the different subcategories of expenditures do not show any significant changes over time neither.

Health and Environmental Effects

The combustion of kerosene is associated with harmful emissions that can lead to respiratory diseases (WHO 2016). Although the relative contribution of kerosene lamps to household air pollution is rather low compared to firewood and charcoal usage for cooking purposes, it is the immediate exposure of people sitting next to a wick lamp for a specific task (e.g., studying), that makes kerosene a substantial health threat (Lam et al. 2012).

Indeed, in our sample kerosene lamps are above all used by children for studying and by women for cooking. In qualitative in-depth interviews preceding the baseline survey many households complained about sooty kerosene lamps leading to recurring eye problems and kids having black nasal mucus. We therefore examined the extent to which the decrease in kerosene lamp usage translates into a perceived improvement of *air quality* and, potentially, into a decrease in *respiratory disease symptoms* and *eye problems*. At the baseline stage the judgement of most households (around 67 percent in both groups) was that air quality in their houses was good, in the follow-up survey 45 percent of treated households and only three percent of control households say that the air quality in their homes has improved in comparison to the baseline period. In an open question, virtually all treated households ascribe this improvement to the Pico-PV lamp. Looking at self-reported health indicators, though, we cannot confirm that this improved air quality leads to a better health status of the household members, which is not surprising given that cooking fuels are still the dominating source of

household air pollution.[13]

Households in nonelectrified areas in Africa are increasingly using dry-cell batteries and LED lamps to light their homes. Therefore, a potential reduction in dry-cell batteries deserves special attention because they might contain harmful materials and a proper collection system does not exist. In fact, in our sample 95 percent of households throw discharged batteries into their pit latrines, that is, nonsealed 3–4 meter holes in their backyard. Two percent of the households collect them with their garbage, and three percent throw them away somewhere in their backyard. Hence, potentially toxic substances can be expected to enter the groundwater. The extent to which this poses a threat to people's health is unclear, as little is known about this process, neither in Rwanda nor elsewhere (see also Bensch et al. 2015).

Domestic Productivity Effects

Building on the substantial usage of the Pico-PV lamp we examine the extent to which this induces a potential gain in domestic productivity. For this purpose, we look at the main users' activities exercised when using the Pico-PV lamp and—in order to assess the extent of the quality improvement—which lighting sources are used among households in the control group for the respective activity.

The most frequent users of the Pico-PV lamp are female adults, of which 87 percent use the lamp mainly for housework (see Table 7). Housework done by women refers

[13] See supplemental appendix, Table S6.2, for more detailed results.

above all to cooking but also includes, for example, child caring, preparing the beds before going to sleep, and repairing clothes. The Pico-PV lamp replaces above all wick lamps and is used by female adults that had not been using any particular lighting device before.[14] Male adults also use the lamp mostly for housework, although these are more diverse activities than for women. For male adults, the Pico-PV lamp replaces wick lamps, ready-made torches, and hand-crafted LEDs and is also used by men who had not used any artificial lighting device before for housework activities.

Table 7. Activity Using Pico-PV Lamp, Adults and Children in Treatment Households (%)

		First Activity		**Second Activity**		**Third Activity**	
Female adult >17 years old	N=149	Housework	87	Study	5	Eat	4
Male adult >17 years old	N=60	Housework	71	Recreation	10	Study	10
Children 6 to 17 years old	N=56	Study	75	Housework	16	Recreation	4

Note: Information on activities stem from an open question among treatment households at follow-up, asking for the main activities the different lamp users are exercising while using the lamp.

Source: Household data set 2011/2012.

Table 8 shows that housework is done primarily during daytime, also in the treatment group, and the total *time dedicated to domestic* work per day does not change significantly. The *total time household members are awake* per day does not change significantly, either. This reveals that the Pico-PV lamp is also used during daytime for housework activities, which is in line with observations made during qualitative

[14] We analyse lamp switching by comparing lamps used for the corresponding activities by treatment and control households. Detailed results of the analysis can be found in the supplemental appendix, Table S6.3.

interviews: the typical Rwandan dwelling is quite dark even during the daytime and people sometimes use artificial lighting in their homes. To the extent the Pico-PV lamp replaces a traditional lighting source for their daytime housework activity, lighting quality clearly improves. Yet, people might also relocate outside activities indoors and replace natural daylight by the Pico-PV lamp. In this case, lighting quality would probably not improve, but still it demonstrates the higher flexibility people have in organizing their daily tasks.

Table 8. Daily Time Awake, Time Spent on Domestic Labor and Any Income Generating Activity

	Treatment	Control	*ITT*	*p*-value
Time awake				
Head of household	14h28	14h27	*0h05*	.739
Spouse	14h46	14h36	*0h11*	.378
Domestic labor				
Head of household, total	2h08	2h10	*-0h01*	.950
Head of household, after nightfall	0h16	0h12	*0h04*	.542
Spouse, total	2h48	2h30	*0h16*	.333
Spouse, after nightfall	0h32	0h31	*0h02*	.779
Any income generating activity of subsistence farmers				
Head of household, total	5h37	5h29	*0h21*	.215
Head of household, after nightfall	0h01	0h01	*0h00*	.823
Spouse, total	5h37	5h25	*0h10*	.354
Spouse, after nightfall	0h00	0h01	*0h00*	.462

Note: The ITT depicts the difference in means at the follow-up stage between the whole treatment and control group,

including also non-complying households. We control for stratum dummies and re-randomization characteristics. Detailed estimation results can be found in the supplemental appendix.

Source: Household data set 2011/2012.

Moreover, Table 8 probes into the question whether *time dedicated to any income generating* activity increases, which might happen because the higher domestic productivity could set free time for other purposes. We concentrate our analysis on subsistence farmers that constitute 86 percent of household heads and 85 percent of spouses at baseline.[15] Both the head of household and the spouse slightly increase the time they dedicate to income generation (by six and three percent, respectively), but this difference is not statistically significant.

The third most important user group are children between six and 17 years. They use the Pico-PV lamp mainly for studying (see Table 7). In order to understand changes in the productivity of studying at home, we first need to analyze children's study patterns and how they divide their study time between daylight time and evening.

As can be seen in Table 9, in around one-third of the households with children at school age, children do not study after school. There is no significant difference between households in the control and treatment groups. The share of children studying after

[15] We distinguish as income generating activities between subsistence farmers, governmental employees, independent occupations, and other dependent occupations. The group sizes of the latter three are small at n=2, n=1, and n=2 for spouses and n=4, n=11, and n=9 for head of households. Therefore, these groups are very unbalanced across treatment and control households at baseline (see Table S6.4 in the supplemental appendix). When estimating effects on time dedicated to income generation including these occupation groups, we find a significant postive effect for overall income generation time for spouses. This difference is driven, however, by these non-balanced sub-groups and can thus not be interpreted as an effect.

nightfall, though, is significantly higher in the treated group. The total study time, that is, after nightfall and during daytime, increases only for male primary school children. Female primary school children just shift their study time from afternoon hours to the evening leading to an increase in study time after nightfall. For secondary school children we do not observe any significant changes. Hence, the Pico-PV kits benefit primarily younger children. Besides the increase of total study time for primary school boys, it seems to increase the flexibility in girl's time allocation, although we do not detect whether they use the freed time during the day for domestic work or recreation. In any case, at least for those children who used wick lamps before, the lighting and air quality increases.

Table 9. Study Pattern (Only HH with Children at School Age; 6–17 years)

	N	Treatment	Control	*ITT*	*p*-value
Share of HH with children studying after school	209	67	61	*5*	.369
Share of HH with children studying after nightfall	209	26	14	*14*	.006
Daily study time after school (in minutes)					
male children 6-11, total	100	0h37	0h26	*0h13*	.009
male children 6-11, after nightfall	100	0h29	0h12	*0h12*	.045
female children 6-11, total	92	0h51	0h30	*0h12*	.533
female children 6-11, after nightfall	92	0h27	0h11	*0h11*	.090
male children 12-17, total	89	1h01	0h54	*0h21*	.191
male children 12-17, after nightfall	89	0h50	0h32	*0h14*	.382
female children 12-17, total	94	1h02	0h58	*0h10*	.327
female children 12-17, after nightfall	94	0h44	0h37	*0h10*	.191

Note: The ITT depicts the difference in means at the follow-up stage between the whole treatment and control group,

including also non-complying households. We control for all stratification and re-randomization characteristics. Detailed estimation results can be found in the supplemental appendix.

Source: Household data set 2011/2012.

Altogether, we observe an effect of Pico-PV kit ownership on time dedicated to domestic activities only in the case of study time of primary school boys. For other Pico-PV users, we only observe a higher flexibility in organizing their domestic duties. Moreover, it is plausible to expect that the improved lighting also increases the effectiveness of the tasks it is used for. Quantifying this effect is beyond the scope of our study, though. At least for the case of students' school test-scores the Furukawa (2014) results advise some caution in making hasty statements about improving learning outcomes based on longer study times and better light.[16]

Conclusion

Our results show that simple but quality verified Pico-PV kits in fact constitute an improvement compared to the baseline energy sources, mostly dry-cell batteries and kerosene. Given the small size of the panel, the charging capacity is obviously not abundantly available, and many households did not manage to use the panel for charging the radio and mobile phones; lighting turned out to be the most often used

[16] Remember that Furukawa (2014) observes even a decline of school children's test scores in spite of an increase in study time in an RCT using solar lanterns in Uganda. One explanation for this puzzling outcome he provides is the potentially bad lighting quality of the solar lamp. In our case, we have no indication for such a bad lighting quality and we believe this would have been disclosed in the various qualitative interviews we conducted (in which many other problems were discussed pretty openly, see Section IV).

service. In these remote and poor areas, lighting is a scarce good and the lamp was indeed intensively used by virtually all treatment group households leading to increases in both the quality and the quantity of lighting usage.

The most important finding of our study is that total energy expenditures and expenditures for dry-cell batteries and kerosene go down considerably. This shows that beneficiaries substitute traditional energy sources instead of just increasing their energy consumption. Beyond the direct effect this has on household welfare, the usage of the lamp also implies social returns. It induces advantages for people's health because kerosene usage is associated with harmful smoke emissions and the environment because dry-cell batteries are usually disposed of in unprotected latrines or in the landscape. Since households in rural Sub-Saharan Africa are rapidly switching from kerosene or candles to LED-lamps that run on dry-cell batteries this finding deserves particular attention.

In addition, we find that beneficiaries use the kit for various domestic production activities like cooking or studying. Although we cannot quantify the benefits, evidence from the literature strongly suggests that the solar lamp allows doing these activities better and faster than with traditional lighting sources, which plausibly results in an overall increase in domestic output. The solar lamp also enables households to allocate their time more freely and to shift activities toward the evening hours. School children, for example, find better and more flexible studying conditions thanks to the improved lighting source. Even if this does not lead to an immediate measurable increase in domestic output, pursuing the activities with better light and in a more flexible way

will at least reduce the effort that is needed to undertake household chores. This would still be an important improvement of household's living conditions.

While ultimate poverty impacts on, for example, income or educational investments might be small compared to productivity gains associated with bigger infrastructure interventions, these effects are still considerable from the poor's perspective, particularly having in mind the low investment costs of the intervention at 30 USD per kit.

Our results hence substantiate the Tier-1-threshold of modern energy access in the SE4All Global Tracking Framework. The Pico-PV kits can in fact meet the need for basic energy services in poor areas where energy consumption is still at a very low level. Yet, comparing our findings to more advanced regions and larger interventions, such as grid extension, it also becomes evident that Pico-PV kits cannot satisfy the whole portfolio of energy demand (Lenz et al. 2016). Hence, in many not so remote areas Pico-PV kits can be considered as either a complement to a grid connection for backup purposes or as a bridging technology toward a grid connection at a later point in time. For very poor areas in the periphery of a country as studied in this paper, in contrast, Pico-PV is in many cases the only option to obtain modern energy because, first, these regions are beyond the reach of the electricity grid for many years to come and, second, other off-grid solutions such as larger solar home systems are too expensive. We therefore argue that households in such remote areas are the major target group of Tier 1 energy systems within the SE4All initiative.

What is crucial for the acceptance of this new technology is the proper functioning and

ease in usage of the kit—in particular if the objective is to set up a market as pursued by programs like Lighting Africa. It has turned out that a relatively mature product such as the Pico-PV kit used in this study, of which the principal components had been tested and certified by Lighting Africa as well as massively sold in other countries, might still exhibit technical problems under real usage conditions. This is in line with findings of Furukawa (2014) who observes that insufficient charging under real usage conditions led to flickering light quality. Testing and certification procedures as well as the development of comprehensible usage guidelines should therefore encompass a strong component of field tests and not only laboratory examinations. This is particularly important in the light of the rapid penetration of rural Africa with non-branded LED lamps that has occurred in recent years (see Bensch et al. 2015). In terms of lighting quality, these dry-cell battery-run lamps are on a par with Pico-PV kits.

Nonetheless, Pico-PV kits that meet quality standards in terms of usability and lifetime are a worthwhile investment. If kerosene or dry-cell batteries are replaced, households with consumption patterns as observed in our research economize on average 0.95 USD PPP per month, which is around two percent of monthly household expenditures. The investment into the Pico-PV kit then pays off after 18 months, which is less than its life-span of 2–3 years, but the interplay of cash and credit constraints, the lack of information, and high discount rates will make most households forego this investment.

This claim points at a dilemma of Lighting Africa and other donor and governmental interventions, which intend to disseminate Pico-PV kits via sustainable markets as a

contribution to SE4All: The major target population will hardly be able to bring up the required investment. Financing schemes might in some regions be an obvious solution. But given the long pay-off period for the bottom of the income distribution and noninternalized advantages, such financing schemes are probably not effective. At the same time, if it is clearly the political will both in national governments and among the international community to provide electricity also to the very poor, one should consider more direct promotion options. Subsidized or even free distribution of kits might then be an alternative to reach the poorest of the poor. While many development practitioners are opposed to a free distribution policy and it would be in stark contrast to the strategies pursued by ongoing dissemination programs, the empirical literature provides evidence from other field experiments that supports such an approach (Kremer and Miguel 2007; Cohen and Dupas 2010; Tarozzi et al. 2014; Bensch and Peters 2015). As a matter of course, a subsidized distribution policy would require establishing institutions that maintain the subsidy scheme including an effective system for maintenance and replacement of broken kits in order to ensure long-term sustainability. Moreover, since subsidies would require public funds, the priority of the SE4All goal would obviously need to be pondered against other development objectives.

Having said this, it is also clear that further experimental studies that can examine the mechanisms behind take-up behavior, such as the households' willingness-to-pay for electric energy, the role of credit constraints, and information are certainly useful. Such research efforts would help to design appropriate least-cost strategies to achieve the

modern “energy-for-all-goals” of the international community.

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A First Step up the Energy Ladder? Low Cost Solar Kits and Household's Welfare in Rural Rwanda

Supplemental Appendix

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Appendix S1: Productivity effects associated with lighting

Since the visual performance of humans strongly increases with the lighting level (Brainard et al. 2001), we assume that the labor productivity in performing these activities increases with the quantity and quality of light. With high quantity and quality of light, activities can be done faster and with more precision, and hence output increases. Productivity in fine assembly work for instance has been shown to increase by 28% as the lighting level increases from 500 to 1500 lm (Lange 1999). But even increasing the lighting level from much lower levels comes with significant productivity effects. Evidence comes for instance from weaving mills (Lange 1999). The literature also shows that light has a stimulating effect on the work mood (Kuller and Wetterberg 1993; Boyce et al. 1997; Partonen and Lönnqvist 2000). It also helps to avoid accidents as alertness increases with light (Daurat et al. 1993). Studies have also shown that the use of higher lighting levels helps to cope with fatigue (Daurat et al. 1993; Grunberger et al. 1993; Begemann et al. 1997). Moreover, Wilkins et al. (1989) show that working in poor or low quality lighting, people can suffer eye strain which again results in poorer performance and is often accompanied by headaches. Headaches and stress in people are also caused by lamp flicker (Kuller and Laike 1998). The literature attributes good quality lighting to devices that provide sufficient light at the visual task, good uniformity of the lighting over the whole task area, balanced luminous distribution throughout the room, a lighting installation without glare, good color rendering and appropriate light color, and lighting without flicker (Lange 1999).

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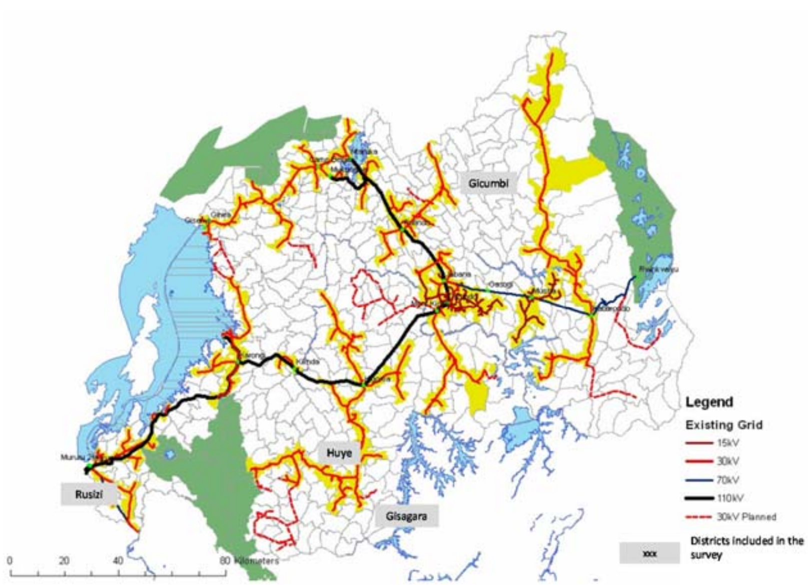
Appendix S2: RCT Implementation

The RCT for this study was conducted between November 2011 and July 2012 in close cooperation with the Rwandan survey company IB&C and the Rwandan Energy Water and Sanitation Authority (EWSA). IB&C team members and EWSA staff were included at all stages of the planning and implementation process. In November 2011, we did a preparation mission to select the regions in which the RCT should be implemented. In order to mimic the effects Pico-PV kits would have on their ultimate target population – households beyond the reach of the electricity grid and its extensions – we selected 15 remote communities equally distributed across four districts in the periphery of the country (see Figure S2.1). The communities do not border each other. According to Rwandan solar experts, these regions show a medium solar radiation level with a yearly average of 5.5 hours of sunlight per day. Also in the (cloudier) rainy season the radiation level is typically enough for the Pico-PV kit to produce sufficient electricity. In order to avoid treatment contamination, none of the few regions were selected in which Pico-PV kits were already available.[17]

Figure S2.1: Map of survey regions



Source: Own representation based on map provided by REG.

Together with IB&C we conducted a baseline survey among 300 randomly sampled households in December 2011. The baseline data was used to build strata of comparable households with regards to the consumed lighting hours per day, usage of mobile phones

[17] For a discussion of the representativeness of these rural communities, please refer to the section on external validity in the supplemental appendix, Section S4.

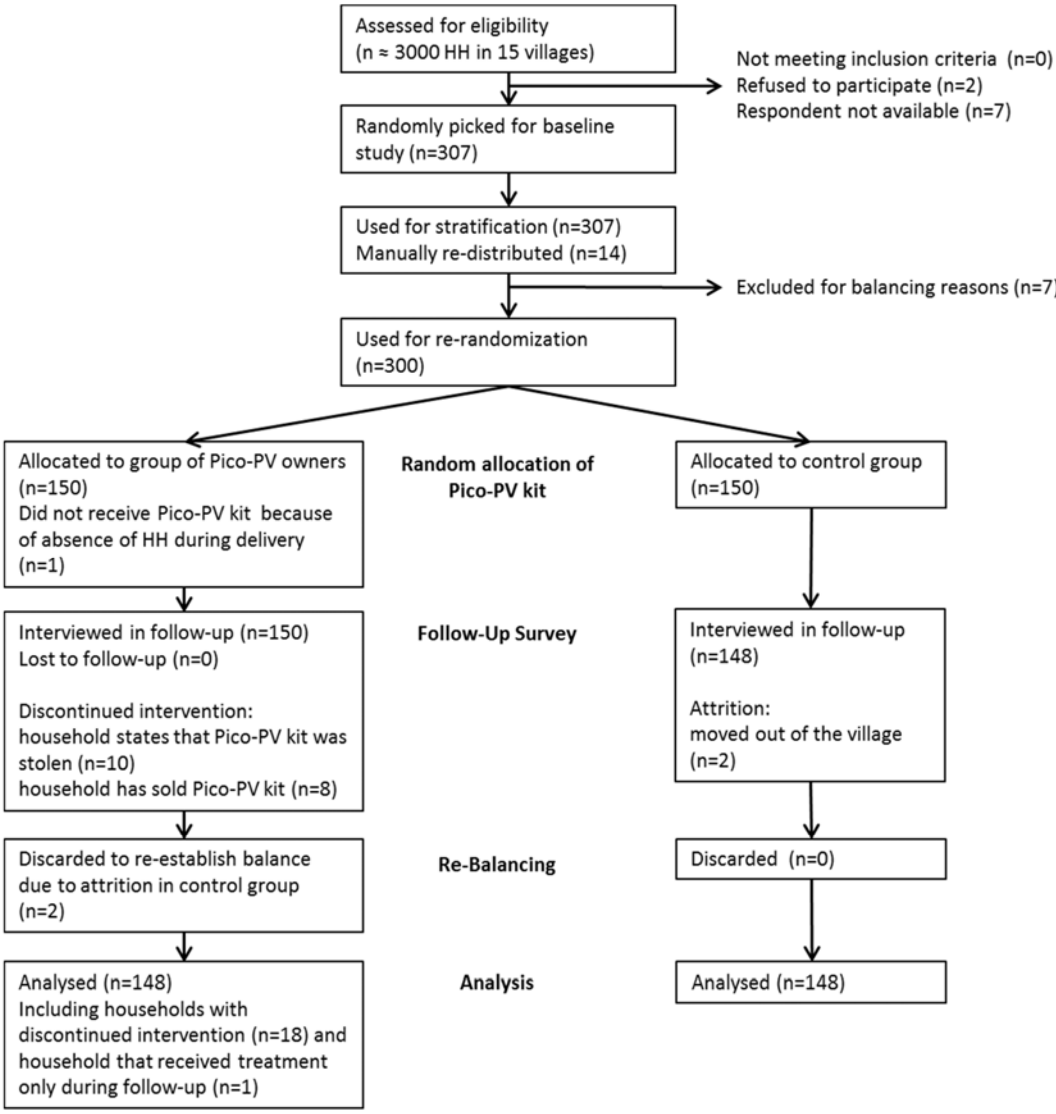
(binary), radio usage (binary), and district. We then randomized the treatment within the 48 strata resulting from this stratification and additionally applied a minmax *t*-stat method for further important baseline criteria (see Bruhn and McKenzie 2009).[18] For the impact analysis, we include stratum dummies according to our stratification process and control for all household characteristics used for re-randomization.

A few days after the baseline survey, the Pico-PV lamps were delivered to the randomly selected households. Those households assigned to the control group received a compensation (one bottle of palm oil and a 5kg sack of rice worth around 7 USD) in order to avoid resentment among the villagers. The Pico-PV "winners" furthermore were instructed on how to use the kit. This instruction was conducted by staff members of the organization that marketed the Pico-PV kit in other regions and who are hence also responsible for instructing real customers that buy a kit at a regular sales man.

Since the survey was embedded into a broader set of evaluation studies in the Rwandan energy sector on other ongoing interventions in different areas of the country, it was presented as a general survey on energy usage and not as a study on Pico-PV or lighting usage. Neither treatment nor control group members were informed about the experiment. An official survey permission issued by the Rwandan energy authority was shown to both local authorities and the interviewed households. Both the Pico-PV kit and the control group compensation were presented to participants not as a gift, but as a reward for participation in the survey. We conducted the randomization in our office using the digitalized baseline data. Local authorities as well as the field staff of IB&C were only informed on the final randomization results.

Figure S2.2: Participants flow

[18] See Ashraf et al. (2010) for an application of this combined stratified re-randomization approach. All balancing criteria are highlighted in Table 2 and 3 of Section 5.1.



Source: own illustration in accordance with guidelines provided in BOSE (2010)

Given the high poverty rates in the region, our local partners assessed the risk of households selling the Pico-PV kit to be fairly high. Since it was our ambition to mimic a policy intervention in which basic energy services are provided for free to all households (and thus potentials to sell the kits would be reduced considerably) we tried to avoid this. Our local research partners addressed this risk by preparing a short contract to be signed by the district mayors and the winners that obliged the winners not to sell the Pico-PV system (see Online Appendix). The governmental authority is well respected also in remote areas of the country and Rwandans generally tend to comply with formal agreements. At the same time we were assured that such a procedure would not induce irritations in the villages. A monitoring visit

among all winners each two months was conducted to ensure the proper functioning of the Pico-PV systems and may remind the winners of their commitment not to sell the systems.
Six months after the randomization we revisited the 300 households for the follow-up survey. Except for two, all households interviewed during the baseline could be retrieved giving us a fairly low attrition rate of only 1 percent. Also compliance turned out to be high with only 18 households that declared their Pico-PV kit to be sold, lost or stolen (it can be suspected that also the lost and stolen ones were sold in fact). One household got the kit only during the follow-up, since the household had been absent during multiple delivery attempts after baseline. The participant flow is visualized in Figure S2.2.

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Appendix S3: Contract for lottery winners

AGREEMENT OF COOPERATION (translated from Kinyarwanda)

Between…………………………………….Representative of RWI/ISS
And the beneficiary of solar kits:

-Name: …………………………....
-Phone number: ………………………...
-Code of household: ………………………...
-Village ………………………...
-Cell: ………………………...
-Sector: ………………………...
-District: ………………………...
-Province: ………………………...

Article 1: This agreement concerns the cooperation between RWI/ISS and beneficiaries of solar kits during research on impact of electricity on living conditions of beneficiaries.

Article 2: The Agreement is valid for one year from the date of signature.

Article 3: RWI/ISS's responsibilities:

- To offer beneficiaries solar kits freely (solar kits consist of 1. solar panel, 2. lamp, 3. battery power pack, 4. active and passive radio connectors, 5. radio, and 6. phone connector)
- To conduct survey on impact of electricity on living conditions of beneficiaries
- Assist beneficiaries in collaboration with Though Stuff in any case of technical problems of solar kits

Article 4: Responsibilities of beneficiaries of solar kits:

– To follow rules given by Though Stuff about how to keep well solar kits
– To give all required information on the impact of electrification on the living conditions
– To communicate Though Stuff on the encountered problems about the use of solar kits
– Don't sell or give freely solar kits to someone else
– Turn back to RWI/ISS solar kits when beneficiaries are not able to keep them

Done at ….., the….December 2011

Signature

Beneficiary's name:……………………………………

Signature

Name……………………………………………………….

Local Authorities representative………………………………….

Signature

Name………………………………………………….

Representative of RWI-ISS

Appendix S4: External Validity of results

External validity refers to the question whether results observed in a certain study can be expected to be transferable to other regions or whether they would also apply if the program under evaluation was upscaled (outside the randomised experiment). It is frequently argued that RCTs are more prone to external validity problems than observational studies. We therefore discuss the hazards to external validity as they are identified by Duflo, Glennerster, and Kremer (2008).

<u>Representativeness of the study population for a different policy population</u>

On purpose, we selected regions that are very remote for Rwandan comparison and have very limited access to modern energy sources. In addition, these regions were not scheduled to be connected to the electricity grid in the subsequent years. The communities are located in four different districts, covering three out of five Rwandan provinces. This might not represent the typical target area of commercial Pico-PV dissemination approaches. For purchasing power reasons such approaches might rather focus on the periphery of the grid covered areas or even on grid-connected and urban areas, in which Pico-PV devices are used as back-up in times of outages. In contrast, it was the aim of this evaluation to assess the extent to which Pico-PV can generally contribute to the combat against energy poverty. This contribution would happen in regions that are far beyond the outreach of the grid (or other more expensive electricity sources with higher capacities). Hence, the results obtained in this study are transferable to other set-ups in which Pico-PV is not only marketed for commercial reasons, but as an instrument to provide modern energy to the poor. This is the explicit goal of SE4All and also the role that is assigned to Pico-PV within this SE4All initiative.

Moreover, in the evaluation report underlying the present study (see Grimm et al. 2013) we compare the RCT sample and usage behaviour in the RCT to real users of the Pico-PV kit in other regions of the country, this is, customers who deliberately decided to buy the kit. In line with expectations, it can be seen that these real-world users are somewhat wealthier than the average RCT user, but usage patterns for the kit's lamp are quite similar (see Grimm et al. 2013, Section 4.4.).

<u>General Equilibrium effects</u>

General Equilibrium effects are effects that only occur or become perceivable if the treatment is provided to a larger population or for a longer period. Hence, these effects might have repercussions on the RCT sample and can only be captured by the RCT if the period between randomization and the impact assessment is long enough and the study population is large enough. In the present case, one could theoretically think of decreasing prices of traditional lighting sources because of a decreasing demand, which in turn could increase consumption of traditional lighting sources by households both in the RCT sample and beyond. This effect can be expected to be very small, though, since energy prices are mostly driven by regional markets if not world markets. On the other hand, in case one would upscale the program to the whole country (i.e. distribute Pico-PV kits on a large scale), for example, such effects could occur for products with a regional value chain (i.e. that do not only depend on world market

prices).

As for the time horizon, our evaluation examines short-term usage and impacts. While we believe that the six months period between delivery of the Pico-PV kit and our follow-up survey is long enough to allow the users' adaptation to the new technology, we cannot rule out that usage behaviour would change over time.

Hawthorne- and John-Henry-Effects

Hawthorne- and John-Henry-effects occur if participants in an experiment change their behaviour because they know that they are participating in an experiment. To the extent that the field work team has to interact with the study population, these effects can hardly be excluded completely in most RCTs. However, there are ways to keep them as small as possible, mostly by reducing the attention that is evoked in the participating household and the villages. The surveys used for this study were presented as part of a general survey on energy usage in relation to on-going and well-known energy interventions. Respondents were asked to consent to participating in the survey, but the randomization or the experimental character were not mentioned. A permission letter issued by the Rwandan Energy Authority was presented to the local authorities as well as the participating households both during the baseline survey and the follow-up survey. In fact, our study was part of a broader evaluation engagement in the country, which also covered 50 different target villages of the Rwandan grid roll-out programme EARP (see Lenz et al. 2016). Although the study regions of the present paper were not scheduled to be connected by EARP in the near future, most of the residents are aware of the electrification programme that possibly will also reach their communities. The survey work was implemented as unobtrusive as possible. Each household was visited individually.

Furthermore, the randomly assigned Pico-PV system was not labelled as a gift, but as a compensation for participation in the survey. Also, households assigned to the control group received a compensation consisting of a sack of 5kg of rice and one litre of cooking oil.[19] As a side effect, this compensation for the control group addresses a potential ethical concern that is sometimes brought forward against RCTs: Randomly assigning a treatment to one group may induce uncomfortable feelings in the other group.

In sum, while some sort of survey effect is unavoidable, there is no reason to expect strong Hawthorne and John Henry-effects, since the participants were not informed about an experiment, both treatment and control groups received a reimbursement for participation and the surveys and interviews were implemented as unobtrusive as possible.

Special Care

The way in which we provided the Pico-PV kit (most importantly the training) was in line

[19] This implementation design follows the approach presented in De Mel, McKenzie, and Woodruff (2008) and was also applied in a RCT with improved cooking stoves in Senegal (Bensch and Peters 2015).

with what the company that marketed the product had foreseen for the marketing process. Although the level of care was probably higher compared to some other Pico-PV kits that are just sold in shops and do not comprise a training, many regular market vendors also offer such trainings.

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Appendix S5: Radio Usage

Table S5.1 portrays the effects of the Pico-PV kit treatment on radio ownership and usage patterns. Since the randomized Pico-PV kit encompasses a radio, the share of radio owners is close to 100 percent in the treatment group, while slightly more than 50 percent of the control group households own a radio. It is above all the head of the household who uses the radio, but the increased number of radios in the households also leads to significantly increased radio usage of other household members. The share of members listening to the radio is significantly higher in the treatment group for all household members. The listening hours for those who use a radio only increases significantly for the head of households.

Table S5.1: Radio ownership and usage

	Treatment	Control	*ITT*	p-value
Radio Ownership	95%	52%	*41%*	0.000
HH member listens regularly to radio				
Head of HH	86%	43%	*41%*	0.000
- Listening hours per day (only user)	4.3	3.2	*1.1*	0.012
Spouse	78%	42%	*34%*	0.000
- Listening hours per day (only user)	3.3	2.7	*0.4*	0.289
Boys 12-17 years	76%	47%	*33%*	0.048
- Listening hours per day (only user)	2.2	2.0	*-0.1*	0.907
Girls 12-17 years	80%	42%	*26%*	0.151
- Listening hours per day (only user)	1.7	2.1	*-0.3*	0.639
Children 6-11 years	63%	33%	*16%*	0.090
- Listening hours per day (only user)	1.9	2.2	*0.4*	0.631

Radios are mostly used to listen to programs that transmit information (see Table S5.2). We asked all radio users to name their two favourite radio programs: the by far most preferred program among adults are news, followed by music. The third preference are programs that people refer to as "théatre". These are radio plays that try to raise awareness on different topics like reconciliation, working attitude, or justice. The last category subsumes special broadcasts topics like politics or health ('broadcasts' in Table S5.2).

Table S5.2: Preferred radio programs per household member

(in percent)		Treatment	Control	*ITT*	p-value
Head of HH	Music	46	62	-17	0.062
(N=193)	News	84	86	-4	0.408
	Theatre	13	5	10	0.056
	Broadcast	13	8	1	0.847
	Other	14	15	3	0.697
Spouse	Music	43	67	-29	0.006
(N=158)	News	71	68	5	0.426
	Theatre	24	14	8	0.245
	Broadcast	10	9	-1	0.893
	Other	16	12	12	0.114
Children	Music	76	71	-2	0.907
6-11 years old	News	31	39	-1	0.963
(N=77)	Theatre	22	14	-7	0.498
	Broadcast	8	11	4	0.709
	Other	4	11	-2	0.836
Male	Music	70	83	8	0.824
12-17 years old	News	47	63	-24	0.425
(N=54)	Theatre	10	17	-20	0.247
	Broadcast	13	8	-21	0.238
	Other	13	8	12	0.562
Female	Music	89	84	16	0.309
12-17 years old	News	44	58	-11	0.613
(N=64)	Theatre	18	16	-2	0.940
	Broadcast	9	5	-3	0.856
	Other	16	11	5	0.777

In line with these usage patterns, radio is by far the most important source of information in the surveyed villages. More than 90 percent of treatment households and 40 percent of control households answer to an open question on their main source of information that they exclusively or together with other sources receive information through the radio (see Table S5.3). Apart from this, direct conversations with other people (community gatherings, neighbours and friends) are the most important sources of information. TVs and newspaper

are only used by a negligible number of households. While for treated households the importance of radio is substantially higher, control households rely more on community gathering and information exchange with neighbours and friends. This obviously creates potentials for spillovers of increased access to information for some households to the whole village.

Table S5.3: Main source of information (multiple answers possible)

	Treatment	Control	*ITT*	p-value
Radio	91	40	*51*	0.000
Community gathering	70	82	*-11*	0.029
Neighbours/friends	28	28	*0*	0.929

Box S5.1: Radio stations in Rwanda

In Rwanda, the biggest radio station is the state-financed Radio Rwanda that reaches more than 90 percent of the population. It broadcasts 24 hours in Kinyarwanda, French, English and Swahili. Radio Rwanda maintains additionally 5 community radio stations that partly broadcast contributions from Radio Rwanda and additionally cover local news and regional information. Since 2002, also private radio stations have received licences to broadcast. Their reception area, though, is mainly restricted to Kigali and bigger towns. Within our survey area, people frequently reported that besides Rwandan radio stations they can also receive radio from Burundi or Congo.

Radio Rwanda and its community radio stations cover both entertainment and information broadcasts. For example at Radio Rusizi, the community radio of Rusizi, on a regular day where they offer program from 5 am to 23 pm, music covers 7 hours, news sum up to almost 4 hours, 3.5 hours of entertainment shows like soap operas (“théatre”), quizzes or sports events, and almost 3 hours on broadcast with some educational background. These educational broadcasts diffuse for example information on hygiene and cleanliness, on agricultural activities, on animal husbandry, on good governance, or to raise workers’ motivation.

Appendix S6: Additional tables

Lamp Usage

Table S6.1: Number of lighting devices and consumption

	Share of households using [lamp]				**Operation hours per day and lamp**	
	Treatment	Control	*ITT*	p-value	Treatment	Control
Pico-PV lamp	0.86	0.00	*0.86**	0.00	2.89	-
Hand-crafted LED lamps	0.28	0.45	*-0.18*	0	3.45	3.40
Ready-made torch	0.14	0.22	*-0.10*	0.01	2.23	2.12
Wick lamp	0.12	0.43	*-0.22*	0	2.47	2.98
Candles	0.07	0.15	*0.04*	0.935	2.05	1.58
Hurricane lamp	0.04	0.10	*-0.07*	0.002	3.2	2.43
Mobile LED lamp	0.03	0.05	*-0.03***	0.014	2	2.57
No lamp	0.05	0.09	*0.03*	0.16	-	-
SUM	**1.62**	**1.43**	***0.16***	**0.004**	**4.3**	**3.8**

Note: The *ITT* depicts the difference in means at the follow-up stage between the whole treatment and control group, also including non-complying households. We control for all stratification and re-randomization characteristics. Rechargeable lamps and gas lamps are not included in the table, since only one control household uses a rechargeable lamp and only one treatment household uses a gas lamp.

*Probit estimation is not applicable, since control group households do not use the lamp leading to convergence problems; we display simple differences in means instead. **Controlling for randomization stratum dummies leads to convergence problems. We include the stratification criteria instead.

Health

Table S6.2: Share of households with household members suffering diseases (in percent)

		Treatment	Control	*ITT*	p-value
Male adult	Respiratory diseases	7	7	*-2*	0.596
	Eye problem	7	8	*0*	0.972
Female adult	Respiratory diseases	5	6	*0*	0.904
	Eye problem	9	13	*-6*	0.128
Male	Respiratory diseases	2	2	*1*	0.785
6-11 years old	Eye problem	2	6	*-3*	0.440
Female	Respiratory diseases	0	0	*0*	---
6-11 years old	Eye problem	9	10	*5*	0.472
Male	Respiratory diseases	0	0	*0*	---
12-17 years old	Eye problem	2	0	*1*	0.672
Female	Respiratory diseases	4	0	*3*	0.452
12-17 years old	Eye problem	6	3	*8*	0.292

Note: The data is self-reported information of whether any household member suffers from any of the diseases. The ITT depicts the difference in means at the follow-up stage between the whole treatment and control group, including also non-complying households. We control for all stratification and re-randomization characteristics.

Lamps used for domestic labor

Table S6.3: Most frequently used lamps for housework by male and female adult (percent of all households)

	Female adults doing housework				**Male adults doing housework**				**Children (6-17 years) studying**			
Lamp	Treat.	Ctrl.	*ITT*	p-value	Treat.	Ctrl.	*ITT*	p-value	Treat.	Ctrl.	*ITT*	p-value
Wick lamp	7	32	*-23*	0.000	3	9	*-7*	0.001	2	12	*-12****	0.000
Ready-made torch	8	12	*-7*	0.056	3	7	*-8*	0.000				
Hand-crafted LED	7	9	*-3*	0.182	1	5	*-6***	0.003				
Pico-PV lamp	72	0	*72**	0.000	26	0	*26**	0.000	30	0	*30**	0.000
None	15	42	*-25*	0.000	68	78	*-9*	0.006	32	41	*-19*	0.000
None and studying at day time only									9	18	*-19*	0.000
None and studying after nightfall									23	22	*-2*	0.633

Note: The ITT depicts the difference in means at the follow-up stage between the whole treatment and control group, including also non-complying households. We control for all stratification and re-randomization characteristics. Detailed estimation results can be found in the following.

*Probit estimation is not applicable, since control group households do not use the lamp leading to convergence problems; we display simple differences in means instead. **Controlling for randomization stratum dummies leads to convergence problems. We include the stratification criteria instead. *** Controlling for baseline kerosene consumption (continuous) causes convergence problems. We include a dummy indicating baseline kerosene consumption yes/no instead.

Table S6.3a: Most frequently used lamps for housework by female adult (% of all households)

	Wick lamp	Ready-made torch	Hand-crafted LED	None
Treatment	-0.228	-0.069	-0.034	-0.249
	(0.000)***	(0.056)*	(0.182)	(0.000)***
Consumption of candles	-0.001	-0.016	0.000	-0.001
	(0.612)	(0.001)***	(0.829)	(0.854)
Consumption of kerosene	0.013	-0.022	-0.017	0.017
	(0.229)	(0.427)	(0.652)	(0.151)
Number of household members	-0.005	0.011	-0.006	0.017
	(0.676)	(0.106)	(0.347)	(0.091)
Number of mobile phones	0.047	0.005	0.013	-0.025
	(0.270)	(0.836)	(0.484)	(0.734)
Plastered dwelling	-0.056	0.071	-0.000	0.147
	(0.481)	(0.024)**	(0.994)	(0.200)
Modern wall	-0.073	-0.106	0.042	0.075
	(0.217)	(0.119)	(0.390)	(0.468)
Modern floor	0.078	0.090	-0.058	-0.136
	(0.094)*	(0.076)*	(0.246)	(0.161)
Hand-crafted LED	-0.082	-0.095	0.071	0.042
	(0.134)	(0.022)**	(0.012)**	(0.507)
Mobile LED	-0.040	0.058	-0.008	0.007
	(0.763)	(0.379)	(0.916)	(0.962)
Household owns land	-0.238	0.104	-0.060	0.147
	(0.003)***	(0.434)	(0.176)	(0.218)
Household owns one goat	-0.064	0.072	-0.005	-0.019
	(0.126)	(0.109)	(0.915)	(0.808)
Household owns several goats	-0.005	0.034	0.060	-0.005
	(0.897)	(0.430)	(0.148)	(0.932)
Household owns one cow	-0.033	0.001	0.025	-0.065
	(0.543)	(0.978)	(0.521)	(0.321)
Household owns several cows	0.026	-0.056	-0.086	0.036
	(0.657)	(0.287)	(0.055)*	(0.722)
Head of household completed primary school	0.046	0.085	-0.002	-0.095
	(0.385)	(0.045)**	(0.937)	(0.083)
Head of household completed secondary school	-0.100	0.185	n.i.	-0.038
	(0.136)	(0.021)**		(0.816)
Redistributed between strata for randomization	-0.029	0.078	n.i.	0.112
	(0.853)	(0.314)		(0.409)
Pseudo R-Squared	0.36	0.32	0.29	0.20
Number of Observations	294	294	294	294

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values; Standard errors are clustered at the village level.
n.i.: not included since variable predicts success or failure perfectly.

Table S6.3b: Most frequently used lamps for housework by male adult (% of all households)

	Wick lamp	Ready-made torch	Hand-crafted LED	None
Treatment	-0.070 (0.001)***	-0.078 (0.000)***	-0.055 (0.003)***	-0.085 (0.006)***
Consumption of candles	0.004 (0.062)*	-0.007 (0.006)***	-0.013 (0.113)	0.002 (0.728)
Consumption of kerosene	0.011 (0.006)***	-0.043 (0.046)**	-0.057 (0.000)***	0.007 (0.545)
Number of household members	0.007 (0.195)	0.009 (0.025)**	0.002 (0.427)	0.003 (0.856)
Number of mobile phones	0.006 (0.794)	-0.005 (0.587)	0.000 (0.979)	-0.048 (0.391)
Modern floor	-0.010 (0.874)	0.050 (0.056)*	n.i.	-0.031 (0.781)
Hand-crafted LED	-0.003 (0.900)	-0.053 (0.047)**	0.037 (0.140)	-0.090 (0.089)*
Household owns land	-0.029 (0.581)	n.i.	-0.022 (0.447)	0.009 (0.942)
Household owns one goat	0.039 (0.168)	-0.051 (0.216)	n.i.	-0.023 (0.723)
Household owns several goats	0.077 (0.004)***	0.082 (0.000)***	-0.044 (0.036)**	-0.107 (0.038)**
Household owns one cow	-0.007 (0.866)	-0.003 (0.896)	n.i.	0.030 (0.614)
Household owns several cows	-0.016 (0.656)	-0.045 (0.244)	0.013 (0.470)	0.130 (0.134)
Head of household completed primary school	0.036 (0.073)*	0.048 (0.138)	-0.025 (0.040)**	-0.036 (0.485)
Redistributed between strata for randomization	0.137 (0.039)**	n.i.	n.i.	0.109 (0.646)
Plastered dwelling	n.i.	0.009 (0.526)	n.i.	0.191 (0.079)*
Modern wall	n.i.	-0.059 (0.073)*	-0.047 (0.049)**	0.072 (0.488)
Mobile LED	n.i.	-0.050 (0.317)	0.121 (0.000)***	-0.110 (0.359)
Head of household completed secondary school	n.i.	0.075 (0.147)	0.020 (0.568)	-0.065 (0.528)
Household owns a radio	n.i.	n.i.	-0.004 (0.811)	n.i.
Household owns a mobile phone	n.i.	n.i.	0.038 (0.000)***	n.i.
Consumption of lighting hours	n.i.	n.i.	-0.001 (0.883)	n.i.
Pseudo R-Squared	0.36	0.51	0.51	0.17
Number of Observations	294	294	295	294

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values; Standard errors are clustered at the village level.
n.i.: not included since variable predicts success or failure perfectly.

Table S6.3c: Most frequently used lamps for studying by children (% of households with children at school age; N=208)

	Wick lamp	No lamp	None and studying at daytime only	None and studying after nightfall
Treatment	-0.118	-0.194	-0.185	-0.020
	(0.000)***	(0.000)***	(0.000)***	(0.633)
Consumption of candles	0.002	-0.004	-0.009	-0.001
	(0.327)	(0.235)	(0.116)	(0.780)
Number of household members	0.021	0.009	0.003	0.006
	(0.049)**	(0.623)	(0.748)	(0.669)
Number of mobile phones	-0.027	0.089	0.059	0.015
	(0.211)	(0.319)	(0.272)	(0.827)
Plastered dwelling	-0.031	-0.053	-0.061	-0.083
	(0.526)	(0.616)	(0.540)	(0.284)
Modern wall	-0.137	-0.069	-0.041	-0.082
	(0.008)***	(0.378)	(0.530)	(0.232)
Modern floor	0.025	-0.088	n.i.	0.049
	(0.692)	(0.525)		(0.453)
Hand-crafted LED	-0.049	-0.092	-0.065	-0.020
	(0.312)	(0.360)	(0.005)***	(0.773)
Household owns one goat	-0.041	0.109	0.083	0.054
	(0.415)	(0.257)	(0.005)***	(0.628)
Household owns several goats	-0.138	0.178	0.027	0.137
	(0.014)**	(0.012)**	(0.644)	(0.015)**
Household owns one cow	-0.022	0.100	0.125	-0.039
	(0.652)	(0.292)	(0.040)**	(0.621)
Household owns several cows	0.118	0.217	-0.051	0.142
	(0.021)**	(0.033)**	(0.674)	(0.086)*
Head of household completed primary school	-0.013	-0.058	0.056	-0.106
	(0.797)	(0.543)	(0.269)	(0.179)
Head of household completed secondary school	0.033	-0.123	-0.027	-0.229
	(0.574)	(0.543)	(0.842)	(0.216)
Consumption of kerosene	n.i.	-0.144	-0.111	-0.060
		(0.015)**	(0.005)***	(0.110)
Household owns land	n.i.	0.055	0.014	0.064
		(0.751)	(0.891)	(0.663)
Redistributed between strata for randomization	n.i.	0.177	-0.655	0.204
		(0.379)	(0.000)***	(0.216)
Mobile LED	n.i.	0.116	n.i.	0.186
		(0.558)		(0.147)
Pseudo R-Squared	0.50	0.27	0.40	0.33
Number of Observations	207	207	207	207

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values;
Standard errors are clustered at the village level.
n.i.: not included since variable predicts success or failure perfectly.

Table S6.4: Main Occupation at baseline (in percent)

		Treatment	Control
Head of household	Subsistence Farmer	90	83
	Government Employee	1	1
	Other independent occupation	3	5
	Other dependent occupation	1	5
	Housewife, Retired	4	6
	Unemployed	1	0
Spouse	Subsistence Farmer	98	93
	Government Employee	2	0
	Other independent occupation	0	1
	Other dependent occupation	0	2
	Housewife, Retired	0	3
	Studies	0	1

Appendix S7: Full regression results of tables in main document

Table 5: Price and consumption of lighting energy

VARIABLES	Cost per lighting hour	Cost per lumen hour	Lighting hours consumed per day	Lumen hours consumed per day
Treatment	-7.022	-0.566	0.585	77.736
	(0.000)***	(0.000)***	(0.074)*	(0.000)***
Consumption of candles	0.182	0.012	0.021	0.026
	(0.013)**	(0.009)***	(0.267)	(0.983)
Consumption of kerosene	1.260	0.109	0.054	-3.696
	(0.001)***	(0.000)***	(0.718)	(0.163)
Number of household members	-0.017	0.001	0.013	-4.296
	(0.911)	(0.950)	(0.851)	(0.374)
Number of mobile phones	-0.392	-0.034	1.296	21.644
	(0.528)	(0.355)	(0.007)***	(0.019)**
Plastered dwelling	-2.112	-0.208	0.709	-14.458
	(0.120)	(0.012)**	(0.372)	(0.607)
Modern wall	1.529	0.147	-1.249	-27.763
	(0.310)	(0.141)	(0.039)**	(0.077)*
Modern floor	3.310	0.132	0.461	-40.420
	(0.064)*	(0.120)	(0.549)	(0.243)
Handcrafted LED	-1.494	-0.059	0.592	-10.708
	(0.136)	(0.414)	(0.295)	(0.452)
Mobile LED	-1.607	-0.167	0.873	47.231
	(0.300)	(0.108)	(0.405)	(0.199)
Household owns land	-1.447	-0.085	-0.181	19.863
	(0.139)	(0.285)	(0.868)	(0.430)
Household owns one goat	-2.448	-0.154	-0.296	-38.858
	(0.119)	(0.090)*	(0.563)	(0.307)
Household owns several goats	0.757	0.024	0.021	-16.033
	(0.591)	(0.789)	(0.967)	(0.608)
Household owns one cow	-0.004	-0.063	0.879	19.648
	(0.998)	(0.409)	(0.078)*	(0.225)
Household owns several cows	1.784	0.213	0.205	75.429
	(0.090)*	(0.044)**	(0.670)	(0.239)
Head of household completed primary school	0.919	0.049	0.492	13.202
	(0.165)	(0.466)	(0.311)	(0.305)
Head of household completed secondary school	3.560	0.276	-0.980	-33.814
	(0.085)*	(0.076)*	(0.543)	(0.348)
Redistributed between strata for randomization	-0.018	0.006	1.319	20.259
	(0.990)	(0.967)	(0.202)	(0.530)
Constant	9.486	0.661	2.138	-17.590
	(0.012)**	(0.023)**	(0.329)	(0.603)
Observations	265	265	288	288
Adjusted R-squared	0.397	0.404	0.121	0.165

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values; Standard errors are clustered at the village level.

Table 6a: Expenditures per month per category (in FRW)

VARIABLES	Candles	Kerosene	Char coal	Big batteries	Small batteries	Mobile phone charging
Treatment	-19.927	-418.007	1.917	-9.344	-43.352	-67.916
	(0.339)	(0.000)***	(0.447)	(0.750)	(0.003)***	(0.407)
Consumption of candles	29.621	8.273	-0.019	0.405	-1.165	19.456
	(0.000)***	(0.165)	(0.780)	(0.911)	(0.537)	(0.039)**
Consumption of kerosene	1.833	169.929	-0.096	9.460	-0.074	7.410
	(0.753)	(0.007)***	(0.594)	(0.133)	(0.978)	(0.686)
Number of household members	8.228	8.295	-0.934	-2.416	1.281	29.491
	(0.267)	(0.567)	(0.382)	(0.829)	(0.678)	(0.383)
Number of mobile phones	-9.833	195.483	7.513	60.265	17.418	1,100.513
	(0.631)	(0.067)*	(0.367)	(0.149)	(0.232)	(0.009)***
Plastered dwelling	16.502	-63.128	-0.548	-70.298	-12.142	205.632
	(0.581)	(0.576)	(0.726)	(0.330)	(0.686)	(0.198)
Modern wall	-44.866	-120.093	-0.820	64.199	-58.167	63.933
	(0.322)	(0.267)	(0.617)	(0.504)	(0.058)*	(0.686)
Modern floor	56.056	281.553	-2.738	-65.299	22.367	-434.782
	(0.246)	(0.050)*	(0.360)	(0.282)	(0.599)	(0.060)*
Hand-crafted LED	18.316	9.387	-4.571	20.710	-15.293	86.275
	(0.392)	(0.925)	(0.334)	(0.686)	(0.440)	(0.552)
Mobile LED	-2.633	255.134	-3.422	139.388	21.636	-84.409
	(0.965)	(0.234)	(0.403)	(0.361)	(0.735)	(0.867)
Household owns land	-0.584	-117.541	5.549	179.692	-19.392	-14.158
	(0.986)	(0.287)	(0.185)	(0.036)**	(0.544)	(0.942)
Household owns one goat	73.643	-134.849	-1.542	26.665	-16.252	-11.673
	(0.000)***	(0.225)	(0.500)	(0.621)	(0.202)	(0.912)
Household owns several goats	10.973	-111.840	-1.314	164.868	33.091	287.823
	(0.609)	(0.363)	(0.510)	(0.042)**	(0.219)	(0.036)**
Household owns one cow	-11.154	-151.915	5.046	134.052	14.472	74.082
	(0.533)	(0.076)*	(0.290)	(0.019)**	(0.707)	(0.600)
Household owns several cows	93.441	91.004	-1.129	68.589	-19.832	-136.453
	(0.027)**	(0.486)	(0.673)	(0.315)	(0.233)	(0.568)
Head of household completed primary school	-27.737	89.954	1.490	115.139	-2.168	26.694
	(0.095)*	(0.332)	(0.353)	(0.004)***	(0.885)	(0.799)
Head of household completed secondary school	83.751	26.200	-0.821	326.077	110.878	-523.982
	(0.277)	(0.880)	(0.717)	(0.047)**	(0.408)	(0.153)
Redistributed between strata for randomization	44.463	56.283	1.826	126.782	-80.459	185.076
	(0.488)	(0.769)	(0.426)	(0.403)	(0.231)	(0.292)
Constant	-227.965	-283.081	- 18.863	-419.144	261.650	-320.098
	(0.049)**	(0.463)	(0.259)	(0.173)	(0.130)	(0.723)
Observations	296	296	295	296	296	296
Adjusted R-squared	0.622	0.356	-0.019	0.275	0.046	0.480

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations. Control variables refer to baseline values;
Standard errors are clustered at the village level.

Table 6b: Expenditures per month per category (in FRW)

VARIABLES	Total traditional energy expenditures (without cooking)	Total expenditures	Share of energy expenditure on total expenditures
Treatment	-556.653	7,249.033	-0.030
	(0.000)***	(0.276)	(0.001)***
Consumption of candles	56.573	-603.375	0.001
	(0.002)***	(0.074)*	(0.017)**
Consumption of kerosene	188.463	2,594.154	0.003
	(0.010)**	(0.002)***	(0.144)
Number of household members	43.955	3,700.456	0.000
	(0.315)	(0.135)	(0.922)
Number of mobile phones	1,371.322	22,314.462	0.013
	(0.004)***	(0.051)*	(0.164)
Plastered dwelling	75.918	21,254.017	-0.023
	(0.724)	(0.165)	(0.066)*
Modern wall	-95.781	23,581.834	-0.002
	(0.672)	(0.137)	(0.893)
Modern floor	-142.721	-7,699.614	0.016
	(0.550)	(0.719)	(0.143)
Hand-crafted LED	114.774	1,974.949	-0.004
	(0.525)	(0.762)	(0.724)
Mobile LED	325.633	-1,101.144	-0.003
	(0.561)	(0.930)	(0.854)
Household owns land	33.578	2,184.018	0.010
	(0.881)	(0.485)	(0.364)
Household owns one goat	-64.025	-7,456.327	0.006
	(0.721)	(0.112)	(0.610)
Household owns several goats	383.684	8,874.944	-0.005
	(0.082)*	(0.524)	(0.643)
Household owns one cow	64.631	-4,661.881	0.001
	(0.693)	(0.381)	(0.924)
Household owns several cows	95.617	14,374.902	-0.015
	(0.777)	(0.171)	(0.302)
Head of household completed primary school	203.383	5,767.114	-0.003
	(0.217)	(0.329)	(0.791)
Head of household completed secondary school	22.096	-8,550.415	-0.004
	(0.965)	(0.701)	(0.836)
Redistributed between strata for randomization	333.947	-9,091.174	0.013
	(0.137)	(0.214)	(0.729)
Constant	-1,007.517	-45,103.310	0.071
	(0.342)	(0.298)	(0.150)
Observations	296	296	295
Adjusted R-squared	0.582	0.250	0.136

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations. Control variables refer to baseline values;
Standard errors are clustered at the village level.

Table 8a: Daily time spent on domestic labour

VARIABLES	Total time of head of household	Time during night of head of household	Total time of spouse	Time during night of spouse
Treatment	-1.674	6.150	26.953	2.752
	(0.950)	(0.542)	(0.333)	(0.779)
Consumption of candles	-0.431	-0.858	3.755	0.320
	(0.871)	(0.099)*	(0.182)	(0.705)
Consumption of kerosene	-6.370	-1.981	-4.528	0.123
	(0.274)	(0.129)	(0.339)	(0.954)
Number of household members	-3.233	-0.591	3.293	5.514
	(0.660)	(0.793)	(0.735)	(0.248)
Number of mobile phones	39.520	7.932	32.397	28.709
	(0.103)	(0.367)	(0.306)	(0.029)**
Plastered dwelling	-2.937	8.097	-15.112	2.584
	(0.952)	(0.556)	(0.764)	(0.890)
Modern wall	-42.319	-10.732	29.055	6.767
	(0.353)	(0.389)	(0.627)	(0.768)
Modern floor	-0.894	15.761	-50.724	-20.211
	(0.986)	(0.211)	(0.184)	(0.430)
Handcrafted LED	-9.829	0.960	-64.496	-19.938
	(0.726)	(0.904)	(0.108)	(0.354)
Mobile LED	-104.698	-13.120	72.072	99.724
	(0.061)*	(0.552)	(0.331)	(0.008)***
Household owns land	-57.488	-18.418	-180.938	-67.553
	(0.314)	(0.378)	(0.135)	(0.113)
Household owns one goat	44.618	11.146	-60.298	-0.667
	(0.359)	(0.438)	(0.186)	(0.965)
Household owns several goats	-10.393	-0.429	-42.010	-28.114
	(0.820)	(0.967)	(0.478)	(0.170)
Household owns one cow	-14.606	-13.052	36.974	8.110
	(0.748)	(0.290)	(0.281)	(0.565)
Household owns several cows	-0.574	-18.584	-38.480	2.483
	(0.989)	(0.065)*	(0.509)	(0.897)
Head of household completed primary school	-10.490	-6.117	-25.867	2.283
	(0.755)	(0.488)	(0.427)	(0.793)
Head of household completed secondary school	-22.247	-20.982	12.455	23.273
	(0.748)	(0.459)	(0.902)	(0.601)
Redistributed between strata for randomization	99.878	-28.758	0.900	55.525
	(0.347)	(0.139)	(0.991)	(0.187)
Constant	463.535	86.662	80.674	-55.506
	(0.054)*	(0.060)*	(0.603)	(0.313)
Observations	287	287	257	257
Adjusted R-squared	0.000	-0.042	-0.006	0.092

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values; Standard errors are clustered at the village level.
Outcome variables have been transformed to a decimal system. For retransformation multiply with 0.6.

Table 8b: Daily time spent on domestic labour and income generation

VARIABLES	Total time of head of household	Time during night of head of household	Total time of spouse	Time during night of spouse
Treatment	34.898	-0.633	16.890	-0.000
	(0.215)	(0.823)	(0.354)	(0.462)
Consumption of candles	0.115	-0.030	-0.038	-0.000
	(0.953)	(0.828)	(0.983)	(0.178)
Consumption of kerosene	17.951	0.640	-44.361	0.000
	(0.022)**	(0.292)	(0.107)	(0.070)*
Number of household members	14.813	0.366	12.094	0.000
	(0.072)*	(0.647)	(0.208)	(0.063)*
Number of mobile phones	27.912	-2.668	-47.178	-0.000
	(0.374)	(0.169)	(0.088)*	(0.029)**
Plastered dwelling	5.573	15.244	-77.895	0.000
	(0.935)	(0.138)	(0.131)	(0.708)
Modern wall	-45.806	-9.566	4.021	-0.000
	(0.471)	(0.071)*	(0.955)	(0.084)*
Modern floor	24.199	6.033	111.740	0.000
	(0.701)	(0.377)	(0.058)*	(0.364)
Handcrafted LED	-13.573	0.767	-90.818	0.000
	(0.729)	(0.637)	(0.073)*	(0.035)**
Mobile LED	90.041	32.162	41.571	0.000
	(0.510)	(0.297)	(0.597)	(0.040)**
Household owns land	34.368	0.377	-113.986	-0.000
	(0.734)	(0.924)	(0.001)***	(0.042)**
Household owns one goat	-61.557	-3.939	-3.032	0.000
	(0.229)	(0.144)	(0.860)	(0.694)
Household owns several goats	-67.281	-4.119	-3.641	0.000
	(0.354)	(0.156)	(0.940)	(0.508)
Household owns one cow	9.356	-3.255	-35.505	-0.000
	(0.850)	(0.116)	(0.366)	(0.898)
Household owns several cows	37.263	4.393	-51.729	0.000
	(0.159)	(0.361)	(0.371)	(0.065)*
Head of household completed primary school	30.875	2.090	13.715	-0.000
	(0.457)	(0.156)	(0.657)	(0.355)
Head of household completed secondary school	62.866	-3.830	-45.834	0.000
	(0.530)	(0.642)	(0.588)	(0.198)
Redistributed between strata for randomization	-58.066	-8.810	-100.196	0.000
	(0.712)	(0.321)	(0.499)	(0.708)
Constant	268.389	-21.343	1,324.191	150.000
	(0.204)	(0.195)	(0.000)***	(0.000)***
Observations	218	218	219	219
Adjusted R-squared	-0.003	0.051	0.189	1.000

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values;
Standard errors are clustered at the village level.
Outcome variables have been transformed to a decimal system. For retransformation multiply with 0.6.

Table 8c: Daily time awake

VARIABLES	Total time of head of household	Time during night of head of household
Treatment	9.019	17.002
	(0.739)	(0.378)
Consumption of candles	-0.913	0.304
	(0.685)	(0.673)
Consumption of kerosene	1.820	-5.699
	(0.689)	(0.133)
Number of household members	13.346	6.049
	(0.046)**	(0.104)
Number of mobile phones	32.596	15.604
	(0.234)	(0.189)
Plastered dwelling	50.196	-30.972
	(0.293)	(0.676)
Modern wall	-39.148	10.260
	(0.222)	(0.751)
Modern floor	-20.131	22.464
	(0.727)	(0.508)
Handcrafted LED	23.839	-52.063
	(0.551)	(0.081)*
Mobile LED	27.487	7.605
	(0.741)	(0.841)
Household owns land	124.099	-46.603
	(0.325)	(0.149)
Household owns one goat	-66.221	-3.483
	(0.068)*	(0.916)
Household owns several goats	-52.641	6.490
	(0.094)*	(0.770)
Household owns one cow	24.014	-20.545
	(0.308)	(0.268)
Household owns several cows	67.650	13.639
	(0.078)*	(0.540)
Head of household completed primary school	59.966	4.630
	(0.083)*	(0.745)
Head of household completed secondary school	101.419	10.572
	(0.160)	(0.781)
Redistributed between strata for randomization	47.874	-15.860
	(0.504)	(0.762)
Constant	1,132.298	1,563.754
	(0.000)***	(0.000)***
Observations	287	256
Adjusted R-squared	0.001	0.040

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values;
Standard errors are clustered at the village level.
Outcome variables have been transformed to a decimal system. For retransformation multiply with 0.6.

Table 9a: Study pattern (only households with children at school age; 6-17 years)

	Share of households with children studying after school	Share of households with children studying at home after nightfall
Treatment	0.053	0.142
	(0.389)	(0.006)***
Consumption of candles	-0.008	-0.006
	(0.188)	(0.088)*
Consumption of kerosene	0.200	0.109
	(0.005)***	(0.028)**
Number of household members	0.013	0.039
	(0.522)	(0.025)**
Number of mobile phones	0.152	-0.062
	(0.077)*	(0.115)
Plastered dwelling	-0.093	-0.029
	(0.405)	(0.768)
Modern wall	0.071	-0.074
	(0.344)	(0.181)
Modern floor	-0.105	0.001
	(0.407)	(0.992)
Hand-crafted LED	0.170	0.111
	(0.093)*	(0.122)
Household owns land	0.084	
	(0.379)	
Household owns one goat	0.160	0.049
	(0.164)	(0.494)
Household owns several goats	0.163	0.009
	(0.081)*	(0.889)
Household owns one cow	0.179	-0.035
	(0.099)*	(0.579)
Household owns several cows	0.139	0.043
	(0.211)	(0.659)
Head of household completed primary school	-0.051	-0.086
	(0.469)	(0.076)*
Head of household completed secondary school	0.174	0.047
	(0.353)	(0.747)
Redistributed between strata for randomization	1.404	0.284
	(0.000)***	(0.021)**
Pseudo R-Squared	0.22	0.29
Number of Observations	209	209

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values; Standard errors are clustered at the village level.

Table 9b: Study pattern (only households with children at school age; 6-17 years)

VARIABLES	(1) Time children study m611 total	(2) Time children study m611 night	(3) Time children study f611 total	(4) Time children study f611 night
Treatment	21.677	20.717	19.396	17.896
	(0.093)*	(0.045)**	(0.533)	(0.090)*
Consumption of candles	-0.056	-0.818	-2.145	-2.005
	(0.968)	(0.525)	(0.354)	(0.142)
Consumption of kerosene	27.913	36.604	35.199	42.368
	(0.141)	(0.021)**	(0.190)	(0.000)***
# of household members	-0.394	-1.548	0.586	-4.349
	(0.926)	(0.728)	(0.952)	(0.132)
Number of mobile phones	17.281	-8.491	-36.963	-13.436
	(0.450)	(0.503)	(0.218)	(0.144)
Plastered dwelling	-14.352	-38.274	-87.895	-35.751
	(0.639)	(0.052)*	(0.183)	(0.072)*
Modern wall	3.435	26.824	91.559	-6.578
	(0.861)	(0.159)	(0.145)	(0.726)
Modern floor	-48.736	-36.603	8.429	-29.381
	(0.397)	(0.131)	(0.889)	(0.071)*
Hand-crafted LED	23.893	25.171	47.443	57.773
	(0.285)	(0.293)	(0.279)	(0.001)***
Mobile LED	47.961	78.711	162.397	139.533
	(0.275)	(0.071)*	(0.023)**	(0.000)***
Household owns land	49.601	41.979	-2.465	0.857
	(0.117)	(0.136)	(0.941)	(0.966)
Household owns one goat	36.085	6.248	-65.871	-2.252
	(0.218)	(0.828)	(0.325)	(0.934)
Hh owns several goats	18.801	14.272	-67.680	29.021
	(0.497)	(0.581)	(0.397)	(0.162)
Household owns one cow	42.575	32.030	88.579	-13.953
	(0.091)*	(0.232)	(0.244)	(0.430)
Hh owns several cows	39.019	69.939	85.677	22.076
	(0.286)	(0.012)**	(0.376)	(0.427)
Head of household completed primary school	-10.078	3.784	-19.635	9.669
	(0.611)	(0.748)	(0.345)	(0.528)
Head of household completed secondary school	8.449	-13.685	-105.612	-18.220
	(0.879)	(0.798)	(0.526)	(0.662)
Redistributed between strata for randomization	-22.938	-37.743	242.863	58.804
	(0.498)	(0.129)	(0.049)**	(0.104)
Constant	-55.092	1.256	-4.198	-33.329
	(0.231)	(0.985)	(0.959)	(0.346)
Observations	100	101	92	92
Adjusted R-squared	0.204	0.258	-0.040	0.329

Note: Robust pval in parentheses; *** $p<0.01$, ** $p<0.05$, * $p<0.1$;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values;
Standard errors are clustered at the village level.
Outcome variables have been transformed to a decimal system. For retransformation multiply with 0.6.

Table 9c: Study pattern (only households with children at school age; 6-17 years)

VARIABLES	(5) Time children study m1217 total	(6) Time children study m1217 night	(7) Time children study f1217 total	(8) Time children study f1217 night
Treatment	35.387	23.497	17.404	16.837
	(0.191)	(0.382)	(0.327)	(0.191)
Consumption of candles	-4.250	-4.168	-1.684	-0.854
	(0.256)	(0.207)	(0.130)	(0.486)
Consumption of kerosene	23.674	24.780	19.667	34.258
	(0.349)	(0.245)	(0.384)	(0.166)
# of household members	7.720	3.868	-0.121	-9.756
	(0.453)	(0.473)	(0.990)	(0.224)
Number of mobile phones	53.754	48.771	16.059	30.158
	(0.096)*	(0.098)*	(0.540)	(0.115)
Plastered dwelling	60.881	16.034	24.574	-23.757
	(0.128)	(0.685)	(0.702)	(0.715)
Modern wall	-84.749	-45.013	-7.744	27.478
	(0.113)	(0.411)	(0.876)	(0.356)
Modern floor	-130.294	-90.490	-40.608	-48.511
	(0.015)**	(0.134)	(0.482)	(0.372)
Hand-crafted LED	-12.113	-5.273	29.156	9.080
	(0.775)	(0.894)	(0.356)	(0.796)
Mobile LED	-98.814	-19.806	75.930	134.141
	(0.163)	(0.761)	(0.459)	(0.104)
Household owns land	30.819	21.946	-40.240	-54.034
	(0.398)	(0.572)	(0.566)	(0.431)
Household owns one goat	69.840	21.248	29.489	4.769
	(0.114)	(0.575)	(0.404)	(0.908)
Hh owns several goats	28.914	26.683	7.878	28.657
	(0.545)	(0.522)	(0.767)	(0.105)
Household owns one cow	-0.046	-20.610	-15.382	-14.186
	(0.999)	(0.555)	(0.538)	(0.712)
Hh owns several cows	-58.250	-81.834	40.908	13.216
	(0.210)	(0.041)**	(0.474)	(0.791)
Head of household completed primary school	25.100	0.865	-25.229	-26.903
	(0.357)	(0.971)	(0.281)	(0.294)
Head of household completed secondary school	21.427	25.836	-96.871	-92.160
	(0.740)	(0.703)	(0.003)***	(0.002)***
Redistributed between strata for randomization	246.270	221.981	16.778	32.953
	(0.008)***	(0.019)**	(0.773)	(0.562)
Constant	-469.789	-337.756	108.898	177.112
	(0.003)***	(0.033)**	(0.487)	(0.294)
Observations	89	89	94	94
Adjusted R-squared	0.131	0.080	-0.152	0.017

Note: Robust pval in parentheses; *** p<0.01, ** p<0.05, * p<0.1;
Randomization strata dummies are included in all estimations; Control variables refer to baseline values;
Standard errors are clustered at the village level.
Outcome variables have been transformed to a decimal system. For retransformation multiply with 0.6.