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The impact of off-grid solar home systems in Kenya on energy consumption and expenditures

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ABSTRACT

This paper assesses the impact of solar home systems (SHS) on energy consumption and energy-related expenditures among Kenyan households. Based on a pipeline comparison approach of more than a thousand households, we find that access to a SHS leads to a net increase of 24 to 36 min in daily lighting use due to a 3 h increase in the use of LED lamps, accompanied by a reduction in the use of "dirty" lamps. We also find a one litre reduction in the monthly use of kerosene for lighting. These changes in energy use along with a decline in the cost of charging mobile phones leads to a reduction in overall monthly expenditure of KSh 193 (about EUR 1.60). For the most popular SHS, these economic effects translate into a payback period of about six years. In addition to the economic benefits, we find small positive environmental effects, increased satisfaction from better quality lighting and an increase in time spent watching TV. Setting the costs against the combined benefits of SHS suggests a positive payoff for this particular off-grid electricity option and a viable way forward in providing off-grid energy solutions with a wide range of functionalities in developing countries.

1. Introduction

Despite considerable progress, *enabling* universal access to electricity remains a challenge. According to the International Energy Agency (2017), in 2016, more than one billion people lacked access to electricity and it is estimated that even in 2030, about 600 million Africans will not have access to electricity. Early responses to increasing energy demands relied on large-scale infrastructure projects to expand national electricity grids. However, grid extensions to remote rural areas are costly and inefficient. For instance, the estimated per capita cost of grid extensions to the African rural hinterland is US$487.7 compared to US$88.5 for cities with a density of 10,000 people per square kilometre (Foster and Briceno-Garmendia, 2010). In contrast, the per capita cost of accessing electricity through off-grid solar home systems (SHS) is estimated to be US$92.3 regardless of where the system is installed (Foster and Briceno-Garmendia, 2010). Implicit in the comparison and based on current demand patterns, Peters and Sievert (2016) argue that a substantial proportion of the electricity needs of rural African households may be met by off-grid solutions. Accordingly, in recent years, in several Sub-Saharan African countries, solar-based off-grid systems have increased in importance as viable alternatives to grid-based approaches.

The East African markets of Kenya, Tanzania, Uganda, Rwanda, and Ethiopia are home to the highest density of off-grid solar energy suppliers (Dahlberg Advisors and Lighting Global, 2018). In particular, Kenya is the largest market in Africa for off-grid solar products (USAID and Power Africa, 2019; GOGLA, 2019) and according to the Kenya National Electrification Strategy (KNES), off-grid solar solutions will play an important role in achieving universal electricity access for all Kenyans by 2022 (Lighting Africa, 2018a). Currently, it is estimated that nearly 10 million Kenyans use off-grid solar products as compared to less than a million in 2009 at the commencement of the World Bank's Lighting Africa project (Lighting Africa, 2018b). However, after several years of expansion, market growth has stabilized and slower uptake of solar products has become a challenge. Market saturation in easy to reach locations, the costs of SHS, variations in product quality, and exaggerated claims of the potential economic and non-economic benefits of access to SHS may underlie their slower uptake. Indeed, despite several years of access to solar products, the impact of access to SHS at the household level in Kenya is still not well documented.

This paper is motivated by the limited evidence on the issue since most existing evidence derives from solar lamps or basic pico-photovoltaic kits. In turn, we set out to examine the effect of access to a SHS that powers multiple lamps, a radio or TV and also allows for connecting other technical devices such as for the charging of mobile phones. Our contribution is threefold. First, we study the impact of SHS on energy consumption (including mobile phone charging and TV watching patterns) and energy expenditure. Second, we calculate the direct environmental effects of access to SHS in terms of reductions in carbon dioxide emissions due to reduced kerosene use. Third, we assess the financial implications of SHS ownership by calculating the payback

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period. Based on this analysis we discuss the potential of SHS in meeting the electricity needs of rural Kenyan households.

The analysis relies on a cross-section dataset of about one thousand purposively sampled households, split equally between owners of a SHS and non-users who have expressed an interest in buying a SHS but have not yet done so (in the pipeline). The pipeline comparison sampling approach is expected to reduce differences in *unobserved* characteristics between users and non-users while statistical methods are used to control for differences in *observed* characteristics and arguably yield credible estimates. Our study finds that access to a SHS leads to about a three-hour daily increase in the use of LED lamps which is accompanied by a two-hour reduction in the use of "dirty" lamps. We also find a one litre reduction in the monthly use of kerosene for lighting. The use of batteries also declines. The reduced consumption of alternative energy sources and a decline in monthly expenditures on mobile phone charging yield an overall reduction in monthly expenditure of KSh 193 (about EUR 1.60) – equally split between the two sources.[1] The 13–14 l annual reduction in kerosene consumption translates into a decline of 37 kg of carbon dioxide equivalent greenhouse gases per year. Based on these estimated economic effects, the payback period for the most commonly used SHS is about 6 years. While the economic gains may seem moderate, they do not take into account greater satisfaction with the quality of lighting and the increase in time spent watching TV (about 45 min per day). Whether such a payback period and these non-monetized benefits are large enough to induce greater uptake remains an open question but has the potential to feed into marketing campaigns.

The remainder of this paper is organized as follows. Section 2 provides a brief literature review while contextual information is presented in Section 3. Section 4 outlines the sampling approach and the empirical framework. Data and descriptive statistics are discussed in Section 5 and the results in Section 6. Section 7 concludes the paper.

2. Literature review

The existing literature on the effects of electrification on various outcomes may be classified into two categories. The first and more developed strand of the literature investigates the impact of on-grid electrification, that is, expansion of and access to the existing electricity grid while a second more recent strand focuses on the impact of off-grid access to electricity, through for instance, solar home systems. While this review discusses both strands of the literature, it focuses primarily on the latter.

2.1. Effects of on-grid electrification

There is a large body of work which has investigated the impact of on-grid electrification on fuel use, energy expenditure, health, income, education and related outcomes in a wide range of countries. These include, among others, Dinkelman (2011) for South Africa, Peters and Vance (2011) for Côte d'Ivoire, Rud (2012) for India, Khandker et al. (2012) for Bangladesh, Khandker et al. (2013) for Vietnam, Grogan and Sadanand (2013) for Nicaragua, Lipscomb et al. (2013) for Brazil, Chakravorty et al. (2014) for India, Grimm et al. (2015) for Indonesia, Barron and Torero (2017) for El Salvador and Lenz et al. (2017) for Rwanda. Overall, the evidence on health, education, and income related outcomes is positive, especially for non-African countries. Studies located in Africa tend to find smaller effects.[2] This is perhaps due to the relative (un-)reliability of the grid-connection and interruptions in electricity supply.[3] Furthermore, most of the studies, except for Barron and Torero (2017) who rely on a randomized encouragement design, use non-experimental approaches to identify impact.

Most recently and closest to the current context, in Rwanda, Lenz et al. (2017) use a panel of 974 households and a difference-in-difference estimation approach to examine the socio-economic effects of access to the electricity grid. Among other effects, they find sharp reductions in the probability of using batteries (65 percentage points) and kerosene (29 percentage points) for lighting, and a 4% decline in total expenditures on energy use. The reduction in expenditure translates into an amortization period, for the connection costs, of about three years. However, there are no effects on health, education and income. One of the main points made by the authors is the importance of comparing the relative costs and benefits of on- versus off-grid electricity solutions.

2.2. Effects of off-grid solar-based electrification

There is a growing and more recent body of work on the effects of access to off-grid electricity on household welfare. This includes studies by Barman et al. (2017), Grimm et al. (2017), Rom et al. (2017), Stojanovski et al. (2017), Bensch et al. (2015), IDInsight (2015), Samad et al. (2013), and Komatsu et al. (2011).

In the Asian context, one of the earliest papers in this genre is by Komatsu et al. (2011) who provide estimates of the effect of SHS on energy use and expenditure in three districts in Bangladesh. Their analysis, which is based on a reflexive comparison shows a sharp reduction in the consumption of kerosene (50 to 60%, depending on the type of SHS) and in the use of rechargeable batteries (almost negligible use) after the introduction of SHS. Also, for Bangladesh, Samad et al. (2013) assess the effect of SHS on a range of outcomes based on a sample of 4000 households split between villages with access to SHS and others with no SHS. The authors rely on propensity score estimation and attribute a number of effects to SHS access including and perhaps most convincing, a two litre reduction (about 67%) in kerosene consumption. More recently, in the Indian context, Barman et al. (2017), among other outcomes, assess the effect of SHS on energy use and mobile phone charging patterns. They apply a reflexive design and base their analysis on a survey of 544 SHS owning households. They found that 9% of the systems were not operational. However, notwithstanding this they report that SHS owning households experienced a 3.5 l (55%) reduction in kerosene consumption, about 16% of households use their SHS for mobile phone charging while about 7% earn extra income through mobile phone charging.

In the African context, one of the earliest evaluations is provided by Bensch et al. (2015) who examine the effect of access to SHS in Burkina Faso using a sample of about 600 households. The authors rely on a propensity score matching approach applied to cross-section data. While acknowledging the methodological challenges, the authors find about a 4 h increase in lighting per day or total time of illumination of 14 h for households with SHS and an increase in time spent watching TV (an increase of 47 min per day for the household head). Stojanovski et al. (2017) follow 375 SHS users in Uganda and 190 SHS users in Kenya and provide a before-after descriptive analysis of the effects of SHS. Their work mirrors the type of results found in Bangladesh and India and shows a sharp reduction in the share of households using kerosene (58% decline in Uganda and 36% decline in Kenya). They also find a sharp decline in outside-the-home charging of mobile phones which falls from 92 to 19% in Uganda and from 72 to 21% in Kenya. Also in

[1] In October 2017, 1 Euro was worth about 121 KSh.

[2] For instance, Barron and Torero (2014) report that on-grid electrification led to a 78% increase in educational related activities among children in El Salvador. In Bangladesh, Khandker et al. (2012) find that time spent on studies increased by about 12 min per day for girls and 22 min a day for boys. In contrast, in Rwanda, Bensch et al. (2011) do not find a statistically significant impact on study time. Similarly, with regard to income, Barron and Torero (2014) find an increase in income generating activities in El Salvador, Khandker et al. (2012) report a 21% increase in income of rural households in Bangladesh while Bensch et al. (2011) do not find any income effects in Rwanda.

[3] Using data from India, Chakravorty et al. (2014) assess the effect of the quality of electricity (outages and hours of electricity per day) on income. Based on a panel dataset of almost 10,000 households the authors find an income effect of 9% among rural households. A remarkable finding is that the income gain amounts to 29% when the grid connection is of higher quality.

Uganda, based on a matching design combined with difference-in-difference, based on repeated surveys of about 1000 households, IDInsight (2015) report a 3 h (29%) increase in lighting per day, a reduction in expenditure on phone charging (84%) and a reduction in expenditure (51%) on non-SHS lighting sources. The payback period was computed to be about 3.1 years. There were no changes on time spent on productive activities or in socio-economic status of SHS users. As the summary shows all studies on SHS rely on non-experimental designs.

Methodologically the most convincing papers in the off-grid genre are papers by Grimm et al. (2017) on Rwanda and Rom et al. (2017) on Kenya. Both papers are based on randomized field experiments and rely on baseline and follow-up survey data. Yet, the studies do not analyse the impact of SHS but of a pico-photovoltaic kit and a solar lamp, respectively. The paper by Grimm et al. (2017) relies on baseline and follow-up data collected in Rao, 2011 and 2012 and on a sample of 300 households where half the households were randomly allocated a pico-photovoltaic (pico-PV) kit consisting of a 1-W solar panel, a four-LED-diodes lamp (40 lm maximum) including a battery, a mobile phone charger, a radio including a charger and a back-up battery package. The authors examined the effect of randomized access to the solar kit on lighting consumption, energy expenditures, time-use and study time. At baseline the two groups were well-balanced in terms of outcome indicators as well as their socio-economic traits. The analysis shows a sharp increase in electricity consumption, and a reduction in expenditure on kerosene (70%), small batteries (60%) and candles (18%). The overall reduction in monthly energy expenditures amounts to about USD 0.92 (ppp). There were no effects on time-use, including for income generating activities and on study patterns. In any event, based on these returns, the payback period to investing in a pico-PV kit was estimated to be about 18 months which may be contrasted with the kit's life-span of 24 to 36 months.[4]

As opposed to randomizing a solar kit, Rom et al. (2017) randomize access to solar lights (solar panel with one light). They work with a sample of 1400 households residing in one county in Western Kenya and provide free solar lights to about 400 households, another 611 households are provided vouchers which enable them to acquire solar lights at a discount and 400 households serve as controls. Their analysis shows that randomization is successful (except for business ownership). The authors are interested in thee price sensitivity of the potential consumers but also examine the effects of solar lights on a range of outcomes. Their clearest result is that access to a functioning solar light reduces kerosene consumption by 1.4 l a month and that the combined effects of reduced expenditure on kerosene and for mobile phone charging translate into costs savings of around USD 1.11 per month. The payback period ranges from 9 months for the cheaper solar light to 22 months for the more expensive solar light. This is comparable to the reduction in expenditures and the payback period found in Rwanda (Grimm et al., 2017).

Our research is motivated by a desire to place discussions on the viability of off-grid electricity solutions such as SHS on a firmer empirical footing. Our review of the literature shows that the existing studies tend to suffer from small samples and that evidence from randomized controlled studies is limited to basic solar lamps/kits with the study by Grimm et al. (2017) being conducted on a very small sample (300 households) and the study by Rom et al. (2017) assessing a very simple product (basic solar lamp) and having a narrow geographical scope (one county) and thus raising concerns about the external validity and the conclusions that can be drawn about off-grid solar solutions based on these two studies. Our study has not only a larger sample (1048 households) as compared to Grimm et al. (2017) but also a more complex product and covers a wider geographic area (see Fig. A1) as compared to Rom et al. (2017). It is one of the few papers that investigates the effects of access to SHS in East Africa's most developed market for such systems. Similar to the existing work, we examine the effect of access to SHS on energy use and expenditure. However, since we work with solar home systems that have greater functionality than the pico-PV kit randomized in Grimm et al. (2017) or the solar lights randomized in Rom et al. (2017), we are able to assess the impact on additional outcomes. For instance, within the broad rubric of energy use, and motivated by the importance of TV and increasingly mobile phones as sources of information and entertainment, we specifically examine whether access to SHS increases time spent watching TV and leads to changes in mobile phone charging patterns. Last but not least, to assess the viability of access to SHS we provide an exploratory payback analysis. Methodologically, we have to rely on cross-section data and a treatment-control approach, as opposed to a randomized control approach which is considered superior. However, as discussed later in the text and demonstrated through the data, arguably, we are able to successfully mimic the ideas behind a randomized evaluation design and provide credible results.

3. Background

3.1. Kenya electricity landscape

In 2015, about 3.3 million Kenyan households or about 32% of the population was connected to the country's electricity grid. While 60% of the urban population was connected, the corresponding figure in rural areas was just 7% (Overseas Development Institute, 2016). In the absence of electricity, most rural households rely on kerosene lamps and torches/devices powered by dry cell batteries for illumination. The government has committed itself to achieving universal energy access by 2022 and recognizes that due to dispersed settlement patterns, the high cost of building infrastructure and connections to the grid, especially for rural households, alternative energy options need to be actively encouraged. Since the country receives good insolation all-year round, solar energy is a prominent option.

In general, the government is supportive of off-grid solutions and has instituted policies such as a waiver of VAT and tariffs on solar photo-voltaic (PV) products. In part, as a result of such policies, and the support of development actors, Kenya is among Africa's leading markets for off-grid solar products and has recorded rapid growth since 2010 (Lighting Global, 2016; Lighting Africa, 2018a). Between 2009 and 2013, the market for solar lanterns grew by over 200% (Lighting Africa, 2018b). According to Lighting Africa (2018b), between January 2009 and June 2018, 4.7 million quality-verified solar products were sold and nearly 10 million people, about 20% of the country's populations, meets its basic electricity needs with such quality-verified off-grid solar products. The growth has largely been based on sales in the more densely populated Western, Central and South-Eastern parts of the country. More than 30 companies offer their products in Kenya and hundreds of retail shops sell solar products ranging from solar lanterns to more advanced solar home systems to customers. The distribution models include direct cash sales to customers, pay-as-you-go systems where customers lease a SHS and pay a daily fee to use the system and loan-based sales via credit groups. Portable Solar lights and SHS which offer up to 10 watts of peak power dominate the market, and represent 90% of products sold in East Africa including Kenya (Lighting Global and GOGLA, 2016).

3.2. Project background

For this study we interacted with a manufacturer and distributor of solar energy systems. The firm offers a range of quality-verified products, it operates across the country and sells almost all its products through a partnership with local financial institutions who have set up credit groups. Members of the credit group are eligible for finance and

[4] The cost of the cheapest system (a solar panel, battery and an LED lamp) randomized by Grimm et al. (2017) was USD 16.50.

are also potential customers.[5] An advantage of such a sales model is that since financing of solar products remains a major bottleneck (Lighting Global, 2016), operating through credit groups unites the demand for energy and the need for financial support to purchase a SHS.

The firm offers a range of solar-based products including four types of SHS. These are (i) Solar 1, which offers a 3 W solar panel with one light and mobile phone charging and costs KSh 2900 (Euro 24) (ii) Solar 2, a 5 W solar panel with two lights and mobile phone charging which costs KSh 6900 (Euro 57) (iii) Solar 4, a system with two 5 W solar panels with four lights, mobile phone charging and a radio which costs KSh 12,990 (Euro 108) and (iv) Solar TV, which offers a 40 W solar panel with four lights, mobile phone charging and a 23 in. LED colour TV which costs KSh 49,990 (Euro 414). All the models offer about 5 h of bright light at their highest settings or an output of between 120 and 150 lm.[6] For all models, the company offers after sales services and a one year warranty. In terms of the energy ladder, where households with no electricity are in Tier 0, these systems fall in Tier I and the start of Tier II of the multi-tier matrix for measuring access to electricity (Bhatia and Angelou, 2015).

4. Empirical framework

Based on the literature as well as our field work, we expect that access to a solar home system is likely to have a variety of effects at the household level. Foremost among these, and the two most widely mentioned during fieldwork, were that access to a new energy source may be expected to lead to a substitution away from traditional methods of illumination. In this case, a movement away from the use of kerosene-powered lamps and devices that run on batteries. This substitution may also be expected to translate into a reduction in energy expenditures. In addition to reduced energy expenditure, the availability of electricity is likely to lead to a substitution away from external (outside the home) mobile phone charging to charging inside the home for one's own devices as well as for others. This is likely to save time, lead to expenditure reductions and generate income.[7] The reduced use of kerosene is also likely to generate positive environmental effects due to reduced air-pollution and deliver concomitant health benefits.[8] Access to electricity may also be expected to affect time-use patterns and translate into greater time spent on income-generating activities, time spent studying or on leisure activities such as greater time spent on listening to a radio, watching TV and greater use of mobile phones. In the long run such changes in time-use may translate into improved school performance, greater awareness of a range of issues which may have effects on health outcomes, fertility, gender rights and social norms.

Given the time frame of the analysis, the paper focuses on patterns of energy use, changes in expenditure, and changes in time use. To identify effects, the evaluation relies on cross-section data and on comparisons between households that own a SHS (treatment group) and households that do not (as yet) own such a system (control group). The main empirical concerns with regard to attribution arise due to two elements. First, households have to determine whether they would like to purchase SHS and second, they need to have the financial ability (cash, access to credit) to enable the purchase. Due to these two aspects, it is quite likely that those who opt to buy a SHS and are able to obtain one are systematically different from those who are not interested or not able to purchase a SHS. In other words, the two groups might differ in terms of their observed traits (e.g., income, education, access to credit) but also in terms of their unobserved traits (e.g., more future-oriented, modern attitudes).

In order to provide a credible assessment of the effects of owning a SHS we carefully developed a sampling strategy tailored to the evaluation problem and the context at hand. The sampling approach was inspired by the sales model used by the firm to sell its energy products, that is, through relatively homogenous credit groups. First, we obtained a list of all members of the approximately 1900 credit groups set up by three financial institutions with which the company worked. We also obtained information about the SHS owning status of each member and the type of SHS owned. Subsequently, we used a stratified random sample approach to select a set of about 500 SHS owning households from among the 2922 members who owned a SHS. We restricted attention to those credit groups where there was at least one SHS owner and the sample was stratified by financial institutions (three), product group (four) and region (fourteen). The proportion of SHS owning households in each strata of the sample was chosen to reflect the underlying distribution in the population of SHS owning households. Having selected a set of SHS owning households, we proceeded to choose about 500 counterfactual households from the same credit groups as the SHS owning households.[9] This was done purposively and we focused on those (pipeline) households who had expressed a desire to purchase a SHS or had indicated that they would be purchasing a SHS in the near future. This information was available from SHS sales staff and thus reliable. This pipeline of prospective customers existed because support from the microfinance institutions was needed for the purchase of the SHS and not all requests for funding were approved at the same time. Moreover, before including a household in the sample we verified that they did not have a SHS and that they were still interested in purchasing a SHS. The advantages of such an approach are that the control group consists of households that have displayed an interest in owning a SHS and this should reduce differences in unobserved characteristics between the treatment and control group. Note that the approach imposes the assumption that recent adopters are similar in unobservable characteristics to prospective buyers of the system. While we cannot test for differences in *unobservables*, we can test for differences in *observable* household characteristics and we show that the two groups (treatment and control) are equal (Table 1); the *p*-value of the overall balance across household characteristics is 0.163; not a single difference is statistically significant at the 1% level and only 4 differences out of a total of 40 comparisons are statistically significant at the 5% level (Table 1, more details can be found in Section 5).[10] It is the rich set of covariates and the very small number of differences found across the treatment and control group that make us confident that we established a credible counterfactual in the absence of an RCT.

[5] Credit groups consist of 10–30 individuals, both males and females. Some groups are occupation based (small business owners, farmers, taxi drivers) while others are location based and may include members working in different sectors.

[6] This may be compared with kerosene fired lamps which, depending on the type of lamp offer between 8 to a maximum of 100 lm. According to Rao (2011), a kerosene lamp producing 37 lm for 4 h per day consumes about 3 l of kerosene per month. In our sample, households without access to solar home systems consume about 1.5 l of kerosene per month suggesting that they have access to kerosene lamps with low output.

[7] Changes in these two expenditure items were consistently mentioned during fieldwork. At the time of the fieldwork, kerosene could be purchased at the main road for KSh 65 per litre or in the villages that were visited, for KSh 90 per litre. Phones needed to be charged at shops located on the main road. The cost of charging phones was KSh 10 per cycle.

[8] Another potential health effect is a reduction in the number of skin burns caused by the use of kerosene lamps.

[9] The overall sample size was set at 1000 households, divided equally between SHS users and potential users. Power calculations, setting alpha at 0.05 and beta at 0.8 and without accounting for clustering as the number of SHS clients per credit group is low (1.54 = 2922/1900), suggests that this sample size is sufficient to detect reasonable effect sizes for the main outcome variable (energy related expenditure). For example, for a relatively small standardized effect size of 0.03 a sample of 1942 households is needed, while for an effect size of 0.25 a sample of 532 households would suffice. The sample size used here lies comfortably between these two options.

[10] The pipeline sampling approach outlined here is similar to that used by Bedi et al. (2017) to identify the impact of access to biodigesters in Rwanda. It was inspired by the nonexperimental pipeline evaluation of the Argentinean "Jefes y Jefas" program by Galasso and Ravallion (2004). As in our approach, the comparison group was constructed from the subset of applicants who were not yet receiving the program. Here it is those who did not yet buy an SHS. Since support from the microfinance organization is needed for purchase, the delay in uptake is to a large extent externally determined and the pipeline comparison is meaningful. As Galasso and Ravallion (2004) we match participants to comparison observations.

Table 1
Balancing of socio-demographic characteristics and wealth variables.

	Full sample		Treatment	Control	Difference in means
	Mean	Std. Dev.	Mean	Mean	*p*-value
Household head characteristics					
Age	45.597	11.964	45.885	45.309	0.449
Head is female	0.187		0.198	0.176	0.370
Schooling					
(Excluded category: No schooling/preschool)					
Primary 1–6	0.060		0.075	0.044	0.044**
Primary 7	0.149		0.147	0.152	0.859
Primary 8 or secondary 1–3	0.365		0.362	0.368	0.843
Secondary 4 or higher	0.391		0.386	0.396	0.745
Occupation					
(Excluded category: Any other occupation)					
Agriculture, hunting, fishing	0.390		0.400	0.380	0.515
Retail/sales	0.141		0.143	0.139	0.855
Private sector formal employment	0.130		0.121	0.139	0.396
Public sector formal employment	0.094		0.091	0.097	0.744
Spouse characteristics					
Age	39.061	10.400	39.248	38.871	0.599
Spouse is male	0.006		0.007	0.005	0.662
Schooling					
(Excluded category: No schooling/preschool)					
Primary 1–6	0.077		0.061	0.093	0.086*
Primary 7	0.143		0.163	0.122	0.086*
Primary 8 or secondary 1–3	0.432		0.452	0.413	0.258
Secondary 4 or higher	0.312		0.303	0.322	0.540
Occupation					
(Excluded category: Any other occupation)					
Agriculture, hunting, fishing	0.463		0.487	0.439	0.164
Retail/sales	0.196		0.187	0.205	0.500
Private sector formal employment	0.055		0.050	0.060	0.523
Public sector formal employment	0.048		0.054	0.041	0.347
Household characteristics					
Respondent is head	0.447		0.473	0.419	0.077*
Household size	4.726	2.021	4.875	4.575	0.016**
Quality of the main building					
Floor is made of cement/brick/ceramic	0.580		0.604	0.556	0.113
Walls					
Walls are made of cement	0.112		0.127	0.096	0.114
Walls are made of bricks (burnt or unburnt)	0.339		0.339	0.338	0.985
Roofing: Iron sheets	0.933		0.932	0.935	0.856
Glass windows	0.512		0.494	0.531	0.238
Number of rooms for living	3.220	1.367	3.301	3.138	0.054*
Agricultural land					
Acres owned	2.930	4.957	3.158	2.699	0.134
Acres cultivated	1.884	2.052	2.025	1.740	0.024**
Livestock					
Number of cows	2.100	2.969	2.330	1.867	0.012**
Number of sheep	1.075	4.861	1.170	0.979	0.524
Number of goats	2.448	16.264	2.917	1.971	0.347
Ownership: Means of transportation					
Bicycle	0.242		0.223	0.262	0.151
Motorcycle	0.244		0.261	0.227	0.195
Car	0.046		0.057	0.035	0.086*
Assets (at least one)					
Gas stove	0.162		0.174	0.150	0.288
Mosquito nets	0.855		0.860	0.850	0.651
Sewing machine (mechanical)	0.086		0.087	0.085	0.885
PPI (excluding lighting)	49.771	12.868	49.525	50.021	0.533
Overall balance test (H_0: Equal means for variables)					0.163

Note: The total number of observations for the household level variables is 1048. For the household head characteristics we have 990 observations and for the spouse of the household head we have 842 observations. The balance test for the overall means is based on 842 observations and also includes regional dummies. ***/**/* indicate significance at the 1/5/10% level, respectively. Poverty probability index (PPI) is based on 10 questions which include household traits and asset ownership.

In addition, both SHS owning and non-owning households are drawn from the same credit group which we imposed to further reduce differences in observed traits and to reinforce the credibility of our approach despite the absence of panel data.

Given the purposively developed sampling approach outlined above, it is possible that comparing differences in outcomes between solar home system owning households ($SHS_i = 1$) and a control group ($SHS_i = 0$), will yield credible estimates. However, since there may be other observable differences between the two groups we estimate linear regression models such as (1),

$$Y_{ifr} = \alpha + \beta SHS_{ifr} + \gamma X_{ifr} + \lambda_f + \mu_r + \varepsilon_{ifr}, \qquad (1)$$

where, Y_{ifr} indicates the outcomes of interest for household i belonging to a credit group set up by financial institution f in region r, X_{ifr} is a set of observable household characteristics (household demographics, education and occupation of the household head, household assets – quality of dwelling, land ownership, livestock, ownership of consumer durables) which may determine both SHS ownership and the outcomes, λ_f indicates financial institution fixed effects while μ_r denotes regional fixed effects.[11] The coefficient of interest is β. Provided that after controlling for observed characteristics and the fixed effects, the $Cov(SHS_{ifr}, \varepsilon_{ifr}) = 0$,then OLS estimates of (1) should yield unbiased estimates of the effects of owning a SHS.[12]

As an additional step, in an attempt to refine the control group, we provide estimates on the basis of the inverse probability weights (IPW) estimator. IPW estimates are computed on the basis of a two-step approach. In the first step we obtain estimates of the probability of owning a SHS using a logit regression. Subsequently, these estimated probabilities are used as weights in a linear regression such as (1). Intuitively, the IPW is used to compute weighted averages of the outcomes for the treatment and control group. Treated households that have a low probability of being treated are given a larger weight (since they are most similar to control households) while control households with a high probability of being treated are given a larger weight (since they are most similar to treated households). This corrects for the potentially unequal probability of receiving treatment in the original sample. If the sampling strategy has delivered a control group that is similar to the treatment group then IPW estimates should not be very different from OLS estimates.[13]

5. Sampling approach, data and descriptive statistics

To implement the empirical strategy, we rely on a cross-section survey of 1048 households (as opposed to an expected sample of 1000 households) with 528 households comprising the treatment and 520 comprising the control group. As shown in Table A1, the distribution of treatment and control households across regions and across the three financial institutions is similar (differences in sample composition are statistically insignificant) and in line with the proposed sampling approach. A detailed comparison between the proposed sampling approach and the actual sample is provided in Table A2. While there are deviations, in particular at the product level, at the regional and financial institution level the actual sample closely matches the proposed sample.[14]

The survey was conducted between July and August Stojanovski et al., 2017, that is, after a majority (69%) of the SHS owners, had had at least one year experience with the system. We gathered information on socio-economic indicators, household demographics, occupation, education, energy-related expenditure, energy use and time-allocation. In addition, the instrument contained a section on the experience with using the SHS and the method used to finance its acquisition. While we were able to collect household level information for 1048 households, information is only available for 990 household heads and 842 spouses of household heads.

Descriptive statistics for the entire sample as well as for the treatment and control group are provided in Table 1. The first panel contains information on the traits of the household head, the second on the spouse of the household head and the third panel contains household level information. The table clearly shows that treatment and control households are not remarkably different. In the case of both treatment and control groups, household heads are about the same age, a similar proportion are headed by females and educational and occupational distributions are not remarkably different. Except for a slightly higher proportion of household heads falling in the category of those with 1 to 6 years of primary education, there are no statistically significant differences between the two groups. Similarly, in the case of spouses of household heads, except for two of the education categories, the two groups are well-matched.

At the household level, except for a few traits, differences between the two groups are not statistically significant and the differences that do exist are not very large in magnitude. For instance, SHS owners have larger households (4.88 versus 4.58 members), dwellings with a larger number of rooms (3.3 versus 3.1 rooms) and are better endowed in terms of acres of cultivated land (2 versus 1.74) and household endowment of cows (2.3 versus 1.9). The overall impression is that while households with SHS may be slightly better off, differences in observable traits are not pronounced. A formal test for balance in overall means between the two groups, including the regional distribution of treatment and control groups (Table A1) yields a p-value of 0.163.

To further assess similarities and differences in the probability of owning a SHS, we estimate a set of logit models. If the two groups are similar, as suggested by the descriptive statistics, then there should not be much explanatory power in the models. Indeed, as displayed in Table A3, most of the observable characteristics do not influence the probability of owning a solar home system. As may be expected, based on the sampling strategy and these regression results, there is considerable common support between the lowest probability of treatment among the treated and the highest probability of treatment among the control sample. The lowest likelihood of treatment for treated individuals ranges between 18 and 20%, the lowest likelihood of treatment for control individuals is 7.7 and 9%. The highest likelihood of treatment for treated individuals ranges between 91.7 and 91.8% and 87.0 to 88.0% for control individuals, respectively. The average likelihood of treatment is roughly 10 percentage points higher for treated individuals.

Overall, the comparison of means and the logit estimates suggest that (i) the sampling approach has led to reasonably comparable groups; (ii) that the differences in estimated treatment probabilities are small and there is sizeable common support to obtain comparable treatment and control groups and (iii) the limited differences in observable traits suggests that the differences in unobserved traits between the two groups is unlikely to be pronounced.

6. Experiences with and the impact of solar home systems

Before turning to a discussion of the impact of access to a SHS, this section provides details on household experiences with SHS. Thereafter, we discuss differences in outcome means between the treatment and control group and subsequently we discuss the econometric estimates.

6.1. Functioning of SHS

For most households (81%) it was their first experience with a SHS and all SHS purchases took place between 2015 and Stojanovski et al., 2017. Almost all the systems (94%) were purchased on credit with a loan duration of a little more than a year (13 months). About 38% of SHS owners have a system with 4 lights and a radio, that is, the Solar 4 system (Table 2). This is followed by the Solar TV system which is owned by 32% of SHS owners highlighting again the difference of our study with respect to studies that assess simpler products, i.e. basic solar lamps. The rest are distributed between Solar 2 and Solar 4 without a radio. A small proportion, about 3%, opted for Solar 1. Thus, as compared to the bulk of the solar home system owning population in Kenya, where cheaper systems with 10 W or lower peak power dominate, the firm that we work with targets a group that is relatively richer.[15]

[11] Standard errors account for clustering at the regional level.

[12] We also estimated specifications which included financial institution interacted with regional fixed effects (42 fixed effects as opposed to 17) while at the same time allowing for clustering at the regional-financial institutional level. Estimates based on such a specification are not discernibly different from those reported in the paper.

[13] Standard errors are adjusted to take into account that the inverse-probability weights are estimates.

[14] Deviations arose as there were discrepancies between the information available from the firm/financial institutions and the actual situation in the field. Nevertheless, these discrepancies are not pronounced and do no hamper our ability to provide credible estimates.

[15] As discussed earlier, portable solar lights and SHS which offer up to 10 watts of peak power dominate the market in Kenya and represent 90% of products sold (Lighting Global and GOGLA, 2016). Households with such systems comprise only 68% of our sample.

Table 2
Distribution of the different Orb solar home systems.

Type of SHS	Number	Share (%)	Cost (KSh)
Solar 1 (1 light)	14	2.7	2900
Solar 2 (2 lights)	79	15	6900
Solar 4 (4 lights)	64	12	.
Solar 4 (4 lights, radio)	202	38.3	12,990
Solar TV (4 lights, TV)	169	32	49,990

Note: The total number of observations is 528. Some Solar 4 systems were provided without a radio or a TV. We do not have accurate figures on the costs of such systems. All SHS come with mobile phone charging functionality.

In almost all cases (96%), the SHS became operational within a month and about 92% of SHS owners indicated that they used their systems actively. The bulk of households (96%) had not incurred any maintenance costs in the last 12 months. Despite this, about 51% indicated that they had had problems with the device, mainly the battery. This may well be because the bulk of the systems are relatively new and lie in the warranty period.

We also inquired among the SHS owners whether access to the solar system had improved the lives of the households (Table 3). The bulk of the households (93%) replied affirmatively: very positive (59%) or positive effects (34%). In terms of the specific areas where the SHS had an impact, education ranked first at 74%, followed by comfort (66%) while a relatively small proportion (20%) highlighted positive health effects. A large proportion (68%) also indicated that they would be willing to recommend the SHS to their friends and family.[16]

6.2. Impact of SHS

We begin by examining differences in means of various outcome variables (Table 4). As motivated in Section 2 we focus on patterns of energy use, energy consumption and costs. In panel 1 we compare the use of three different sources of lighting and their daily use. That is, the use of clean lamps, LED lamps and dirty lamps. Clean lamps include traditional bulbs, neon tubes and energy savers, LED lamps are used in the SHS but also in rechargeable lamps and torches while dirty lamps include gas lamps, kerosene-powered lamps, biogas lamps, candles and firewood. There is a clear pattern across treatment and control group. SHS owning households use about 2 LED lamps more than non-owners. Only one in five SHS owning households still continue to use dirty lamps while in the case of non-SHS households the use of such lamps is universal. Consistent with the number of lamps used, SHS owners report that they use their LED lamps for about 3 h a day and resort to using dirty lamps for only about 24 min a day. In contrast, SHS non-owners rely on dirty lamps for about 108 min a day.

Panel 2 deals with the use of media devices. As may be expected, given the high rate of SHS owners who bought the Solar TV system, the ownership of a TV is substantially higher among SHS owners (48 versus 37%). Moreover, they also use these TVs more intensively. On average, SHS owners watch TV for 118 min per day as compared to 82 min per day for non-SHS owners. Differences in TV watching time are especially pronounced for the spouse of the household head in SHS owning households. There are no differences in radio ownership, although, SHS households tend to have their radios on for a slightly longer time period (183 versus 168 min a day) as compared to control households. With regard to mobile phones, we observe that treated households are far more likely to charge mobile phones for others (about 3.9 versus 2.5 times a week) although differences in earnings from charging phones for others are not pronounced. The key difference is that SHS owners only pay about KSh 8 a week, on average, for charging their mobile phones whereas households in the control group pay KSh 24 a week.

[16] Note that the SHS related satisfaction questions were only posed to SHS-owners and we do not have a counterfactual for these specific questions. Therefore, they are not assessed in the impact analysis.

Table 3
Satisfaction with the system.

	Response percentage	Significantly positive	Positive	Neutral	Negative
Effect of SHS on your life?					
Areas of life where SHS had the greatest effect		59.09	33.90	5.87	1.14
Education	73.86	68.97	28.97	1.79	0.26
Comfort	65.53	54.05	41.04	4.91	
Income	43.37	65.94	30.13	2.62	1.31
Security	36.93	49.23	45.64	4.62	0.51
Leisure	32.77	45.09	47.98	6.94	
Social interaction	31.44	56.63	37.35	6.02	
Health	19.51	70.87	23.08	5.83	
		Very likely	Likely	Neutral	Unlikely
Recommend Orb SHS to friends or family		38.07	29.55	25.00	7.39

Note: All figures are in percentages. The shares of respondents giving a particular answer with respect to the effect of a SHS are calculated on the basis of 528 SHS-owning respondents. For every area of effect, the share of significantly positive, positive, neutral and (significantly) negative answers is conditional on indicating the particular category as an area of greatest effect.

Panel 3 provides information on monthly consumption of different energy sources while panel 4 contains information on energy expenditures. We expect that SHS owners will be far less likely to use sources such as candles, kerosene-powered devices and batteries. The means across the two groups shows that about one in four SHS owning households still continue to use candles while it is one in two households in the case of non-owners. There is a sharp reduction in the use of kerosene for lighting with SHS owners using only 0.6 versus 1.5 l among non-SHS owners and there is also a reduction in the use of batteries in the case of SHS owning households. Consistent with expectations, there is no change in energy sources that are primarily used for cooking – that is, kerosene for cooking and charcoal. Consistent with the pattern of change in energy use, SHS owners spend less on candles (KSh 3 versus 5 a month), on kerosene for lighting (KSh 34 versus 99 a month) and batteries for their radios (KSh 27 versus 37 a month). Perhaps surprisingly, there is an increase in expenditure on firewood with the result that overall there are no changes in energy expenditures between the two groups (see Panel 4).[17]

Econometric estimates based on OLS (Eq. 1) and IPW which control for household traits (specification 1) as well as for household and head of household characteristics (specification 2) are provided in Tables 5 (use of lighting), 6 (energy consumption and expenditures) and 7 (use of media devices).[18] Across all estimates, the results are not sensitive to the inclusion of head of household traits nor are they sensitive to the estimation approach used.[19]

[17] One interpretation of the increase in expenditure on firewood may be that the reduction in energy spent on lighting allows households to spend more resources on energy for cooking. However, it could also be a consequence of poorly measured variables. It is notoriously difficult to get a good measure of the amount and the cost of firewood. Firewood is sold in bundles but there is no standard definition of a bundle and the cost of a bundle differs widely across markets.

[18] The household level control variables are as follows: Respondent is head, household size, poverty probability index (PPI), floor is made of cement/brick/ceramic, walls are made of cement, walls are made of bricks, roofing is made of iron sheets, house has glass windows, number of rooms for living, acres of agricultural land owned, acres cultivated, number of cows, number of sheep, number of goats, means of transportation: bicycle, motorcycle, car, assets owned (at least one): gas stove, mosquito nets, sewing machine (mechanic), two dummies for microfinance banks, location: urban, peri-urban, use of the national grid in past 5 years, regional controls.

[19] We also estimated specifications which included the traits of the spouse of the household head. This led to a decline in the number of observations but the results were not sensitive to the inclusion of these traits.

Table 4
Descriptive statistics of the outcome variables.

	Mean	Std. Dev.	Treat. mean	Control mean	DiM p-value		Mean	Std. Dev.	Treat. mean	Control mean	DiM p-value
Panel 1: Use of lighting						*Panel 2: Use of media devices*					
# of clean lamps used	0.255	1.110	0.153	0.358	0.003***	Ownership of (at least) one TV	0.426	0.495	0.483	0.367	0.000***
# of LED lamps used	1.130	1.682	2.045	0.200	0.000***	Minutes TV is turned on per day	99.812	136.520	117.790	81.558	0.000***
# of dirty lamps used°	0.549	1.085	0.193	0.910	0.000***	Head: Hours watching TV p. day	0.210	0.903	0.271	0.150	0.050*
Daily use hours: Clean lamps§	2.606	4.203	2.145	3.074	0.000***	Spouse: Hours watching TV p. day	0.901	1.550	1.125	0.680	0.000***
Daily use hours: LED lamps	1.906	2.992	3.259	0.533	0.000***	Children: Hours watching TV p.day	0.458	0.750	0.502	0.410	0.191
Daily use hours: Dirty lamps§	1.099	2.233	0.406	1.803	0.000***	Times mobile charged for others	3.239	9.606	3.964	2.502	0.014**
Satisfaction with lighting	4.046	1.144	4.472	3.613	0.000***	Weekly income phone charging	23.535	93.870	26.714	20.308	0.270
						Weekly costs phone charging	16.317	53. 182	8.324	24.433	0.000***
Panel 3: Monthly consumption						*Panel 4: Monthly expenditure (in KSh)*					
Candles (#)°	0.358	1.435	0.271	0.446	0.048**	Candles°	3.895	15.656	2.924	4.881	0.043**
Gas (kg)	1.164	2.561	1.223	1.105	0.452	Gas°	197.235	430.704	206.354	187.976	0.49
Kerosene (cooking, litre)°	0.686	2.165	0.627	0.746	0.377	Kerosene (cooking)°	48.354	143.302	45.253	51.502	0.481
Kerosene (lighting, litre)°	1.026	3.397	0.58	1.479	0.000***	Kerosene (lighting)°	66.333	172.989	34.420	98.737	0.000***
Charcoal (debe)°	3.031	7.497	3.017	3.045	0.953	Charcoal°	386.638	887.177	362.098	411.556	0.367
Firewood (bought, bundle)°	3.517	17.183	4.307	2.715	0.134	Firewood (bought, bundle)°	347.611	1504.927	446.487	247.213	0.032**
Batteries (radio)°	1.141	2.463	0.917	1.369	0.003***	Batteries (radio)°	31.763	76.811	26.991	36.610	0.043**
						Monthly costs for all energy resources	1089.49	1879.53	1131.64	1046.69	0.465

Note: The total number of observations for every outcome variable is 1048 except for the household head, spouse and child hours of TV watching. The total number of observations for the hours of TV watching per day is 851, 859 and 458 for household heads, spouses and children, respectively. ***/**/* indicate significance at the 1/5/10% level, respectively. °These variables were adjusted for outliers. We replaced the top 1% of the observations with the minimum value in the top 1%.

Table 5
Effect of SHS on lighting.

	Household level controls only (1)	Head controls added (2)	Household level controls only (3)	Head controls added (4)
	OLS	OLS	IPW	IPW
Use of lighting				
# of clean lamps used	−0.141** (0.056)	−0.153* (0.063)	−0.128* (0.066)	−0.141** (0.072)
# of LED lamps used	1.746*** (0.205)	1.767*** (0.209)	1.813*** (0.087)	1.852*** (0.090)
# of dirty lamps used	−0.822*** (0.100)	−0.827*** (0.099)	−0.893*** (0.072)	−0.909*** (0.077)
Hours of use per day: Clean lamps	−0.493* (0.276)	−0.522* (0.284)	−0.651** (0.275)	−0.690** (0.290)
Hours of use per day: LED lamps	2.523*** (0.392)	2.532*** (0.397)	2.697*** (0.165)	2.764*** (0.166)
Hours of use per day: Dirty lamps	−1.627*** (0.197)	−1.659*** (0.196)	−1.746*** (0.144)	−1.792*** (0.157)
Satisfaction with lighting	0.945*** (0.090)	0.940*** (0.089)	0.944*** (0.070)	0.945*** (0.072)

Note: Results from OLS and inverse probability weighting (IPW) are presented. We employed clustered and robust standard errors, respectively. ***/**/* indicate significance at the 1/5/10% level, respectively. The number of observations is 1048 for the model with household level controls and 990 for the model that adds household head controls. Only the coefficient estimates associated with SHS ownership are displayed.

As was already evident from the comparison of means, SHS users are more likely to use LED lamps and this increase in the use of LED lamps is matched by a reduction in the use of dirty lamps. Similarly, in terms of the hours of use - LED lamps are used for about 2.5 to 2.8 additional hours per day while there is a corresponding reduction in the combined use of clean and dirty lamps (1.9 to 2.4 h). Hence, the overall increase in net hours of lighting is limited but there is a substitution between lighting types and an increase in the quality of lighting as suggested by the 1-point increase in the Likert scale on responses to satisfaction with lighting. The increased satisfaction with the quality of lighting provided from SHS hints at wellbeing gains from solar systems that are reinforced by changes in energy consumption and use patterns from the different lighting sources.

With regard to consumption of energy, there is a clear reduction in the use of kerosene for lighting and batteries for powering radios (Table 6). The consumption of kerosene for SHS owning households drops by between 1.03 and 1.14 l per month (p-value < 0.000). This effect is slightly smaller but in the same range as in Rom et al. (2017) who reported a reduction of 1.4 l in Kenya. In addition, SHS owners use between 0.56 and 0.73 fewer batteries per month for their radios (p-value < 0.000). At the same time the use of gas, kerosene and charcoal for cooking is unaffected by access to a SHS. Consistent with this pattern, there is a reduction in expenditure on kerosene for lighting (KSh 73 to 79 per month) which is precisely estimated across specifications. The reduction in the use of kerosene is consistent with other studies that have examined the effect of access to SHS, although the magnitude of the reduction found here is at the lower end (Rom et al., 2017; Barman et al., 2017; Komatsu et al., 2011). A smaller effect in terms of cost savings is observed for batteries used for radios. It ranges between KSh 12 and 17 across specifications. The identified total reduction in expenditure on kerosene for lighting and batteries for radio amounts to, at best, KSh 96 a month. As already mentioned earlier, SHS owners tend to spend more on firewood (KSh 197 to 258 per month).[20] This may well be due to the reduction in expenditure on other sources, although the increase in expenditure outstrips the decline. Consequently, in terms of total energy expenditure, we find an increase for SHS owners although it tends to be statistically insignificant. Notwithstanding the effect on firewood, the clear patterns in terms of changes in the consumption of lighting sources (expenditure) and the lack of effect on energy sources used for cooking, lends greater credibility to the idea that the effects that we do identify are due to SHS.

[20] This result is not driven by outliers. As indicated in Table 4, this variable has been adjusted for outliers.

Table 6
Effect of SHS on monthly fuel consumption and expenditures.

	Household level controls only (1)	Head controls added (2)	Household level controls only (3)	Head controls added (4)		Household level controls only (5)	Head controls added (6)	Household level controls only (7)	Head controls added (8)
	OLS	OLS	IPW	IPW		OLS	OLS	IPW	IPW
Monthly consumption of					**Monthly expenditure on (in KSh)**				
Candles (#)	−0.155	−0.131	−0.145	−0.120	Candles	−1.663	−1.292	−1.495	−1.153
	(0.101)	(0.120)	(0.094)	(0.097)		(1.055)	(1.231)	(0.992)	(1.028)
Gas (kg)	0.155	0.124	0.190	0.165	Gas	28.315	22.115	32.931	28.337
	(0.124)	(0.124)	(0.137)	(0.140)		(19.939)	(20.826)	(22.952)	(23.303)
Kerosene (cooking, litre)	−0.046	0.043	−0.098	0.027	Kerosene (cooking)	−1.697	3.944	−3.958	3.443
	(0.116)	(0.140)	(0.138)	(0.133)		(7.637)	(8.864)	(8.879)	(8.814)
Kerosene (lighting, litre)	−1.036***	−1.094***	−1.056***	−1.135***	Kerosene (lighting)	−73.439***	−75.558***	−75.019***	−79.403***
	(0.228)	(0.221)	(0.212)	(0.243)		(11.732)	(11.628)	(11.101)	(12.363)
Charcoal (debe)	0.276	0.320	0.413	0.469	Charcoal	−8.170	−9.093	2.184	3.173
	(0.449)	(0.441)	(0.405)	(0.433)		(47.093)	(55.106)	(49.265)	(53.446)
Firewood (bought, bundle)	1.621	1.857	1.681	2.175**	Firewood (bought)	196.517**	222.266*	220.181**	257.582***
	(0.978)	(1.077)	(1.060)	(1.084)		(89.470)	(105.943)	(90.293)	(92.516)
Batteries (radio, #)	−0.560***	−0.627***	−0.680***	−0.734***	Batteries (radio)	−11.836**	−13.758**	−16.217***	−17.162***
	(0.140)	(0.146)	(0.181)	(0.188)		(4.865)	(4.959)	(5.859)	(5.903)
					Total energy costs	127.091	147.497	157.544	192.758*
						(97.949)	(120.718)	(109.631)	(114.838)

Note: Results from OLS and inverse probability weighting (IPW) are presented. We employed clustered and robust standard errors, respectively. ***/**/* indicate significance at the 1/5/10% level, respectively. The number of observations is 1048 for the model with household level controls only and 990 for the model that adds household head controls. Only the coefficient estimates associated with SHS ownership are displayed.

Table 7 provides estimates for ownership, use and charging of electric devices. Since a substantial proportion of the SHS include a TV, it is not surprising to find that SHS owners are 13 to 16 percentage points more likely to report TV ownership as compared to the control group. Ownership also translates into more TV watching. SHS owners watch between 40 and 46 min, or about 50% more TV per day as compared to the control group (p-value<0.000). The bulk of the increase may be attributed to adult female household members who increase their daily TV watching time by about half an hour. There is an increase for children as well but it is smaller and is less precisely estimated. A clear effect of having access to a SHS is that owners are more likely to charge mobile phones for others. On average, SHS owners provide phone charging services about 1.5 to 1.7 more times per week (p-value < 0.000). However, the income from providing such services is not large (KSh 7–8 a week) and the effect is not robust to the estimation approach. A more discernible effect is that only 8% of SHS owning households charge their phones outside their home as compared to 46% for non-owners. In terms of costs, this works out to a reduction in phone charging costs of between KSh 19 and 24 per week (p-value<0.000). In terms of expenditure, combining the reduction in energy costs for kerosene and batteries and the cost savings accruing from changes in mobile phone charging patterns, on average, the overall reduction in expenditure for SHS owners amounts to between KSh 144 (OLS estimates) to 193 (IPW estimates) a month. If we work with the larger figure, this amounts to roughly EUR 1.60 a month. The monthly reduction in expenditure is twice the size of the effect reported in Grimm et al. (2017) study in Rwanda, where randomized access to a SHS leads to a FRW 557 or EUR 0.7 reduction in monthly expenditure. The reduction in monthly expenditure in their paper is attributed to reductions in the use of candles, batteries and mainly reduced purchase of kerosene. The smaller cost reduction may also be attributed to the SHS which is randomized in their paper, which is equivalent to the Solar 1 system which is only used by a small proportion (3%) of the households in our sample.

6.3. Reduction in carbon dioxide emissions

The reduction in the use of kerosene may be expected to translate into positive health effects, although there is no clear evidence on this aspect (see Grimm et al., 2017), in part as air quality and the expected health effects are likely to be confounded by the continued use of firewood and charcoal for cooking. Instead of examining health effects, we use information on the reduction in kerosene consumption to identify positive environmental effects which may be attributed to SHS. Based on the estimates in Table 6 (column 4), the reduction in kerosene use amounts to about 14 l a year. The associated reduction of greenhouse gases may be computed based on methodology AMS-I.A., which describes how such effects may be obtained when fossil-fuel-based technologies are replaced by renewable electricity generation (United Nations Framework Convention on Climate Change, 2016). We calculate the annual reduction of greenhouse gases in kilograms of CO^2 by multiplying the annual reduction in the use of kerosene times the net calorific value of kerosene times its emission factor. Based on the Intergovernmental Panel on Climate Change emission factor data base, the net calorific value of kerosene is 0.04475 Tera Joules per ton and its emission factor is 71.9 tons per Tera Joule. Hence, per SHS, this yields an annual reduction of about 36.8 kg of carbon dioxide equivalent greenhouse gas.[21] Converting this figure into financial terms is challenging as there is no clear price for a ton of carbon dioxide. According to a World Bank results brief, in 2017, 80% of emissions were not covered by carbon pricing and the median value of those emissions covered by carbon pricing initiatives was less than Euro 9 per ton.[22] This implies that the financial value of the reduced carbon dioxide emissions may be pegged at about 30 Euro cents or KSh 25 per year.

6.4. Payback period

Although limited to the economic effects that we have been able to identify and clearly rudimentary, it is nevertheless instructive to obtain a sense of the payback period associated with investing in a SHS. The main economic effects that we have been able to detect are (i) reductions in expenditure on kerosene and batteries for radio use (ii) reductions in expenditure on mobile phone charging. In total, these amount to at most about KSh 193 per month or savings of about KSh 2316 a year. The most commonly used SHS is Solar 4 which costs

[21] More information can be found here: http://www.ipcc-nggip.iges.or.jp/EFDB/main.php [Last accessed: March 22nd, 2019].

[22] See: https://www.worldbank.org/en/results/2017/12/01/carbon-pricing. [Last accessed: July 16, 2019].

Table 7
Effect of SHS on use of devices.

	Household level controls only (1)	Head controls added (2)	Household level controls only (3)	Head controls added (4)
	OLS	OLS	IPW	IPW
Ownership of (at least) one TV	0.135*** (0.035)	0.142*** (0.039)	0.147*** (0.029)	0.156*** (0.030)
Minutes TV is turned on per day	40.572*** (10.559)	41.134*** (11.087)	44.161*** (8.153)	46.062*** (8.308)
Household heads: Hours watching TV per day	0.099 (0.074)	0.098 (0.078)	0.099 (0.072)	0.105 (0.072)
Spouse: Hours watching TV per day	0.508*** (0.128)	0.553*** (0.123)	0.550*** (0.096)	0.590*** (0.098)
Children: Hours watching TV per day	0.150 (0.108)	0.146 (0.118)	0.156** (0.079)	0.148* (0.087)
Times mobile charged for others	1.578*** (0.460)	1.548*** (0.450)	1.693*** (0.538)	1.660*** (0.564)
Weekly income from mobile phone charging for others	7.048** (3.168)	6.654* (3.504)	8.230 (5.043)	7.735 (5.254)
Weekly cost savings from mobile phone charging	−20.060*** (5.114)	−19.412*** (4.914)	−24.198*** (4.396)	−23.025*** (4.327)

Note: Results from OLS and inverse probability weighting (IPW) are presented. We employed clustered and robust standard errors, respectively. ***/**/* indicate significance at the 1/5/10% level, respectively. The number of observations is 1048 for the model with household level controls only and 990 for the model that adds household head controls. Only the coefficient estimates associated with SHS ownership are displayed. The results for the hours of TV watching per day result from smaller samples due to missing observations.

KSh 12,990. These figures translate into a payback period of about six years. The expected lifespan of the various components which make up the system vary, with the batteries expected to last for 5 years, the lights for about 10 years and the panel for about 15 years.[23]

Clearly, if the benefits are restricted to just the replacement costs of alternative energy sources and mobile phone charging, investing in a SHS may not be considered a very attractive proposition. However, this does not take into account the quality of lighting which is clearly superior to that experienced by the control groups, nor the benefits of additional TV watching time and the positive effects mentioned by respondents concerning education, comfort and security.

7. Concluding remarks

Against the background of the goal to enhance access to electricity in Africa and specifically in Kenya and the challenges associated with on-grid electrification, alternative solutions such as stand-alone solar home systems are being offered as a plausibly important and cost-effective way of achieving this goal (Lighting Africa, 2018a; World Bank, 2018). Motivated by the potential of SHS and the aim of placing debates on the potential of on-grid versus off-grid electricity options on a stronger empirical footing, this paper investigated the impact of SHS access on lighting use, energy consumption and expenditure and the use of electric devices (TV, radio, mobile phones). The paper adds to the recent literature on the effects of pico-photovoltaic kits in Rwanda (Grimm et al., 2017) and solar lamps in Kenya (Rom et al., 2017). Contrary to the existing studies about small-scale solar solutions that mainly provide lighting, SHS offer the opportunity of completely covering the electricity needs of a household and providing all power that developed households require. Put differently, we SHS have greater functionality than the solar kits studied in the other two papers.

The paper was based on a sample of 1048 households, approximately, evenly split between SHS system owners and non-owners. Methodologically, to control for observed and unobserved differences between the two groups, we used a pipeline sampling approach which compares owners with non-owners who have expressed a strong desire to purchase a SHS. The data suggest that the approach delivered comparable groups as the two groups have similar socio-economic characteristics.

The main contributions of the study are threefold: First, we identify energy consumption effects: (i) access to a SHS leads to a three-hour increase in the daily use of LED lamps and is accompanied by a reduction in the use of “dirty” lamps; (ii) the use of kerosene for lighting falls by about one litre a month; (iii) these changes in energy use along with a sharp decline in the cost of charging mobile phones led to a reduction in overall monthly expenditure of KSh 193 (about EUR 1.60). Second and in addition to the economic benefits, we find small positive environmental effects, increased satisfaction from better quality lighting and an increase in time spent watching TV. Third, for the most popular SHS, Solar 4, strictly on the basis of the direct economic benefits to the household, these effects translate into a payback period of about six years. This may be compared to the expected lifespan of the various SHS components which vary between five and 15 years. Factoring in the higher quality of lighting and the greater range of leisure time options, it is not surprising that 93% of the respondents mentioned that access to a SHS had led to an improvement in their lives. Overall, in terms of uptake, the analysis suggests that even if one excludes social benefits, the combination of private economic and non-monetized benefits identified in this paper are large enough to persuade households to buy a SHS.

However, there are three caveats to our findings. First, the analysis at hand only assesses the satisfaction with the quality of lighting between SHS and non-SHS owners. SHS owners are further requested to report about their satisfaction with the system. Yet, impacts of SHS on overall life satisfaction or other indicators of (subjective) wellbeing have not been studied. Future research should go beyond energy consumption and energy-related expenditures and also examine how off-grid solar solutions influence wellbeing.[24] Second, our results are only valid for the socio-economic group of households targeted by the firm in question. Comparing the average per capita expenditure of households in our sample to national data suggests that the sampled households belong to the second quintile of the expenditure distribution. Regionally, the households are located in the Central, Southern and Western parts of the country. Hence, the affordability and the viability of using SHS such as the Solar 4 or Solar TV is restricted to somewhat better off households and we cannot draw any conclusions for households located in Northern and North-eastern Kenya. However, even with these restrictions, the number of households (about 660,000) lying in the targeted expenditure category is large enough to support the use of such SHS to enhance energy access. Third, in terms of the debate on off-grid versus on-grid access to meet energy needs in rural Africa – clearly the use of SHS which may be purchased for less than USD 100 and come equipped with 4 lights, mobile phone charging functionality (and a radio) are affordable for a wider range of households as compared to on-grid access. However, this is conditional on rural households restricting their needs to Tier II access (lighting, phone charging, TV, fans) as opposed to medium or high-powered appliances. Thus, reprising Grimm et al. (2017) and Rom et al. (2017), while their papers suggest that basic pico-PV systems or solar lights support households in terms of reaching the first step of the energy ladder, this paper shows that climbing the second step based on the use of quality-verified solar products is possible and affordable for somewhat better off households, and provided that the benefits of such systems are articulated and sustained, this may be achieved without resorting to subsidies.

[23] These prices and payback calculations refer to the situation on the ground at the moment of our survey. In the meantime, the costs of the Solar 4 SHS have dropped to KSh 10,990 resulting in a payback period of less than 5 years.

[24] We thank an anonymous referee for pointing this out.

Credit author statement

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Appendix A. Appendix

Table A1
Geographical balancing and balancing at the microfinance group level between treatment and control sample.

	Share (%)	Treatment share (%)	Control share (%)	Difference in means *p*-value
Region				
Central Eastern	9.35	9.10	9.60	0.77
Central Nyanza	8.49	8.70	8.30	0.80
Central Rift	6.77	6.60	6.90	0.85
Coast Island	7.63	8.30	6.90	0.39
Eastern Nyanza	4.77	4.70	4.80	0.96
Lower Eastern	6.30	5.70	6.90	0.41
Mount Kenya East	3.15	3.20	3.10	0.90
Mount Kenya North	4.01	3.80	4.20	0.72
Mount Kenya West	2.58	2.50	2.70	0.81
Nairobi Zone	2.29	2.30	2.30	0.97
North Coast	4.20	4.20	4.20	0.96
North Rift	15.46	15.50	15.40	0.95
South Nyanza	1.15	1.10	1.20	0.98
South Rift	11.93	11.00	12.90	0.34
Transnzoia	9.64	10.60	8.70	0.29
Western	2.29	2.70	1.90	0.43
Microfinance Organization				
MFI 1	14.22	14.40	14.00	0.87
MFI 2	26.81	25.90	27.70	0.52
MFI 3	58.97	59.70	58.30	0.65

Table A2
Comparison between the proposed sampling strategy and the actual treatment and control sample.

	Proposed sampling strategy among existing clients		Treatment sample	Control sample
Central Eastern				
MFI 1	Clients	Sample		
SOLAR TV	2	0	4	
SOLAR 2	8	1	0	
SOLAR 4	23	4	1	
MFI 1 Total	33	6	5	7
MFI 3				
SOLAR TV	71	14	15	
SOLAR 2	56	11	6	
SOLAR 4	123	24	21	
MFI 3 Total	250	43	42	43
Central Eastern Total	283	49	47	50
Central Nyanza				
MFI 1	Clients	Sample		
SOLAR TV	23	4	6	
SOLAR 2	14	2	1	
SOLAR 4	33	6	3	
MFI 1 Total	70	12	10	12
MFI 3				
SOLAR TV	114	20	19	
SOLAR 2	14	2	3	
SOLAR 4	52	9	12	
MFI 3 Total	180	31	34	31
Central Nyanza Total	250	43	44	43

(continued on next page)

Table A2 (*continued*)

	Proposed sampling strategy among existing clients		Treatment sample	Control sample
Central rift				
MFI 1	Clients	Sample		
SOLAR TV	1	0	1	
SOLAR 2	8	1	0	
SOLAR 4	14	2	2	
MFI 1 Total	23	4	3	4
MFI 2				
SOLAR TV	4	1	1	
SOLAR 2	20	3	1	
SOLAR 4	40	7	7	
MFI 2 Total	64	11	9	9
MFI 3				
SOLAR TV	34	6	6	
SOLAR 2	24	4	6	
SOLAR 4	47	8	8	
MFI 3 Total	105	18	20	23
Central Rift Total	192	33	32	36
COAST Island				
MFI 1	Clients	Sample		
SOLAR TV	1	0	0	
SOLAR 4	10	2	2	
MFI 1 Total	11	2	2	2
MFI 3				
SOLAR TV	95	16	24	
SOLAR 2	25	4	2	
SOLAR 4	80	14	13	
MFI 3 Total	200	34	39	34
Coast Island Total	211	36	41	36
Eastern Nyanza				
MFI 1	Clients	Sample		
SOLAR TV	9	2	4	
SOLAR 2	5	1	0	
SOLAR 4	19	3	2	
MFI 1 Total	33	6	6	6
MFI 2				
SOLAR 2	4	1		
SOLAR 4	31	5	6	
MFI 2 Total	35	6	6	6
MFI 3				
SOLAR TV	33	6	6	
SOLAR 2	7	1	0	
SOLAR 4	34	6	7	
MFI 3 Total	74	13	13	13
Eastern Nyanza Total	142	24	25	25
Lower Eastern				
MFI 3	Clients	Sample		
SOLAR TV	111	19	22	
SOLAR 2	7	1	0	
SOLAR 4	64	11	8	
MFI 3 Total	182	31	30	36
Lower Eastern Total	182	31	30	36
Mount Kenya East				
MFI 1	Clients	Sample		
SOLAR 4	5	1	1	
MFI 1 Total	5	1	1	1
MFI 2				
SOLAR 2	3	1		
SOLAR 4	22	4	9	
MFI 1 Total	25	4	9	8
MFI 3				
SOLAR TV	27	5	5	
SOLAR 2	5	1	0	
SOLAR 4	4	1	2	
MFI 3 Total	36	6	7	7
Mount Kenya East Total	66	11	17	16
Mount Kenya North				
MFI 1	Clients	Sample		
SOLAR TV	2	0	0	
SOLAR 2	2	0	0	
SOLAR 4	8	1	1	
MFI 1 Total	12	2	1	2
MFI 2				
SOLAR TV			2	

Table A2 (*continued*)

	Proposed sampling strategy among existing clients		Treatment sample	Control sample
SOLAR 2	1	0	0	
SOLAR 4	31	5	8	
MFI 2 Total	32	5	10	10
MFI 3				
SOLAR TV	23	4	3	
SOLAR 4	28	5	5	
MFI 3 Total	51	9	8	10
Mount Kenya North Total	95	16	19	22
Mount Kenya West				
MFI 1	Clients	Sample		
SOLAR TV	6	3	2	
SOLAR 2	4	2	1	
SOLAR 4	28	13	4	
MFI 1 Total	38	18	7	7
MFI 2				
SOLAR 4	10	2	1	
MFI 2 Total	10	2	1	2
MFI 3				
SOLAR TV	20	3	2	
SOLAR 2	4	1	1	
SOLAR 4	8	1	1	
MFI 3 Total	32	5	4	5
Mount Kenya West Total	80	14	12	14
Nairobi Zone				
MFI 1	Clients	Sample		
SOLAR TV	11	2	2	
SOLAR 2	2	0	0	
SOLAR 4	36	6	6	
MFI 1 Total	49	8	8	8
MFI 2				
SOLAR TV	7	1	0	
SOLAR 2	2	0	1	
SOLAR 4	4	1	1	
MFI 2 Total	13	2	2	2
MFI 3				
SOLAR TV	7	1	0	
SOLAR 4	3	1	2	
MFI 3 Total	10	2	2	2
Nairobi Zone Total	72	12	12	12
North Coast				
MFI 3	Clients	Sample		
SOLAR TV	48	8	7	
SOLAR 2	28	5	8	
SOLAR 4	51	9	6	
MFI 3 Total	127	22	21	22
North Coast Total	127	22	21	22
North Rift				
MFI 1	Clients	Sample		
SOLAR TV	12	2	1	
SOLAR 2	16	3	1	
SOLAR 4	24	4	7	
MFI 1 Total	52	9	9	11
MFI 2				
SOLAR TV	15	3	1	
SOLAR 2	144	25	16	
SOLAR 4	168	29	32	
MFI 2 Total	327	56	49	50
MFI 3				
SOLAR TV	43	7	12	
SOLAR 2	11	2	7	
SOLAR 4	27	5	5	
MFI 3 Total	81	14	24	19
North Rift Total	460	79	82	80
South Nyanza				
MFI 1	Clients	Sample		
SOLAR TV	1	0	0	
MFI 1 Total	1	0	0	0
MFI 3				
SOLAR TV	12	2	2	
SOLAR 2	9	2	2	
SOLAR 4	12	2	2	
MFI 3 Total	33	6	6	6
South Nyanza Total	34	6	6	6

(continued on next page)

Table A2 (*continued*)

	Proposed sampling strategy among existing clients		Treatment sample	Control sample
South Rift				
MFI 1	Clients	Sample		
SOLAR TV	7	1	1	
SOLAR 2	4	1	0	
SOLAR 4	4	1	1	
MFI 1 Total	15	3	2	3
MFI 2				
SOLAR TV	4	1	4	
SOLAR 2	42	7	2	
SOLAR 4	241	41	25	
MFI 2 Total	287	49	31	40
MFI 3				
SOLAR TV	44	8	6	
SOLAR 2	11	2	4	
SOLAR 4	40	7	14	
MFI 3 Total	95	16	24	24
South Rift Total	397	68	57	67
Transnzoia				
MFI 1	Clients	Sample		
SOLAR TV	16	3	5	
SOLAR 2	13	2	5	
SOLAR 4	23	4	6	
MFI 1 Total	52	9	16	10
MFI 2				
SOLAR TV	4	1	0	
SOLAR 2	27	5	8	
SOLAR 4	72	12	11	
MFI 2 Total	103	18	19	17
MFI 3				
SOLAR TV	53	9	8	
SOLAR 2	19	3	4	
SOLAR 4	32	5	8	
MFI 3 Total	104	18	20	18
Transnzoia Total	259	44	55	45
Western				
MFI 1	Clients	Sample		
SOLAR TV			2	
SOLAR 2	2	0	0	
SOLAR 4	4	1	0	
MFI 1 Total	6	1	2	0
MFI 3				
SOLAR TV	36	6	8	
SOLAR 2	8	1	0	
SOLAR 4	17	3	4	
MFI 3 Total	61	10	12	10
Western Total	67	11	14	10
Grand Total	2917	500	514	520

Table A3
Logistic regression estimates for the probability of owning a SHS (marginal effects).

	Household level controls only (1)	Head controls added (2)
Respondent is head	0.063* (0.032)	0.082** (0.037)
Household size	0.021* (0.011)	0.025** (0.012)
Poverty: Adjusted PPI score	0.001 (0.002)	0.002 (0.002)
Quality of the main building		
Floor made of cement/brick/ceramic	0.098** (0.040)	0.106** (0.041)
Walls (excluded category: Other material)		
Cement walls	0.108* (0.057)	0.081 (0.059)
Brick walls	0.027 (0.042)	0.022 (0.044)
Roofing made of iron sheets	−0.020 (0.062)	−0.011 (0.064)
Windows covered with glass	−0.081** (0.038)	−0.077* (0.039)
Number of rooms for living	0.012 (0.015)	0.009 (0.016)
Agriculture		
Number of acres owned	0.002 (0.003)	0.002 (0.003)
Number of acres cultivated	0.004 (0.009)	0.006 (0.009)
Livestock		
Number of cows	0.010 (0.007)	0.009 (0.007)
Number of sheep	−0.003 (0.005)	−0.003 (0.004)
Number of goats	0.001 (0.001)	0.001 (0.001)
Means of transportation		
Bicycle	−0.073* (0.039)	−0.053 (0.040)
Motorcycle	0.024 (0.037)	0.021 (0.038)
Car	0.130 (0.080)	0.138* (0.081)
Assets (at least one)		
Household owns a gas stove	0.076 (0.048)	0.066 (0.049)
Household owns mosquito nets	−0.002 (0.047)	−0.010 (0.048)
Household owns a mechanic sewing machine	−0.044 (0.054)	−0.041 (0.056)
Use of the national grid in past 5 years	−0.306*** (0.043)	−0.320*** (0.044)
Household head characteristics	No	Yes
Observations	1048	990

Note: Marginal effects are displayed. The household head characteristics include age, gender, schooling (primary 1–6, Primary 7, Primary 8 and Secondary forms, higher) and occupation (Agriculture, hunting, fishing, retail, private sector formal employee, public sector formal employee). None of the characteristics of the household head are statistically significant. In addition, the specifications include micro-finance institution, region, and location (urban, peri-urban) fixed effects.

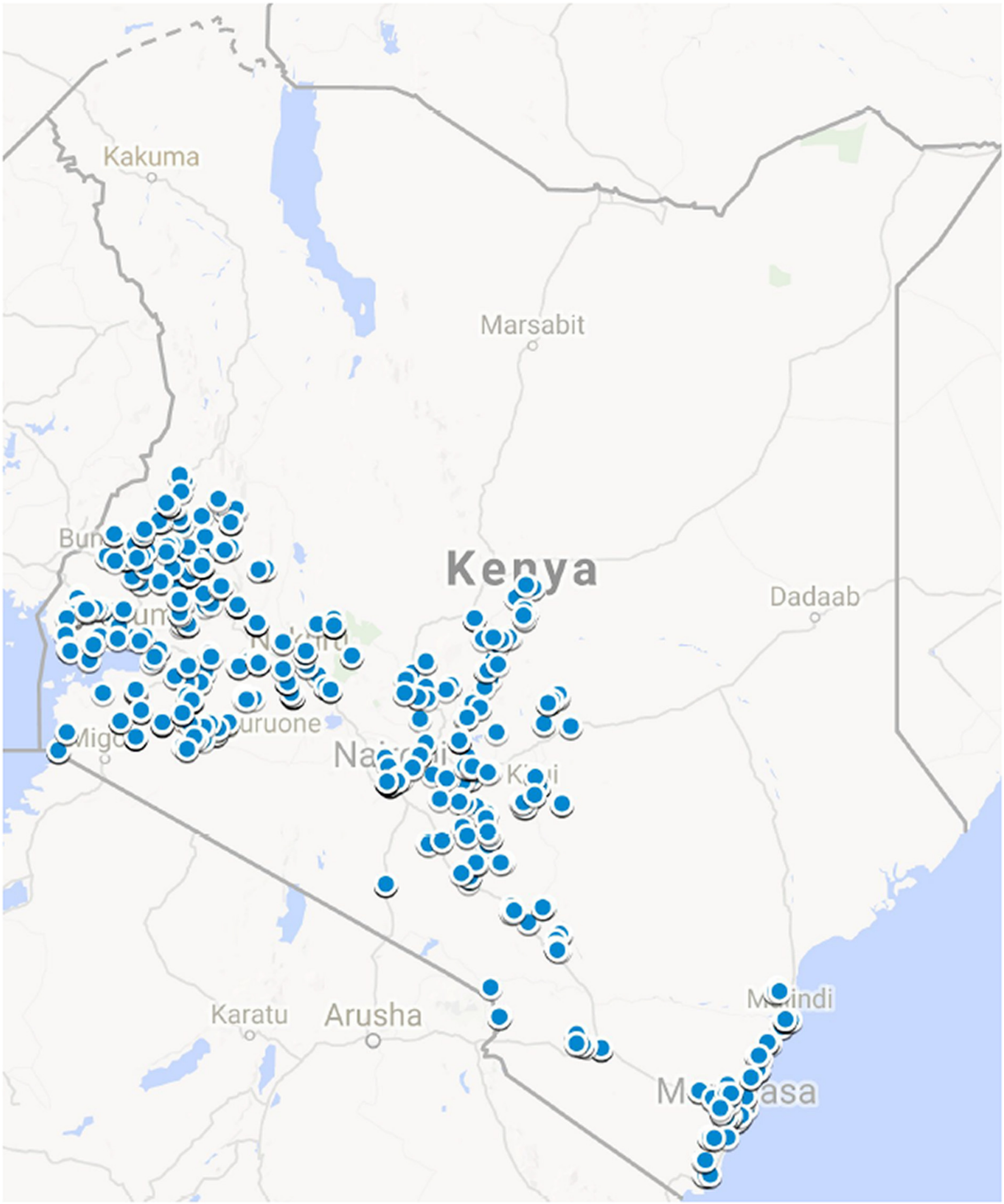

Fig. A1. Map locating the surveyed households.

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