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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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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, we examine uptake and impacts of a simple Pico-Photovoltaic kit that barely exceeds the modern energy benchmark defined by the United Nations. We 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. JEL codes: D13, H23, H43, I31, O13, O18, Q41.

Keywords: Sustainable Energy for All (SE4All), household welfare, household technology adoption, Sub-Saharan Africa, Randomized Controlled Trial.

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

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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. (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.

I. 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

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.

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 fig. 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.

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 a quality certificate 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. The objective of Lighting Global's initiative in the region, *Lighting Africa*, is to provide access to certificated Pico-PV kits to

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.

Figure 1. Traditional lighting devices

Source: Own illustration

250 million people by 2030. The Pico-PV lantern and the panel used for the present study were certified by Lighting Africa.[3]

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

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.

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

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.

II. 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 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 non-agricultural 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]

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, available at http://wber.oxfordjournals.org/), we do not further investigate any of these effects as most households use the Pico-PV kit only for lighting.

III. 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

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.

FIGURE 2. The Pico-PV kit

Source: Own illustration

phone charger, a radio including a charger, and a back-up battery package (see Fig. 2).[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.

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 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

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).

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.

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 min-max 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 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.

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.

IV. 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 table 2).

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

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

	Treatment		Control total (SD)	*t*-test/chi-2-test (total treated vs. control *p*-values)
	total (SD)	noncompliant (SD)		
Household size [1]	4.85 (2.0)	5.5 (1.5)	5.0 (2.0)	0.491
HH's composition (%)				
Share children 0–15 years	39 (24)	51 (16)	38 (23)	0.680
Share elderly 65+	7 (20)	2 (6)	5 (16)	0.389
HH's head male (%)	76	84	76	0.892
Age of the HH's head	47 (15)	45 (17)	48 (15)	0.795
Education of HH head (%) [1]				
None	35	53	35	0.857
Primary education	61	42	60	
Secondary education and more	4	5	5	
Cultivation of arable land (%) [1]	99	100	98	0.314
Ownership of arable land (%) [1]	95	90	95	0.791
Ownership of cows (%) [1]				
No cow	63	84	69	0.542
One cow	22	11	19	
More than one cow	15	5	12	
Ownership of goats (%) [1]				
No goat	68	79	74	0.476
One goat	16	5	14	
More than one goat	16	16	12	
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	0.854
District (%) [2]				
Gicumbi	19	16	20	0.997
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.

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

	Treatment		Control total (SD)	*t*-test/chi-2-test (total treated vs. control *p*-values)
	total (SD)	non-compliant (SD)		
Lighting hours, categorized [2] (%)	19	26	19	
No lamps or candles				
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	0.910
Usage of hand-crafted LED[1] (%)	37	26	35	0.628
Usage of mobile LED[1] (%)	4	5	3	0.520
Consumption of candles[1] (pieces per month)	1.25	2.32	1.76	0.356
Usage of wick lamps (%)	49	47	47	0.727
Usage of no artificial lighting (%)	12	16	11	0.715
Consumption of kerosene for lighting [1] (in liter per month)	0.46	0.35	0.54	0.372
Radio ownership [2] (%)	64	32	64	1.000
Mobile phone ownership [2] (%)	36	32	36	1.000
Number of mobile phones [1]	0.49	0.21	0.47	0.876
N	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.

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 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.

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.

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.

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.

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

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.

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.

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.

Looking at *total energy expenditure* (table 6), 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. 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.

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

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[a]	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.
[a]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.

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.[12]

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

12. See supplemental appendix, table S6.2, for more detailed results.

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 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.[13] 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 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 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.

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.[14] Both the head of household and the

13. 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.

14. 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

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. 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.

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.

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.

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 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.

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.[15]

V. 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 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.

15. 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).

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.

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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