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

Abstract

More than 1.3 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 initiative Sustainable Energy for All (SE4All) has proclaimed the goal of providing modern energy to all by 2030. In recent years, Pico-Photovoltaic kits have become a lower-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 benchmark of what the UN considers as modern energy. We find significant effects on households' budget, productivity and convenience. Despite these effects, the data shows 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 Classification: O13, O18, Q41, D13, I31

Keywords: Energy access; household productivity; household technology adoption; Sub-Saharan Africa; Randomized Controlled Trial

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1. Introduction

More than 1.3 billion people in developing countries lack access to electricity. Some 590 million of them live in Africa (IEA 2012), where the rural electrification rate is only 14 percent (SE4All 2013). Providing access to electricity is frequently considered a precondition for sustainable development and the achievement of the Millennium Development Goals (MDGs, UN 2005). Based on such assumptions, the United Nations aims for universal access to electricity by 2030 via their initiative Sustainable Energy for All (SE4All, see also UN 2010). The investment requirements of achieving this target are enormous, estimated by the IEA (2011) to be about 640 billion US Dollars.

In recent years, costs of 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 behaviour and the changes in people's living conditions when households make this first step towards modern energy. We examine this using 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 29.50 USD. This is the first study to examine whether the Pico-PV kits meet the energy demands of the main target group of Pico-PV technology, i.e. the bottom-of-the-pyramid living in a country's periphery that will not be reached by the electricity grid in the years, probably decades, to come.

The role of governments and the international community in the promotion of Pico-PV technology is not defined so far. The expectation of World Bank's Lighting Africa program, for example, as well as other donors is that Pico-PV kits can in principle make inroads to African households via commercial markets and without public subsidies. While this assumption might be true for the relatively well-off strata in rural areas, it is most notably the major target group of Pico-PV kits that is located way beyond the reach of the grid in more remote areas and that is short on cash and access to credit. These households 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 in fact 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. It is the purpose of our paper to provide empirical substance to this debate.

Only very little evidence exists so far on the take-up and impacts of Pico PV kits. To our knowledge, the only published study is Furukawa (2014), which concentrates on educational outcomes alone. Based on an RCT in Uganda with a Pico-PV lamp he examines the effect on educational outcomes. This study finds that kids' study hours clearly increased among solar lantern owners, but no effects on test-scores are observed. On the contrary, kids in solar lantern owning households show weaker test results than non-owners. A related branch of literature examines the socio-economic effects of rural electrification on households; this is access to higher tier electricity technologies such as a grid connection and solar home systems. They typically find positive effects after provision of electricity access. Grogan and Sadanand (2012) observe an increase in female labour market participation in Nicaragua. Khandker, Barnes, and Samad (2012, 2013), for example, observe a substantial increase in household income and completed schooling years in Bangladesh and Vietnam. Van de Walle et al. (2013) examine effects of rural electrification in India and find also evidence for an increase in consumption and improved schooling outcomes.

The only study that examines such effects in the African context is Bensch, Kluve, and Peters (2011). Using data from Rwanda they find that people use electricity mostly for lighting and hardly for other appliances. They observe no further changes in household behaviour; also kids' home study hours and household income are not affected significantly. Samad et al. (2013) examine solar home system usage in Bangladesh. The authors find positive effects on evening studying hours of school kids, an increase in TV usage, followed by an increase in female decision-making power, a decrease in respiratory disease symptoms resulting from reduced kerosene usage as well as an increase in expenditures.

The present paper therefore is the first to study the effectiveness of the low-cost alternative to on-grid electrification and solar home systems in combatting energy poverty on a broader set of socio-economic indicators. The research questions we pursue are as follows: First of all, it is far from obvious that rural households use the new technology at all. Cohen and Dupas (2010) provide a short review of why goods that are given away for free may be under-utilized. Second, provided that households use the kit, it is interesting to know which household member uses it. Because of its limited capacity, within each household the kit shares more characteristics with a rivalrous than a non-rivalrous good (in contrast to a high-capacity grid connection) and hence it is plausible to assume that there is competition to use the kit among household members. Third, it is important to examine usage patterns: do beneficiaries use the kit in addition or as a substitute to traditional lighting sources, such as candles, battery-driven torches and kerosene lamps? In other words, does the income effect that results from the free access to the kit (albeit in limited quantity) override the substitution effect? Fourth, it is interesting to analyse for which purpose people use the device. Do they expand their activities that require lighting into night-time, or do they just shift activities from daytime to night-time?

We do not make an attempt to measure impacts on market income, labour supply and alike. The reason is that the potential effects of the treatment in terms of market-oriented activities are only very modest. Market access in such remote areas is very limited and income is virtually only generated by subsistence agriculture. Therefore, potential time savings cannot plausibly translate into measurable effects on market income, even if the sample size was much bigger than ours. Hence, we concentrate on productivity effects in domestic production and budget effects through the reduction of energy expenditures. In addition, we look at convenience effects that are induced through higher quality lighting and improved accessibility of simple energy services.

Our findings show that households use the kits intensively and that they can reduce their energy expenditures substantially. The consumption of harmful kerosene, candles and small batteries is significantly reduced. Moreover, we find that children shift part of their homework into the evening hours, albeit in sum they do not study more. 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. First, when solar kits replace kerosene lamps, the use of solar kits reduces the incidence of respiratory diseases. Thus, from a public health perspective, usage of the solar kits bears a potential externality. Second, if children study longer or better, educational achievements might improve, which constitutes an important externality in terms of the economy-wide human capital stock. Third, battery waste is a significant threat to the environment in Africa, where appropriate disposal systems do not exist. A reduction in battery consumption hence is another positive externality. Finally, a reduction in energy expenditures helps to reduce poverty, which is a political goal in all developing countries.

The remainder of the paper is organized as follows: Section 2 provides the policy and country background. Section 3 describes the underlying theoretical model that will guide our empirical analysis. Section 4 presents our experimental design. Section 5 discusses all results, and Section 6 concludes.

2. Background

2.1 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. The most common ones are small LED-torches and mobile LED-lamps that exist in various shaping, for example a battery driven hurricane lamp (see Figure 2). In addition, many rural households use hand-crafted LED lamps, i.e. LED-lamps that are removed from torches and installed somewhere in the house or on a stick that can be carried around. Yet, both traditional lighting sources and dry-cell batteries are expensive and the costs per lumen hour are much higher than for grid or solar fed lighting sources (if investment costs are not included). For rural households in Africa, lighting expenditures 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. It is against this background that the United Nations have launched the Sustainable Energy for All initiative (SE4All) to provide modern energy to everybody by 2030 (see UN 2010, SE4All 2013). 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 or even a situation in which lighting can hardly be considered a scarce good (like in industrialized countries). A regular connection to the national electricity grid is of course much more powerful and hence allows for usage of more appliances than a connection to a mini-grid or an individual solar home system.

This continuum has sometimes been referred to as the *energy ladder*. In fact, SE4All has now defined different tiers of modern energy access within its Global Tracking Framework (SE4All 2013) according to the electricity supply that is made available. A regular connection to the national grid allowing for using general lighting, a television, and a fan the whole day would thereby qualify, for example, for Tier 3 or more. A solar home system would qualify for Tier 1 or 2 (depending on its size). 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.[1] 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 29.50 USD, World Bank (2009) estimates a cost range for on-grid electrification in rural areas of 730 to 1450 USD per connection.

The promotion of Pico-PV kits is most prominently pursued by the World Bank program *Lighting Africa.* 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, provides market research and facilitates access to finance to market players, and has introduced a quality certificate. The objective of 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 are certified by Lighting Africa.[2]

2.2 Country Background

Rwanda's energy sector is undergoing an extensive transition with access to electricity playing a dominating role. While the focus is clearly on the huge Electricity Access Roll-Out Program (EARP) and no particular government interventions so far are targeting off-grid and solar solutions, the Government of Rwanda explicitly welcomes activities that intend to improve the access to solar

[1] The investment requirements calculated by IEA (2011) of additional 640 billion US Dollars 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.

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

energy in rural areas. Also for Pico-PV, no particular promotion scheme is in place, but the Government cooperates with Lighting Africa and in general is very favourable towards private sector players. The few existing firms that sell Lighting Africa-certificated Pico-PV kits 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-assured, but cost only between 500 FRW (0.82 USD) 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. The investment into the Pico-PV lamp used for this study amortizes after 1200 lighting hours if it replaces an LED hurricane lamp and after less than 600 lighting hours if it replaces a kerosene driven lamp. Assuming that a household uses the lamp for four hours per day, the Pico-PV lamp pays off after 10 months if the LED hurricane lamp is replaced and after less than 5 months if it replaces a kerosene driven lamp.

3. The Theoretical Model

In what follows, we present a theoretical framework that will guide our empirical analysis. We rely on a model that Van de Walle et al. (2013) developed for the evaluation of electrification effects and adapt it to the particularities of providing access to Pico-PV kits. We assume that the Pico-PV treatment affects three dimensions of living conditions: First, the *productivity* of domestic production, i.e.

production not intended to be traded on competitive markets. The reason for only focussing on domestic production is that the Pico-PV kit will not affect agricultural production, which in turn is virtually the only source of tradable goods produced in these remote areas with only very limited access to markets.

Second, 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. Third, the *convenience effect* which refers to the direct effect that the Pico-PV kit has on people's well-being, as it improves the quality and quantity of light at home relative to traditional lighting sources such as kerosene and candles or hand-crafted LED-torches. This effect is independent of any reallocation of time across activities.

As in van de Walle et al. (2013), we assume that households derive utility from goods, $\boldsymbol{Z}$, and recreation or leisure time, $\boldsymbol{R}$. Hence, the utility function is defined as strictly increasing and quasi-concave and has the following form:

$$\boldsymbol{U} = \boldsymbol{U}(\boldsymbol{Z}, \boldsymbol{R_L}, \boldsymbol{R_D}). \tag{1}$$

Leisure can be spent under light, $\boldsymbol{R_L}$, or in darkness, $\boldsymbol{R_D}$ (here and in what follows light includes non-electric sources of light). We further assume that the marginal utility of recreation in light $\boldsymbol{R_L}$ is higher than the recreation in darkness $\boldsymbol{R_D}$, because recreation under light allows for a wider set of potential activities than darkness. These activities may include reading or socializing. Moreover, in the given context it is plausible to assume that the household is light constrained, i.e. $\boldsymbol{U'_{R_L}} > \boldsymbol{U'_{R_D}}$.

We abstract, as do van de Walle et al. (2013), from preference shifts induced by electric lighting. While such shifts are imaginable in the case of full electricity access because of, for example, the increased usage of information technologies related to electricity access or the psychological effects of improved lighting, in the present case of a Pico-PV treatment it is less likely to be relevant.

The good $\boldsymbol{Z}$ is domestically produced according to the following production function:

$$\boldsymbol{Z} = \boldsymbol{Z}(\boldsymbol{D}(\boldsymbol{E}), \boldsymbol{C_e}, \boldsymbol{C_o}), \tag{2}$$

where $\boldsymbol{D}$ denotes domestic labour and $\boldsymbol{C_e}$ denotes consumption of energy in any form, such as firewood, kerosene, dry-cell batteries, candles and also electricity as generated by a Pico-PV kit. The productive activities may for instance include cooking, studying or charging a cell phone. $\boldsymbol{C_o}$ stands for the quantity of other goods consumed. $\boldsymbol{E}$ refers to access to electricity and increases the labour productivity in household production. In this model, $\boldsymbol{E}$ is treated as a continuous variable which reflects the non-binary character of electricity access ranging from Pico-PV kit to a high quality grid connection. In the empirical analysis, though, we will take it as a binary variable, since no other competing electricity source is available in the region.

As for recreation, for labour we also distinguish labour under electric light, $\boldsymbol{D_L}$, and labour in darkness, $\boldsymbol{D_D}$. Since $\boldsymbol{E}$ shifts the production function, we assume that labour under electric light is more productive than labour in darkness, hence $\boldsymbol{Z'_E} > \boldsymbol{0}$ and $\boldsymbol{Z'_{D_L}} > \boldsymbol{Z'_{D_D}}$.

We can now write the time constraint of the household as follows:

$$\boldsymbol{T} = \boldsymbol{D} + \boldsymbol{R} = \boldsymbol{D_L}(\mathbf{E}) + \boldsymbol{D_D} + \boldsymbol{R_L}(\mathbf{E}) + \boldsymbol{R_D}, \tag{3}$$

where each time use is positive: $\boldsymbol{D_L}(\boldsymbol{E}) \geq \boldsymbol{0}$, $\boldsymbol{D_D} \geq \boldsymbol{0}$, $\boldsymbol{R_L}(\boldsymbol{E}) \geq \boldsymbol{0}$ and $\boldsymbol{R_D} \geq \boldsymbol{0}$. We normalize the time endowment to one so that the allocation of time is characterized through fractions of the total endowment $\boldsymbol{T}$. The time endowment $\boldsymbol{T}$ does not include an incompressible time window people need to spend sleeping (typically in darkness) and the time they spend in a labour market activity, typically on their own farm or in paid employment. These two time uses are exogenously fixed and are not significantly affected by the availability of a Pico-PV kit. Hence, farm or market income, $\mathbf{Y}$, is also exogenous.

Hence, the budget constraint can be written as follows:

$$\boldsymbol{p_e}(\boldsymbol{E})\boldsymbol{C_e} + \boldsymbol{C_o} = \boldsymbol{Y}. \tag{4}$$

The price of C_0 is set equal to one, it is hence the *numéraire* in our model. An increase of E is assumed to reduce the price of energy including light, i.e. $p'_{eE} < 0$, since all alternative available energy sources are associated with higher costs per lumen hour.

The Lagrangian associated with the constrained maximisation problem can be written as follows:

$$L = U(Z, R_L, R_D) - \gamma(p_e(E)C_e + C_0 - Y) - \mu(D_L(E) + D_D + R_L(E) + R_D - 1). \quad (5)$$

Assuming E as exogenously determined, the first order conditions are:

$$\partial L / \partial Z = U'_Z - \gamma\left(p_e(E)C'_{e_Z} + C'_{0_Z}\right) - \mu\left(D'_{L_Z} + D'_{D_Z} + R'_{L_Z} + R'_{D_Z}\right) = 0 \quad (6)$$

where in the optimum we must have $U'_Z = U(Z'_{D_{L(E)}} + Z'_{C_e} + Z'_{C_0})$,

$$\partial L / \partial R_L = U'_{R_L} - \mu = 0 \text{ and} \quad (7)$$

$$\partial L / \partial R_D = U'_{R_D} - \mu = 0. \quad (8)$$

Hence, the household chooses simultaneously the optimal amounts of Z, R_L and R_D given the exogenous available level of lighting as well as the budget and time constraints. The choice of Z in turn requires to choose D_L, C_e and C_0. Labour, energy and market goods are used in order to equate the marginal rates of transformation with the shadow price of labour, the price of energy and the price of market goods. The marginal rates of substitution between consumption of the domestically produced good and recreation under light and in darkness are equated to the price ratios between the shadow price of the domestically produced good as well as the shadow prices of recreation under light and in darkness. The marginal utility of recreation under light is equated to the marginal utility in darkness.

If in the optimum access to electricity E changes exogenously the optimization problem above implies that the price of energy is reduced, electric light is available (for free) and domestic labour is more productive. The increase in the productivity of labour leads to an increase in the output of household production. This is the *productivity effect*. The lower price of energy will increase energy consumption and recreation given the income effect and depending on the rate of substitution between the domestically produced good and leisure lead to an increase or decrease of consumption of the domestically produced good. This is the *budget effect*. The increased availability of electric light (for free) leads to a substitution between recreation in the darkness by recreation under light. This is the *convenience effect*. Hence, the model implies that $\mathbf{d}\boldsymbol{U}/\mathbf{d}\boldsymbol{E} > \mathbf{0}$, since

$$\frac{\partial \boldsymbol{Z}}{\partial \boldsymbol{D}_{\boldsymbol{L}}}\frac{\mathrm{d}\boldsymbol{D}_{\boldsymbol{L}}}{\mathrm{d}\boldsymbol{E}} > \mathbf{0}, \quad \frac{\partial \boldsymbol{Z}}{\partial \boldsymbol{C}_{\boldsymbol{e}}}\frac{\mathrm{d}\boldsymbol{p}_{\boldsymbol{E}}}{\mathrm{d}\boldsymbol{E}} > \mathbf{0} \text{ and } \frac{\partial \boldsymbol{U}}{\partial \boldsymbol{R}_{\boldsymbol{L}}}\left(-\frac{\mathrm{d}\boldsymbol{R}_{\boldsymbol{D}}}{\mathrm{d}\boldsymbol{E}}\right) > \mathbf{0},$$

where the first term refers to the *productivity effect*, the second to the *budget effect* and the third to the *convenience effect.* In our empirical analysis we seek to identify causal evidence in support of these three effects.

4. Research Approach and Data

4.1 Treatment and Identification Strategy

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. 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 (i.e. inside or after nightfall). The complete kit costs around 29.50 USD, the smallest version with only the solar panel and an LED lamp including an installed battery costs around 16.50 USD.

Figure 1: The Pico-PV kit

Source: Own illustration

The identification strategy relies on the randomized assignment of the Pico-PV kits at the time of the baseline survey. Households do not select themselves into the treatment and thereby the confusion of impacts of the program with other factors that are correlated with the outcomes of interest and selection into the treatment group is avoided. As a consequence, unobserved characteristics cannot distort the impact assessment afterwards. All differences in follow-up outcomes can be attributed to the treatment.

We estimate intention-to-treat effects (ITT). They are obtained by simply comparing mean values of impact indicators for the treatment and control group, without accounting for non-compliance from households that were assigned to the treatment group, but for some reason do not use the Pico-PV kit. In our case, the ITT is almost identical to the average treatment effect on the treated (ATT) given the high compliance rate in the treatment group and no selection into treatment in the control group. Since all results are robust with regard to both ways of estimating impacts, we generally display in the following only the more conservative ITT results.

4.2. Impact Indicators

As a pre-condition for the three effects on budget, productivity and convenience, which we identified in the theoretical model, the households' usage behaviour is our first matter of interest. We look at usage and charging patterns of the Pico-PV kit and analyse 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 Section 5.2.1), we focus in particular on this service.

For budget effects, we first look at changes in the price of the energy service. For this purpose, we calculate the *price per lighting hour* and *price per lumen hour* the households effectively pay. Second, we analyse whether price effects translate into a change in lighting consumption as suggested by the model. 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 (kerosene, batteries, candles) by the number of lighting hours consumed. For calculating lumen hours we multiply the lamp specific lighting hours with the amount of lumen (lm) emitted per lamp.

The different lighting sources used by the households emit very different amounts of lumen. The 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 a mobile LED lamp reaches levels around 100 lm (O'Sullivan and Barnes 2006). Lumen levels emitted by hand-crafted LED lamps vary substantially depending on the number and quality of diodes and batteries used. 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 connected to a battery package of three very low batteries and three slightly fuller batteries, respectively) in a laboratory at the University of Ulm, Germany, using standard lumen emission test procedures. Based on these tests we estimate an average level of 10 lm emitted by hand-crafted LED lamps.

Finally, we look at changes in *total energy expenditures* and in the expenditures for the different energy sources kerosene, batteries, candles, and charcoal (for ironing only). We also examine to what extent the reduced usage of kerosene leads to a perceived improvement of *air quality* and, potentially, into a decrease in *respiratory disease symptoms* and *eye problems*.

Figure 2: Traditional lighting devices

hurricane lamp	traditional tin lamp	ready-made torch	hand-crafted LED lamp	mobile LED lamp

Source: Own illustration

For productivity effects we look at the main users' domestic labour activities exercised when using the Pico-PV lamp. The main domestic labour activity for adults is housework while children use the lamp mainly for studying. We assess the gain in household productivity by analysing the *lighting source used* for these respective activities. Following the theoretical model, households become more productive when they switch from a lower quality lighting source to the Pico-PV lamp. A switch from no artificial lighting to the Pico-PV lamp is also considered a productivity gain.

To this end, 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. For the head of household and the spouse, interviewees specified the time these persons get up, the exact periods in the course of the day when they exercise income generating activities (including subsistence farming) and do housework, and when they go to bed. For children we furthermore elicited from which time to which time children study at home and outside their home (at a neighbour's house etc.) after school.

Since we know the exact time of each activity for every household member, we are able to distinguish between activities that are pursued before and those that are pursued after nightfall. If a certain activity pursued by the household is not

associated to 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 by other household members.
In order to analyse whether the higher productivity also leads to an increase in total domestic labour input, we analyse the total amount of *time dedicated to domestic labour per day*.

We have not made an attempt to measure whether increased productivity in domestic production may indirectly also affect production for the market, which would require focusing on business incomes and alike. In line with the hypotheses built in our theoretical model, Pico-PV kits can only provide energy for basic needs including lighting and small appliances. It is the very 'first step' on the energy ladder and the provision of energy at this level is typically not intended to enhance market income generating or improve agricultural production.

For convenience effects, we assess how household members distribute their time given the increased availability and higher quality of lighting. For this purpose, we look at the *time dedicated to recreation*. We calculate the recreation time by subtracting the time household members spend on income-generation activities and time dedicated to domestic labour from the total time household members are awake. For children at school age we subtract 4 hours and 8 hours for primary and secondary school time, respectively, which corresponds to the time children normally spend each day at school in Rwanda. Again, the theoretical model assumes that time spent on income generation activities and the total time household members are awake are not significantly affected by the treatment; this assumption can also be corroborated in our sample.

4.3 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 in the periphery of the country. 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 should be 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.

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 (binary), radio usage (binary), and district. We then randomized the treatment within the 48 strata resulting from this stratification, which ensures that the resulting treatment and control groups are balanced with regards to the stratification criteria (see Bruhn and McKenzie 2009).

We applied additionally a minmax *t*-stat method in order to assure balance for further important baseline criteria that could not be accounted for in the stratification because of dimensionality reasons.[3] Examples for such "secondary" balancing criteria are usage of dry-cell battery driven LED-lamps and wealth indicators such as housing conditions or the educational level of the head of the household. 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) in order to

3 See Ashraf et al. (2010) for an application of this combined stratified re-randomization approach.

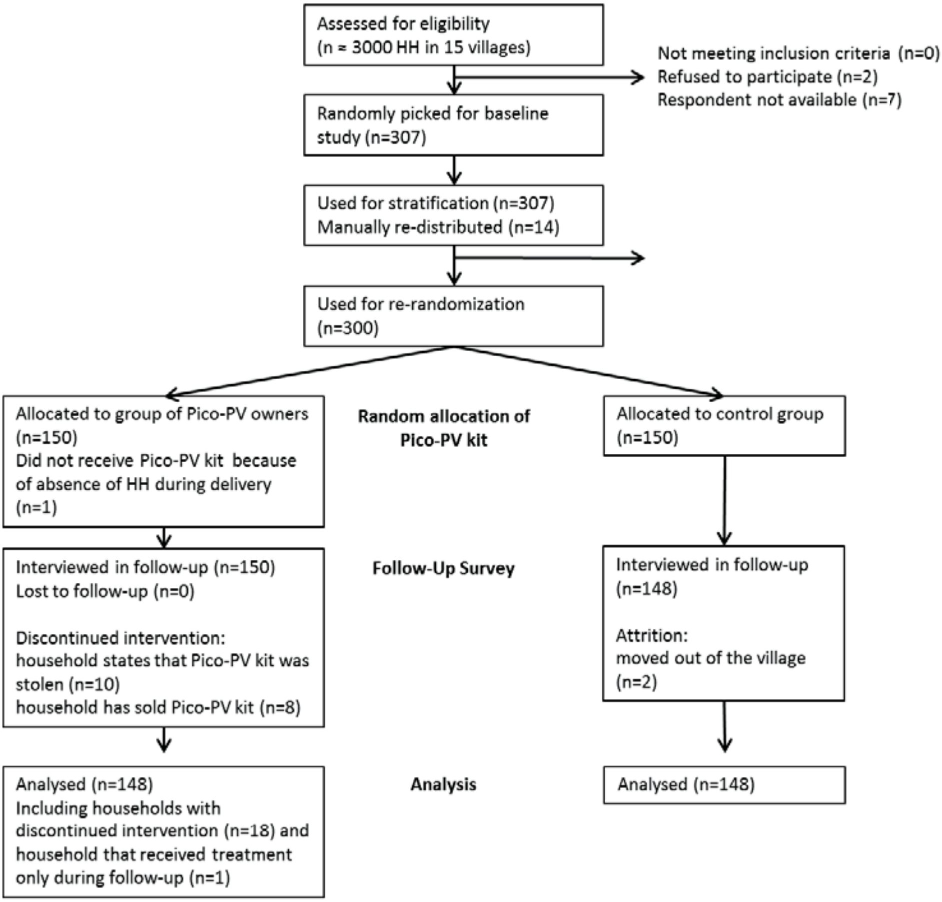
avoid resentment among the villagers. The Pico-PV "winners" furthermore were instructed on how to use the kit. This instruction was conducted by staff members of the organisation that marketed the Pico-PV kit in other regions and who are hence also responsible for instructing real customers that buy a kit at a regular sales point. Also, the content of the instruction was congruent with the ordinary instruction a real-world customer receives. Members of IB&C participated in this instruction.

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.[4] 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.

We deem the risk for spill-over effects to be rather low, since the small size of the Pico-PV kits prevents households from sharing it with other households. Indeed, we do not find any indication in our data for such effects. For example, control households do not go out more frequently after nightfall, which they would if they used the lamp for whatever purpose at the neighbour's house. Neither do control group children increase their study time outside the household.

[4] A similar procedure as applied by De Mel, McKenzie and Woodruff (2008) in an RCT on business grants among micro-enterprises in Sri Lanka

Figure 3: Participants flow



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 Annex).

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 or other issues 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 to 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 2.

5. Results

5.1 Balance of socio-economic characteristics of participating households

This section examines the balancing between treatment and control group and at the same time portrays the socio-economic conditions in the study areas. Baseline values of the households' socio-economic characteristics show that the randomization process was successful in producing two perfectly balanced groups (see Table 1). We do not find any significant difference between the treatment and the control group, neither for the characteristics used for stratification and re-randomization nor for further household characteristics. We also estimated a probit regression regressing the treatment status on all covariates and run an LR Chi-Squared test showing that there is no joint effect of the set of covariates.

The surveyed households are mainly subsistence farmers that live in very modest conditions, even by Rwandan standards. 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 1.07 USD PPP a day per person with the lower 25%-stratum having only 0.18 USD PPP (not displayed in the table). Even the upper quartile has cash expenditures of 2.86 USD PPP only. By all definitions, the sampled households qualify as extremely poor.

Also energy consumption patterns illustrate the precarious situation of most households (see Table 2): They consume on average only around 3 hours of lighting per day which is mainly provided through kerosene-driven 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 because we did not elicit usage hours for candles and torches at the baseline stage. Almost 65 percent of the household own a radio, around 40 percent have a cell phone.

If we look at the group of non-compliers, we see that they differ substantially along several characteristics that are indicative for their wealth. This suggests that non-compliers 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 1: 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)	non-compliant (sd)	total (sd)	
Household size *	4.85 (2.0)	5.5 (1.5)	5.0 (2.0)	0.491
Hh's composition (in percent)				
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 (in percent)	76	84	76	0.892
Age of the HH's head	47 (15)	45 (17)	48 (15)	0.795
Education of hh head (in percent) *				
None	35	53	34	0.855
Primary education	61	42	60	
Secondary education and more	4	5	5	
Cultivation of arable land (in percent) *	98	100	99	0.314
Ownership of arable land (in percent) *	95	90	95	0.791
Ownership of cows (in percent) *				
No cow	63	84	69	0.542
One cow	22	11	19	
More than one cow	15	5	12	
Ownership of goats (in percent) *				
No goat	68	79	74	0.476
One goat	16	5	14	
More than one goat	16	16	11	
Material of the walls (in percent) *				
Higher value than wood, mud, or clay	14	11	14	1.000
Material of the floor (in percent) *				
Higher value than earth or dung	11	5	11	0.854
District (in percent) [S]				
Gicumbi	19	16	20	0.997
Gisagara	26	32	27	
Huye	27	26	27	
Rusizi	27	26	27	
Number of observations	148	19	150	

Note: * used for re-randomization: [S] used for stratification

Table 2: 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)
N		129	19	150	
Lighting hours, categorized S					
	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*		3.1	2.7	3.2	0.910
Usage of hand-crafted LED* (in %)		37	26	34	0.629
Usage of mobile LED* (in %)		3	5	4	0.520
Consumption of candles* (pieces per month)		1.34	2.32	1.76	0.445
Usage of wick lamps (in %)		49	47	47	0.727
Usage of no artificial lighting (in %)		12	11	16	0.715
Consumption of kerosene for lighting * (in litre per month)		0.46	0.35	0.54	0.373
Radio ownership S (in %)		64	32	64	1.000
Mobile phone ownership S (in %)		36	32	36	1.000
Number of mobile phones *		0.49	0.21	0.47	0.815

Note: * used for re-randomization: S used for stratification

5.2 Impact assessment

5.2.1 Take-Up and Lighting Usage

Out of the 149 Pico-PV sets we originally randomized, 18 households do no longer possess the kit at the follow-up stage because they sold it (8 households) or it got stolen (10 households). Among the remaining 131 households that still have a Pico-PV kit, usage rates are very high (see Table 3). 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 borderline capacity of the panel, which only allows for charging all devices completely within one day if conditions are almost perfect and sunlight is exploited at a maximum. Given the households preference for lighting, too little capacity is left for the other two services. For cell phone charging, non-compatibility of the solar charger with most widely used cell phones 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 2 hours[5]).

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 use it for lighting.[6] The Pico-PV lamps are mainly used by female adults, followed by male adults (see Table 3). Children use the lamp less frequently.

Table 3: 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 6 and 11 years old	5

Traditional lamp usage goes down substantially, with 47 percent of the treatment group using exclusively the Pico-PV lamp for lighting purposes[7]. 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

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

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

[7] Table A1 in the Electronic Appendix shows a comprehensive presentation of lamp usage in the treatment and the control group.

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.

Overall, we find that the Pico-PV lamp was extensively used by the vast majority of households and has largely substituted the usage of traditional lamps. Moreover, households seem to have a clear preference for the lighting device over the other two services the Pico-PV kit allows for. This revealed preference, though, has to be interpreted with some care, since technically the lamp was the easiest to use.

5.2.2 Budget Effects and Kerosene Consumption

The major transmission channel for most impacts of the Pico-PV lamp is the price of energy and – given the primary usage of the lamp for lighting – the *price per consumed lighting hour* and the *price per consumed lumen hour* in particular. This price is decisive for the household's choice on the optimal level of lighting it consumes, both as input in the household production function as well as for spending recreation time under light.

As can be seen in Table 4, a control household pays approximately five times as much per lighting hour as a treatment household (950 FRW vs. 180 FRW; 1.56 USD PPP vs. 0.30 USD PPP) with this difference being obviously more pronounced for the price per lumen hour: A control household pays seven times more per lumen hour than a treatment household (70 FRW vs. 9 FRW; 0.12 USD vs. 0.02 USD).

This reduction in lighting costs effectively translates into a massive increase in the amount of *lumen hours consumed per day* in treatment households, which is more than two times as high as in control households (see Table 4) – reflecting the very poor lighting quality of traditional lighting sources. But also without accounting for the improved quality of lighting, the Pico-PV kit leads to an increase in lighting consumption. While baseline levels for *lighting hours consumed per day* are almost perfectly balanced between the treatment and control group, the treatment group consumes significantly more lighting hours after having received the Pico-PV lamp (15 percent more).

Table 4: Price and consumption of lighting energy

	Treatment	Control	*ITT*	p-value
Cost per lighting hour (in FRW per 100 hours)	176	950	*-702*	0.000
Cost per lumen hour (in FRW per 100 hours)	9	70	*-57*	0.000
Lighting hours consumed per day	4.43	3.85	*0.59*	0.074
Lumen hours consumed per day	142	61	*78*	0.000

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

Looking at *total energy expenditure* (see Table 5), we observe that households spend around 5 percent of their overall expenditures on kerosene, candles, and dry-cell batteries, the lighting fuels typically used in non-electrified areas. In treatment households, the Pico-PV lamp has mainly replaced wick lamps, but also LED-lamps that run on dry-cell batteries (see Section 5.1) and, as a consequence, we expect a decrease of the respective expenditures. In fact, we observe a significant and considerable reduction of kerosene expenditures of almost 70 percent. This has potentially also important implications for the households' health (see our discussion below).

Two types of dry-cell batteries are used in the households, big (Type D) and small (Type AA) batteries. While more than 90 percent of small batteries are used for lighting, more than three fourth of big batteries are used for radios. As a consequence, for small batteries, we observe a significant reduction, whereas the consumption of big batteries is not affected. Also the consumption of candles is reduced significantly. For expenditures on cell phone charging, we find a considerable reduction. The difference is not significant, though, which might be due to the small number of households that use the kit for phone charging. [8]

Table 5: Expenditures per month per category (in FRW)

	Treatment	Control	*ITT*	p-value
Candles	42	109	*-20*	0.339
Kerosene for lighting	155	609	*-418*	0.000
Charcoal	2	0	*2*	0.447
Big batteries	358	352	*-9*	0.750
Small batteries	30	72	*-43*	0.003
Mobile phone charging	407	520	*-68*	0.407
Total traditional energy sources (without cooking energy)	993	1662	*-557*	0.000
Total expenditures	37,971	31,334	*7,249*	0.276
Share of energy expenditure on total expenditures	0.04	0.07	*-0.03*	0.001

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 Electronic Appendix. Exchange rate as of November 2011: 1 USD = 607 FRW)

In total, energy expenditures without cooking energy are 557 FRW (0.92 USD PPP) lower in the treatment group with this difference being highly 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 3 percentage points from 7 percent to 4 percent.

Next to the immediate effects on the households' expenditures, the reduction of kerosene consumption might have beneficial effects on people's health. The combustion of kerosene is associated with quite harmful emissions that can lead to respiratory diseases. 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

[8] Estimating an ATT only among mobile phone users by instrumenting the effective usage of the solar mobile phone charger with the random allocation of the Pico-PV kit shows a statistically significant reduction of costs for phone charging of 1662 FRW (2.74 USD). The average households that pays for charging the mobile phone pays 1400 FRW per month (2.31 USD).

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, and during open qualitative baseline interviews many households complained about sooty kerosene lamps leading to recurring eye problems and kids having black nasal mucus.

We therefore examine the extent to which the decrease in kerosene lamp usage translates into a perceived improvement of *perceived air quality* and, potentially, into a decrease in *respiratory disease symptoms* and *eye problems*. While at the baseline stage the judgement of most households was that air quality in their houses was good (among both groups around 67 percent of the households rated the indoor air quality as good, the rest rating it as bad), in the follow-up survey 45 percent of treated households say that the air quality in their houses has improved in comparison to the baseline period, while hardly anybody in the control group makes this statement (3 percent). In an open question, virtually all treated households ascribe this improvement to the Pico-PV lamp. However, looking at reported health indicators we cannot confirm that this improved air quality leads to a better health status of the household members, which is not surprising given the rather subtle effect size over a six months period and the sample size at hand.

5.2.3 Productivity Effects

Building on the substantial usage of the Pico-PV lamp we examine the extent to which this induces a potential gain in household productivity. For this purpose, we look at the main users' domestic labour 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 control households for the respective activity.

The most frequent users of the Pico-PV lamp are female adults, of whom 87 percent use the lamp for housework. Housework done by women refers above all to cooking, but also to child caring, preparing the beds before going to sleep, and other housework activities (see Table 6). By looking at lamps used for housework among control households, we see that the Pico-PV lamp replaces lower quality lighting sources (see Table 7): The lamp is used by women who formerly had not been using any lighting device for housework and replaces wick lamps. While 42 percent of the households in the control group do not use any lighting device for housework, only 15 percent in the treatment group do. Usage of wick lamps for housework is reduced from 32 percent to seven percent.

Table 6: Activity using Pico-PV lamp per household member (in percent)

		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 between 6 and 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 what are the main activities the different lamp users are exercising while using the lamp.

Male adults also use the lamp mostly for housework, which are mainly general activities in their case, i.e. time that is not used for one particular task but for various housework activities that are difficult to specify for the respondent (but excluding recreational activities). If we compare again the lamps used by control households for these activities, we see similar patterns as for women. The Pico-PV lamp replaces wick lamps (9 percent vs. 3 percent) and is used by males who formerly had not been using any lamp for these activities (78 percent vs. 68 percent). Furthermore, the usage of ready-made torches (7 percent vs. 3 percent) and hand-crafted LEDs is reduced (5 percent vs. 1 percent). Accordingly, also male adults experience a gain in productivity for doing housework, if, again, we assume that these activities can be done better under the higher quality light of the solar lamp compared to the traditionally used lamps.

Interestingly, the total time dedicated to domestic labour per day does not change significantly (see Table 8). While for household heads the difference between treatment and control group is negligible and statistically not significant, spouses in treatment households work more than in control households. The difference is statistically not significant, though. Of course, if such effect can be confirmed, the implications for women's welfare are unclear, as the increased workload might be the result of women's low decision-making power. The third most important user groups are children between 6 and 17 years. They use the Pico-PV lamp mainly for studying (see Table 6).

Table 7: Most frequently used lamps for housework by male and female adult (percent of all households)

	Female adults				Male adults			
Lamp	Treat.	Ctrl.	*ITT*	p-value	Treat.	Ctrl.	*ITT*	p-value
Wick lamp	7	32	*-23*	0.000	3	9	*-7*	0.001
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
None	15	42	*-25*	0.000	68	78	*-9*	0.006

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 Electronic Appendix.

*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.

In order to understand changes in the productivity of studying at home, we first of all have to analyse children's study patterns and how they divide study time between daylight time and evening. We present first the time dedicated to studying per day and afterwards examine the lighting source that is used when children study after nightfall.

Table 8: Daily time spent on domestic labour

	Treatment	Control	*ITT*	p-value
Head of household, total	2h08	2h10	*-0h01*	0.950
Head of household, after nightfall	0h16	0h12	*0h04*	0.542
Spouse, total	2h48	2h30	*0h16*	0.333
Spouse, after nightfall	0h32	0h31	*0h02*	0.779

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 Electronic Appendix.

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 with no significant differences between control and treatment households. The share of children studying after nightfall, though, is significantly higher in the treatment group. The *time dedicated to studying per day* shows a comparable pattern. The total study time, i.e. after nightfall and during daytime, does not increase. We do observe, though, that children shift their study time from afternoon hours to the evening leading to an increase in study time after nightfall.[9]

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	208	67	61	*6*	0.368
Share of HH with children studying after nightfall	208	58	38	*27*	0.000
Time children study after school, total (in minutes)	208	0h54	0h50	*0h01*	0.932
Time children study after nightfall (in minutes)	208	0h41	0h25	*0h19*	0.002

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 Electronic Appendix.

[9] This result is in contrast to the findings of Furukawa (2014)

Two further important changes can be observed when looking at the lighting devices used for studying (see Table 10): First, the share of children that use wick lamps for studying is significantly reduced. Wick lamps are the most common lighting source for studying among control households. Second, the share of children studying without any lighting device is also significantly reduced; from 41 percent in the control group to 32 percent among treatment households. This effect is driven by children who study during daytime, what is in line with what we saw above: Because of the Pico-PV lamp, children switch from studying at daytime to studying at night time. When studying at daytime, children normally do not use artificial lighting. Still, more than 20 percent of children both in the treatment and the control group do not use any lighting device for studying at all. These children use indirect lighting from lamps that are used by other household members for other activities. Here, no significant difference between the two groups can be seen.

Table 10: Most frequently used lamps for studying by children (percent of HH with children at school age; N=208)

	Children (6-17 years)			
Lamp	Treat.	Ctrl.	*ITT*	p-value
Wick lamp	2	12	*-12**	0.000
Pico-PV lamp	30	0	*30***	0.000
No lamp	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 Electronic Appendix.

*Controlling for baseline kerosene consumption (continuous) causes convergence problems. We include a dummy indicating baseline kerosene consumption yes/no instead. ** 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.

Altogether, we do not observe an effect of Pico-PV kit ownership on the quantity of time children dedicate to studying. We do, however, find clear evidence for an improved quality of learning time and also for more flexibility of children to learn as indicated by the shift towards learning during evening hours. Both can be plausibly expected to increase the effectiveness of learning. Measuring this effectiveness for example in terms of improved test-scores at school is obviously beyond the scope of our study.

Finally, it is important to note here that we did not find any evidence for spill-over effects on the children of other households. For instance, in the control group the share of children studying outside their home did not increase. We also scrutinized people's activities after nightfall which we meticulously elicited in the interviews. If control households joint their treated neighbours, we would observe an increase in the indicator "going out/meeting people" – which again we did not find. 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.[10]

5.2.4 Convenience effects

Given the substantial productivity effects on domestic labour activities and the price reduction for electric lighting, we analyse how household members distribute their time between household production and recreation and assess the *time dedicated to recreation* (see Table 11).

It turns out that recreation time of most household members is not affected. Only for spouses we observe a significant difference. Spouses in treatment households enjoy significantly less recreation than those in control households. This is qualitatively in line with the observation that treatment spouses do more housework (see Section 5.2.3), but quantitatively the two effects do not add up properly, which we assume has to do with measurement error. Recreation time for male children between 6 and 11 is also substantially lower among treatment households with the differences being close to statistical significance.

[10] Table A2 in the Electronic Appendix shows some descriptive statistics on activities after nightfall.

Table 11: Daily time spent on recreation

	Treatment	Control	*ITT*	p-value
Head of household	6h49	6h48	*-0h09*	0.693
Spouse	6h10	6h35	*-0h42*	0.008
Male children 12-17	5h51	5h44	*-0h18*	0.389
Female children 12-17	5h48	5h38	*0h01*	0.966
Male children 6-11	9h20	9h23	*-0h16*	0.105
Female children 6-11	9h20	9h23	*0h06*	0.841

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 stratum dummies and re-randomization characteristics. Detailed estimation results can be found in the Electronic Appendix.

In order to assess changes in the time household members spend on *recreation under light*, we compare lighting sources used for recreational activities (see Table 12). Here, we observe that treatment households do not spend more recreation under light compared to control households. The share of households that do not use any lamp for recreational activities is similar among both groups (around 86 percent) and no substantial changes can be observed for other lighting devices.

Table 12: Most frequently used lamps for recreation (percent of all HH)

	all household members			
Lamp	Treat.	Ctrl.	*ITT*	p-value
Wick lamp	0	2	-2*	0.083
Ready-made torch	4	5	-2	0.262
Hand-crafted LED	3	5	-3	0.133
Candle	2	1	2**	0.014
Pico-PV lamp	8	0	*8**	0.001
No lamp	85	87	-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 stratum dummies and re-randomization characteristics. Detailed estimation results can be found in the Electronic Appendix.

*Probit estimation not applicable, since nobody uses lamp in control group leading to convergence problems; we display simple differences in means instead. ** Inclusion of randomization stratum dummies leads to convergence problems. We include the stratification criteria instead.

Altogether, we observe that the Pico-PV lamp is hardly used for recreational activities and convenience measured through our two indicators presented above does not increase. By contrast, the higher flexibility in when to pursue domestic production activities mentioned in Section 5.2.3, shows that the Pico-PV lamp nevertheless simplifies the organization of the daily routine.

6. Conclusion

This paper analyzed the usage and benefits of very simple but quality-certified small solar systems that were freely distributed among households in a randomized way. The 1 Watt panel and the basic energy services the Pico-PV kit provides just barely exceed the benchmark of what the United Nations Sustainable Energy for All (SE4All) initiative considers as access to modern energy (so-called Tier 1 energy access). At the same time, these Pico-PV kits are at the very bottom of the cost range for different electrification options. It can be used for a four diodes lamp and to charge cell phones and radios, but is not intended to provide energy for income generating activities.

Guided by a theoretical household utility framework we have examined the extent to which the kit increases household's welfare through lower energy expenditures per lumen (the 'budget effect'), a higher productivity in housework (the 'productivity effect'), and a higher convenience during recreation (the 'convenience effect'). Our results show that 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 mostly used service. The lamp was indeed intensively used by virtually all treatment group households. In these remote and poor areas, lighting is a scarce good and the availability of the lamp has increased 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 mere effect this perceivably has on household welfare, the usage of the lamp also implies social returns, such as major advantages for people's health (because kerosene usage is associated with harmful smoke emissions) and the environment (because dry-cell batteries are usually disposed 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 work processes like cooking or studying. Although we cannot quantify this, we assume that the solar lamp allows doing these activities better and faster than with traditional lighting sources. The solar lamp also enables households to allocate their time more freely and to shift activities towards the evening hours. Children for instance tend to shift their homework to the evening hours. Their total time spent on homework does however not increase. Also for other household members we do not find a substantial change in how they allocate the amount of time between different activities and recreation. Only for women we find some indication that the time spent on housework increases, while the time spent on recreation decreases.

Our results hence underpin 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, at least in such poor areas with very low energy consumption levels. If our findings are compared to other data sets from less remote areas, for example a comparable study that has recently been conducted on the Rwandan grid extension program (Peters et al. 2014), it also becomes evident, though, that Pico-PV kits cannot satisfy the whole portfolio of energy demand due to their capacity restrictions.

Accordingly, 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 towards 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 a market establishment policy is pursued as programs like Lighting Africa do. 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. Testing and certification procedures 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 low-quality LED lamps that has occurred in recent years without any governmental involvement. 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 life-time 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. However, it is easy to imagine that the interplay of cash and credit constraints of the target population, the lack of information, and high preferences for today's consumption 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-pyramid target group and non-internalized advantages, a rapid effectiveness of such financing schemes is questionable. At the same time, if it is clearly the political will both in national governments and among the international community to provide energy access also to the very poor – not least because of the clear social externalities related to the reduction in the consumption of kerosene and dry-cell batteries, 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 programmes, the empirical literature provides evidence from other field experiments that supports the idea (Cohen and Dupas 2010; Kremer and Miguel 2007; Tarozzi et al. 2012). 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 avoid a flash-in-the-pan effect. 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 behaviour, such as the households' willingness-to-pay for electric energy, the role of credit constraints, and information would certainly be useful. Such research efforts would help to design appropriate strategies to achieve the modern energy for all goals of the international community.

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Annex: 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