Energy for Sustainable Development 37 (2017) 33–50

Contents lists available at ScienceDirect

Energy for Sustainable Development

Rural energy access through solar home systems: Use patterns and opportunities for improvement

Ognen Stojanovski [a,*], Mark Thurber [a], Frank Wolak [a,b]

[a] Program on Energy and Sustainable Development (PESD), Stanford University, United States
[b] Department of Economics and PESD, Stanford University, United States

ARTICLE INFO

Article history:
Received 24 November 2016
Accepted 28 November 2016
Available online xxxx

ABSTRACT

Solar photovoltaic (PV) products are touted as a leading solution to long-term electrification and development problems in rural parts of Sub-Saharan Africa. Yet there is little available data on the interactions between solar products and other household energy sources (which solar PVs are often assumed to simply displace) or the extent to which actual use patterns match up with the uses presumed by manufacturers and development agencies. This paper probes those questions through a survey that tracked approximately 500 early adopters of solar home systems in two off-grid markets in Africa. We find that these products were associated with large reductions in the use of kerosene and the charging of mobile phones outside the home. To a lesser extent, the use of small disposable batteries also decreased. However, solar home systems were, for the most part, not used to power radios, TVs, or flashlights. We also did not observe adopter households using these solar products to support income-generating activities.

Background and motivation

Sub-Saharan Africa is home to approximately 600 million people without access to electricity (IEA, 2014). This is a function of both the limited ability of low-income populations to pay for electricity and the institutional barriers in many countries that hinder a build-out of the national electric grid. Over the past decade, solar photovoltaic (PV) products have emerged as a possible solution to Africa's long-term electrification and associated development problems. Adoption rates have been dramatic, with market-based sales of household-sized or smaller solar units in the region soaring to well over 10 million since 2011 (Lighting Global, 2016).[1]

The dominant products sold to date to rural, non-electrified populations have been basic, so-called "picoPV" products that have just one LED light bulb powered by a small solar panel of less than 10 W. Larger "advanced picoPV" products are also common, and feature a 10–20 W solar panel that powers a longer-lasting and brighter light, as well as limited phone charging functionality; these products can charge 1–2 basic mobile phones per day. Beyond that, household-sized solar home systems ("SHSs") are increasingly common, although they are estimated to represent less than 5% of the off-grid solar market by number of products sold as of June 2016 (GOGLA and Lighting Global, 2016). They typically have a larger solar panel installed on a building's roof that charges an external battery which, in turn, powers several electric bulbs and can charge multiple phones each day. Higher rungs on the solar PV "energy ladder" involve the use of still larger SHSs that can power radios, TVs, and even energy-efficient refrigerators for the largest models (see e.g. Lighting Global (2014)).

The solar industry across Africa is led by for-profit social enterprises that are typically beneficiaries of significant market development support provided by many multilateral institutions, development agencies, non-governmental organizations (NGOs), foundations, governments, and impact investors. These stakeholders are thought to be attracted to the sector by the vision of solar PV products as environmentally sustainable solutions that provide brighter, safer, and healthier lighting than traditional sources. Solar products are also perceived by many of these stakeholders as a way to provide basic electrification at scale more reliably, cheaply, and quickly than other modern but unreliable or environmentally unsustainable solutions like national grids or diesel generators.

Despite the extremely encouraging sales trends and broad appeal of the potential for socially-desirable impacts, important questions remain about the nature and role of consumer-facing solar products in Africa. In particular, there have been few systematic investigations into how households that adopt solar products use them or the extent to which actual use patterns match up with the ones presumed by the African solar industry or its supporters. Recognizing that applications valued

* Corresponding author.
E-mail address: ognen@stanford.edu (O. Stojanovski).

[1] These are very conservative estimates as they only account for verified sales of small solar products and exclude the larger, household-sized ones; in addition, they do not account for the so-called "generics" or "no-name" brands that are estimated to account for a majority of actual off-grid solar PV product sales in the region (Lighting Global, 2016).

http://dx.doi.org/10.1016/j.esd.2016.11.003
0973-0826/

by consumers are not always those prioritized by development agencies or solar enterprises, this paper proceeds by presenting the results of an original survey that tracked the self-reported use patterns of solar home systems. The methodology is described in Section 2 and the result detailed in Sections 3–6.

We find that once adopted, a SHS is associated with a significant reduction in kerosene use and the transition to modern electric lights as a household's dominant lighting source. We also observe dramatically lower rates of charging mobile phones outside the house. The story is not as clear, however, when it comes to the displacement of disposable dry-cell batteries or the ability of SHSs to readily and adequately power flashlights, radios, or televisions. Our results suggest that a number of barriers still need to be overcome in order for SHSs to be effective tools for broader basic electrification. In particular, the widespread use of battery-powered flashlights and radios (as well as ownership of inefficient CRT TVs in a minority of households) *prior* to the purchase of a SHS significantly complicates matters; as a result, it will likely take more time and effort to achieve energy access goals beyond the more immediate impacts on household lighting and basic phone charging patterns. Finally, we observe an overwhelming tendency to use SHS products only as a means to make a home more comfortable rather than for income-generating activities.

In the conclusion (Section 7), we evaluate the extent to which our data appear to support common assumptions with respect to the use of SHS products and, more broadly, the development impacts of the off-grid solar PV industry in Africa. The results are strictly observational and descriptive but they are nevertheless among the first data-driven systematic efforts to offer insights into actual adoption and use patterns in this space. They can also help support the development of more nuanced household energy models, such as the framework proposed by Kowsari and Zerriffi (2011), to better explain the solar-driven energy transitions currently under way in rural Africa.

Our hope is that this research will help solar social enterprises, nonprofit organizations, development agencies, and governments better direct scarce resources towards achieving their energy access and development goals. We also offer potential strategies that may enable future end-users to gain further benefits of SHS ownership beyond the ones we already observe. These insights are a first step in evaluating whether SHSs are realizing their potential to deliver sustainable energy or broader development benefits, for which more research is needed.

Research approach

We partnered with a solar manufacturer to interview and track new purchasers of mid-sized and large solar home systems (SHSs) from two sales points, one shop in western Uganda and one in western Kenya. We chose these locations because East Africa has been at the center of the significant entrepreneurial activity in solar products. Uganda and Kenya have seen the entry of many businesses competing to sell low-power picoPV products. These are also the countries that saw the earliest meaningful deployment of household-sized SHSs, although sales of SHSs continue to be only a fraction of the region's picoPV deployment. The two specific sales locations that our research focused around were newly-opened shops in mid-sized towns that served as centers for the surrounding (overwhelmingly rural and non-electrified) communities. Both shops were among the first to offer SHSs of this size in their respective regions, although the market for picoPVs had been well established for several years prior in both locations.

We focused this research on SHS adoption and use because this scale of solar product appears to be especially poorly understood. Prior studies have tended to focus on picoPVs, as that is where the industry and market supporters have centered their efforts. Yet SHSs are perceived as having much greater energy access and development potential relative to picoPVs and, since 2015, more efforts have been made to support the scale-up of these products and encourage existing adopters of picoPVs to "climb the energy ladder" and buy SHSs (see, e.g. Chattopadhyay et al., 2015; Lighting Global, 2014; RMI, 2015).

The SHS products we studied had solar panels of between 15 and 100 watts (W), with lead acid battery capacities of between 7 and 38 ampere-hours. They were all able to power at least 4 light points (0.5–2.0 W LED bulbs) for 4–6 hours per day, in addition to charging several phones (with the bigger units capable of charging more than 30 phones daily). They could all also power a small radio and the majority of the systems could also be connected to an energy-efficient TV. Such radios and TVs were also sold by the SHS manufacturer from the same shops. Depending on the size of the SHS, a customer would need to balance loads on their battery and perhaps reduce the daily lighting and phone charging amounts in order to power these other electronics.

Our efforts focused on interviewing the customers of the two SHS shops. Baseline interviews were conducted at the time of purchase (in the shop), during SHS installation (at the customer's home), or shortly thereafter by research staff hired for this project and embedded in the two shops.[2] The final data consists of 375 customer interviews in Uganda, undertaken between September 2013 and March 2015, as well as 190 in Kenya, carried out between March 2014 and October 2014. The interviews focused on characterizing the non-cooking energy options to which SHS adopters have access, as well as associated use and expenditure patterns. Face-to-face endline interviews collected the same information for all participants in November 2014. At the time of the endline interviews, most participants had owned their SHS between 3 and 6 months. Although baseline data collection continued in Uganda with about 100 additional customers through March 2015, this group was not invited for an endline interview. Sample screenshots of the survey instrument are included in the Appendix. We also carried out five rounds of brief 10-minute phone interviews (in March, April, June, July, and September 2014) with a randomly selected subset of the participants. These phone interviews were much narrower in scope and were intended to detect whether the users were experiencing any problems or otherwise needed after-sales support for their newly-acquired SHS (see Table 1).

The results that follow should be interpreted within the context that the data was gathered in. First, the population under study is self-selected early adopters of SHSs in areas where the technology was relatively new. We cannot say much about how the broader rural population would use such products if there was a more concerted effort to scale-up their adoption among households who would not otherwise choose to purchase them. Nor can we speak about the longer-term sustainability or use patterns of the SHSs in this early adopter population (although we are planning a round of follow-up data collection with our study participants in 2017). Second, the study tracked the customers of only one SHS manufacturer. Although this company continues to be among the leading companies in the African off-grid solar PV industry, with products of similar size and functionality as other SHS manufacturers, we do not have a way to measure the extent to which the results would have been different had we tracked a broader pool of SHS products or how this manufacturer's other services (warranty support, financing mechanisms, product installation,...) impacted the use patterns we observed. Third, caution should be exercised in generalizing the results beyond the rural areas in Uganda and Kenya, where traditional kerosene use is well entrenched and the solar market quite robust. Finally, the results are descriptive and we make no claims to establishing

[2] Initially, all new customers of the two newly-opened shops were invited to participate in the research, and nearly all accepted the invitation to be interviewed. When the volume of new customers began exceed the interviewing capacities of the enumerators assigned to each shop, they interviewed as many as they could. Although no formal randomized selection was enforced, enumerators were instructed to at all times interview the latest person that had bought a SHS at their shop. We have no reason to believe that there is systematic bias in the SHS adopters that participated in the study and those who were not interviewed, especially since the total sample size represents a significant fraction of all customers at those shops during the relevant time periods.

Table 1
Data collection summary.

	Uganda	Kenya
Total baseline interviews with SHS adopters	375	190
Number of baseline participants targeted for endline interviews	276	190
Total successfully completed endline interviews in Nov 2014 (% targeted)	255 (92%)	176 (93%)
Total brief phone calls to randomly-selected participants		
–Sep 2014	149	79
–Jul 2014	110	58
–Jun 2014	80	39
–Apr 2014	43	19

definitive causal links between SHS adoption and energy access or development outcomes.

Despite these important caveats, this study is among the first to track a large group of SHS users over an extended period. Importantly, we had very low attrition rates, which was an important part in of our ability to meaningfully contribute to filling the knowledge gap about what happens to solar PV products after they are sold.

It is also important to keep in mind that SHS use patterns are largely influenced by the energy environment where the products are used. Fig. 1 shows all the non-cooking energy sources used by households in our study before and after the purchase of their SHS. Household energy use profiles at baseline are dominated by three basic energy services: kerosene for lighting, small disposable batteries, and the charging of mobile telephones outside of the home (in the vast majority of cases, at charging shops). At endline, we also observe significant solar PV use thanks to the purchase of the SHS we tracked and studied.

Solar home systems as a leading option to replace kerosene lights

One of the most important results of our study is the substantial drop in the number of households reporting kerosene use. In the time

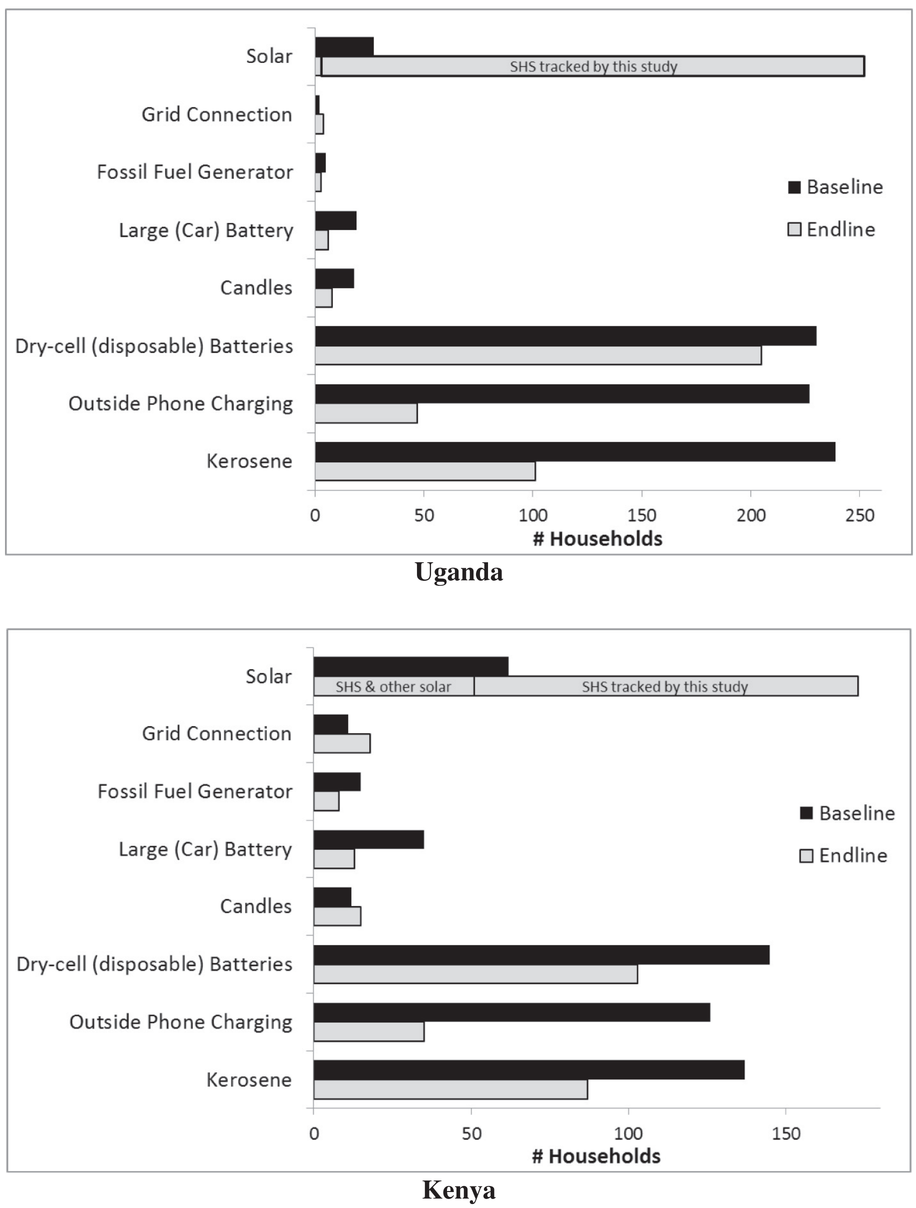


Fig. 1. Household (non-cooking) energy stock of SHS adopters.

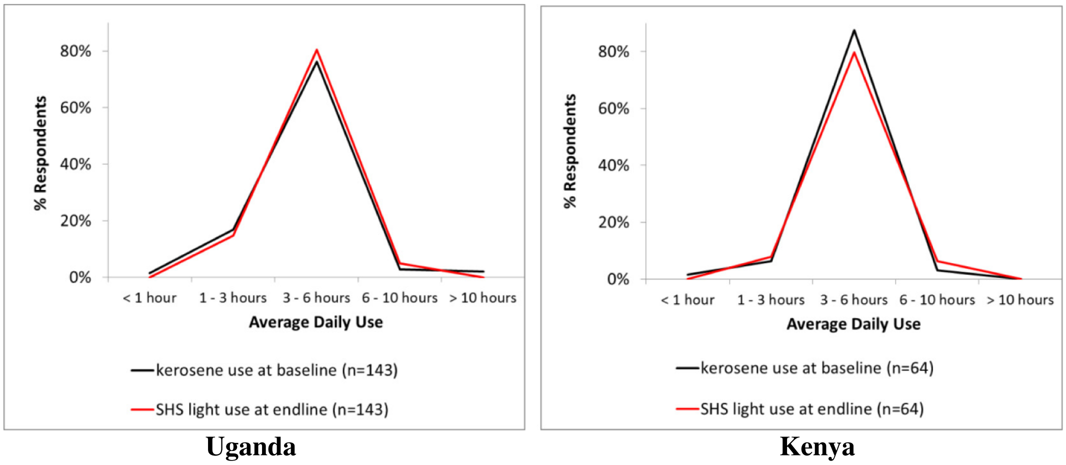


Fig. 2. Use of kerosene and SHS lights in households that stopped using kerosene.

between the SHS purchase and the endline interviews[3], this decrease was 58% in Uganda and 36% in Kenya (Fig. 1). Most of the reduction is attributable to households that used kerosene as their primary lighting source when they purchased the SHS but had completely stopped doing so soon thereafter.[4] Fig. 2 shows the surprisingly tight overlap between the average daily length of use of kerosene lights (pre-SHS) and SHS-powered LED bulbs (post-SHS) for these kerosene “disadopters.” In effect, these households report using the new solar-powered bulbs for exactly the same lengths of time as the previously used kerosene. Other data we collected on lighting applications (for cooking, socializing, reading, etc.) also support the conclusion that SHS-powered electric lights are mostly used in the same manner as traditional kerosene lamps (Fig. A1 in Appendix 1). It is unclear, however, whether kerosene and the SHS were both able to fully satisfy some relatively fixed lighting demands of these households (in which case they just switched from one lighting source to another) or, alternatively, if the SHS adopters were using solar lights in the same manner as kerosene out of habit (in which case, over a longer period of time, they might begin to change SHS-powered lighting use patterns).

There is also a displacement of kerosene in the households that *continued* using kerosene. As shown in Fig. 3, after the adoption of a SHS, there is a shift in the distribution of kerosene use in these households: whereas the large majority reported using kerosene lights for 3–6 hours per day when they purchased the SHS, they report, on average, using kerosene lights for only 1–3 hours daily after. Consistent with these results, the median monthly spending on kerosene among these households was 40% lower (in both countries) than the median spending by kerosene-using households at baseline.[5]

In this study, SHS adoption was associated with a meaningful – albeit not complete – reduction in the use of kerosene. This is especially important because kerosene was the dominant source of lighting for the populations we studied (Fig. 4).[6] Even though some households had electric lighting, especially in Kenya (where grid connections, generators, car batteries, and other solar products that can power electric bulbs are more common), kerosene lighting was far more important. When asked to identify their household's most important pre-SHS light source, 70% of Kenyan and 80% of Ugandan respondents indicated kerosene lamps.

Much of the social enthusiasm and development agency support for the continued growth of the African off-grid solar PV industry derives from the potential for health, climate, and household budget improvements thanks to the type of kerosene displacement we observed (see, e.g. Adkins et al., 2010). Yet changes in kerosene light use patterns have not been widely tracked in the handful of empirical studies in this space. A notable exception is Grimm et al. (2015), who do find similar reductions among “bottom of the economic pyramid” households that were given solar products.[7] Meanwhile, the industry has focused on scaling the sales of small, stand-alone picoPV solar lanterns intended to replace one kerosene lamp each (Harrison et al., 2016), although Brüderle (2011) suggests that actual replacement displacement rates may be much lower. In addition, Lee et al. (2016), working in rural Kenya at the same time as our project, report high rates of kerosene for lighting use among households owning a variety of solar products, and even grid-connected homes.

We build upon the prior work by directly tracking and comparing the use patterns of kerosene and solar lights over relatively large samples and time frames. We hypothesize that our broadly encouraging kerosene displacement results are largely a function of our choice to focus on larger SHSs rather that picoPVs; off-grid solar solutions may need to exceed a minimum threshold of size and functionality before they can replace kerosene lanterns on a household level. On average, households in our study regularly used 2 kerosene lanterns before purchasing their SHS (with about a third of the sample using 3 or more lamps). They also reported purchasing 4 such lights in the 3 years before the baseline interview (Table 2). We would therefore not expect as dramatic a reduction in kerosene use if only one picoPV light were to be introduced in that environment. So our focus on larger solar products (with at least four light bulbs that could each last six hours daily) may well have been what enabled us to detect the types of large and systematic declines in kerosene use that have not previously been widely reported.[8]

[3] The exact time between SHS adoption and endline interview was anywhere from 2 months to a little over 1 year for our study participants, with the median period being 5.5 months.

[4] In Kenya, we also observe 12 households that did *not* report using kerosene at the time of SHS purchase but did so during the endline interview. Half of those were not actually using their SHS at the time of the endline, as it was broken and/or had been repossessed due to missed financing payments. For these households, adopting the SHS seems to have had a negative consequence in that their unavailable SHS left them reliant on kerosene, highlighting the importance of solar product quality and durability.

[5] The end-user price of kerosene remained flat throughout our study.

[6] Although flashlights and mobile phones were also common sources of lighting, these were primarily used when walking in the dark outside the house or when preparing for bed. For the most part, they were only used around 30 min each day.

[7] Adkins et al. (2010) also report significant reductions in kerosene use associated with the adoption of LED lanterns, although the one week time gap between “pre” and “post” interviews makes it difficult to ascertain whether such changes are durable.

[8] This is in line with another study that tracked smaller SHSs is Uganda at about the same time and found greater kerosene displacement than that generally reported in the picoPV literature but less than what we observed (IDInsight, 2015). Meanwhile, the focus of Grimm et al. (2015) on the poorest households using, on average, just one traditional lighting source for only a few hours each day, may explain the observed kerosene reductions in that study.

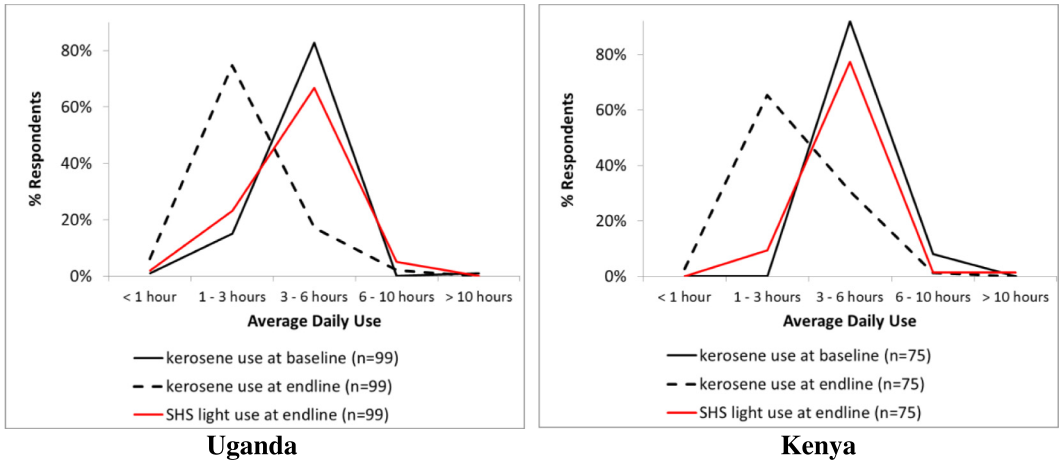


Fig. 3. Use of kerosene and SHS lights in households continuing kerosene use.

We do not believe that our observed decrease in kerosene use is being driven primarily by factors external to the adoption of the solar home systems. There were no general decreases in kerosene consumption or availability, nor were there any prices shocks, in the areas of Kenya and Uganda we worked in during the research period; indeed, kerosene prices at the pump were flat. Baseline interviews were spread out over more than one year (Uganda) and seven month (Kenya) periods, and there are no notable systematic differences in the rates or patterns of pre-SHS kerosene use among study participants that took the baseline interviews at different points in time.

Notable differences between solar and kerosene lights

Although we detect a nearly one-to-one replacement of kerosene lights with solar-powered bulbs in terms of hours of daily use for households that disadopt kerosene, it is important to note that a solar home system does not merely provide a different means of powering traditional lights. Instead, the LED bulbs of a SHS are generally thought to be functionally superior, providing far brighter and more pleasing ambient lighting than traditional kerosene lanterns. This aspect of the displacement was often commented on by study participants in open-ended unprompted questions. So although the coarse use patterns of the solar-powered lights look very similar to those of the replaced kerosene lanterns, the solar-adopting households themselves seem keenly aware that they have acquired more than just an alternative power source for their lighting demands. The LED bulb is perceived as a qualitatively better light beyond its capacity to replace kerosene lanterns, as also noted by Grimm et al. (2015).

In addition, a more detailed inspection of the data reveals a notable opportunity to even further increase SHS utility and replace kerosene. Namely, SHS light bulbs are not used to light kitchens and other food preparation areas (or to do other household chores that are usually done by women) nearly as much as kerosene lanterns (Table 3 and Fig. A1).

One likely reason for this is the common practice of cooking outdoors or in structures separate from the main house. As in the rest of rural Kenya, about two-thirds of households in the region where we collected our data do exactly this (USAID, 2014a).[9] Even though the SHS adopters we tracked are more affluent than the average rural household, our field visits lead us to believe that a significant portion of them also cook and perform other chores outside the main house. However, the SHS products we studied provided only eight-meter cables to connect light bulbs to the battery, which was likely too short to reach the cooking spaces of many households.

It is therefore possible that relatively minor design modifications could help bridge this potential gender discrepancy in the utility of the SHS while also encouraging more complete kerosene displacement. Simply providing longer cables of 15 to 20 meters (even if for just one of the bulbs) could be the first step. Alternatively, including a portable cable-less LED lantern that could be charged by the SHS could also help. An additional improvement would be guidance on how to hang electric bulbs above food preparation areas, which often lack the sturdy walls and ceilings of the main dwelling and so may seem better suited for a floor-based light like a kerosene lantern.

Throughout our study, we also observed a strong demand from SHS users to leave at least one light bulb – usually on the porch – on overnight for security reasons. This is in line with many anecdotal reports, as well as another study of SHSs in Uganda (IDInsight, 2015) highlighting the end-user perceptions of electric lights as desirable security systems. However, most SHSs sold in East Africa are ill-suited to this purpose. To keep costs low, even larger products are not sized to be able to power one light bulb for more than six hours daily unless the remaining lights are used less or battery load is otherwise curtailed through less phone charging or radio listening. Such a balancing act is non-intuitive and difficult to communicate to customers; yet it is especially important for systems like the ones we studied that use lead-acid batteries, as they can be permanently damaged if consistently overloaded and fully drained. The Kenyan end-users we tracked used security lights less than the ones in Uganda (Table 4). This was likely the result of a focused customer education effort by the Kenyan shop that we understood to be resource-intensive and potentially difficult to scale.[10]

This issue of security lights is a prominent example of the broader challenge of customer education and expectations management. In many cases, it may be intuitive and desirable (from the end-users' perspective) to regularly "misuse" (from the solar company's perspective) the solar product by leaving lights and appliances on until the battery completely drains. After all, most solar users are accustomed to filling lanterns with kerosene and burning them until the kerosene runs out. And their impression of grid electricity – which they may believe a SHS is more or less equivalent to – may well be that lights and

[9] We do not have similar data for Uganda but anecdotal reports suggest a similar situation in that country.

[10] The Kenyan shop opened several months after the Ugandan one and – learning from the Ugandan experience – staff were instructed to focus on strongly discouraging customers from using the SHS lights for more than 6 hours daily, specifically highlighting that the product was not designed for overnight security light purposes. Nevertheless, sales agents struggled to deliver the message and required close oversight from management in Kenya and even Europe since this message interfered with the intuitive appeal of the SHS for prospective customers.

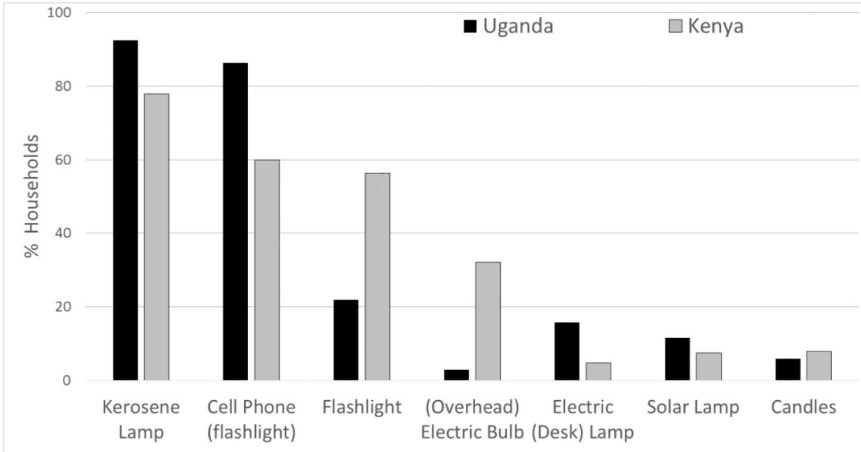


Fig. 4. Household lighting stock at time of SHS adoption.

appliances can be left running for as long as one wishes. But behaving in that way with a SHS, where a customer must consider battery capacity and where changing levels of sunshine impact the ability to fully recharge the battery, means that users may end up with less and less hours of electric lighting over time (because the battery is damaged and/or recharged to increasingly lower levels whenever it is drained). As a result, solar companies may be well served to consider more technical solutions to this problem (such as by triggering an automatic shut-off once battery levels reach a certain threshold even though some battery charge remains) rather than hoping that customers will eventually understand and respond to instructions to only use their products in certain ways and not others.

Overall, there is reason to be optimistic that electric lighting from a SHS can provide even more lighting benefits beyond the replacement of the traditional kerosene lantern. But as the challenges of providing SHS-powered lighting in cooking areas and for security purposes illustrate, such broader benefits do not derive automatically and may require more focused attention and resources from solar companies.

Table 2
Pre-SHS kerosene lamp ownership.

	Uganda	Kenya
Number of kerosene lamps regularly used per household		
–Mean	2.3	2.2
–Median	2	2
–Minimum	1	1
–Maximum	7	7
–% households using 3 or more kerosene lamps	35%	27%
Number of kerosene lamps purchased in last 3 years		
–Mean	4	4
–Median	4	3
–Minimum	0	0
–Maximum	20	15
Type of kerosene lamps used (% kerosene-using households)		
–Small wick lamp (made of a tin)	86%	57%
–Larger lamp with a chimney	77%	86%
–Pressure lamp/hurricane light	3%	4%

Table 3
Use of kerosene and SHS lights to illuminate food preparation areas.

	Uganda	Kenya
% SHS lights used in food preparation – endline survey	66%	58%
% kerosene lanterns used in food prep – endline survey	86%	89%
% kerosene lanterns used in food prep – baseline survey	99%	95%

Solar home systems and the convenience of In-home phone charging

We observed a large reduction – over 70% in both countries – in the numbers of households that reported charging their mobile phones outside of their homes. Before the SHS, households in our study, like most people in rural Africa, generally charged their phones at a shop or kiosk where they paid for this service. By the time of the endline survey, over 90% of respondents reported using the SHS to charge their phones, which appears to be largely driven by the convenience of charging at home. In addition, a sizeable number of SHS users charged phones for people not in their household, although very few started an actual phone charging business, as detailed in Section 5, (Table 5 and Fig. 5).

While around 20% of phone users continued to at least occasionally charge phones outside their homes, we did not observe a meaningful difference in the patterns of charging phones *at home* (with the SHS) between that group and the 80% who no longer charged outside at all. But this minority that does continue charging outside does charge their phones more frequently *overall* than they did prior to buying the SHS. For those who switched to exclusive SHS-based phone charging, we observed an increase in the reported frequency of charging phones in Uganda but not so in Kenya, where SHS-adopting households were already reporting fairly frequent outside the home phone charging habits pre-SHS (Fig. A2 in Appendix 1).

Table 4
Use of SHS lights for night-time security.

	Uganda	Kenya
% SHS light users reporting a security light	53%	35%
% using security light 6–10 h daily	23%	18%
% using security light >10 h daily	23%	9%

Table 5
Pre and post SHS phone charging patterns (% phone users completing both baseline and endline surveys).

	Uganda	Kenya
Charge phones outside the house pre-SHS	92%	72%
Charge phones outside the house post-SHS	19%	21%
Use SHS to charge phones at home at endline	96%	92%

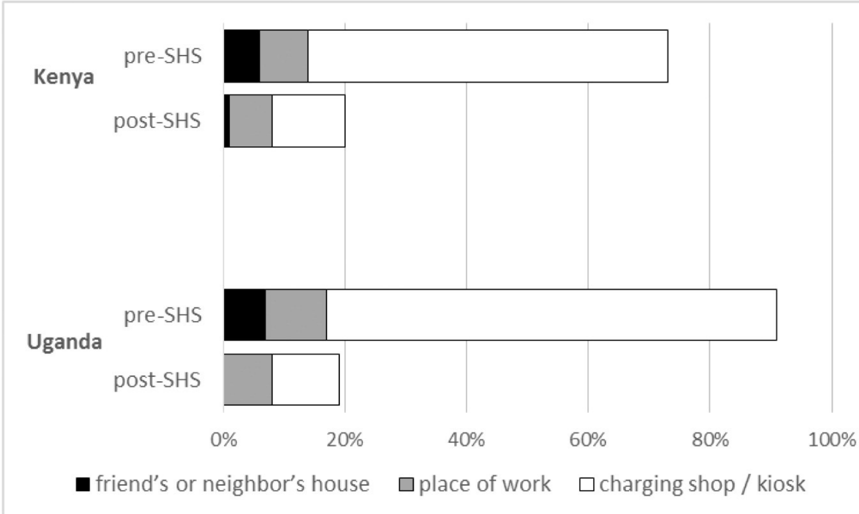


Fig. 5. Pre and post SHS phone charging locations outside the home (% phone users completing both baseline and endline surveys).

Overall, these results are consistent with expectations that solar products might largely remove the need to charge phones outside the home and thereby promote increased mobile phone use and associated benefits. This broad success is largely the result of the ease and convenience of connecting a mobile phone to a solar PV product. Since it is well known that phone penetration is high even among rural, entirely non-electrified populations in Africa (GSMA, 2015), the vast majority of solar products capable of charging telephones are sold with a wide variety of plug adapters that can easily connect to nearly all phone models that are used locally. It is therefore not surprising that we observed mass use of the SHSs we tracked for charging phones, as it is both convenient and straightforward to do so.[11]

No increase in income-generating activities following SHS adoption

Despite the dramatic reductions in kerosene use and outside the home phone charging, we did not observe evidence of a corresponding systematic use of solar products to increase productivity or generate income among our sample of over five hundred SHS users. As Tables 6 and 7 show, over 90% of those we surveyed used their SHS for domestic purposes, viewing it as a means of improved comfort and lifestyle rather than as an opportunity to improve the family's financial situation.

Among the distinct minority who used the SHS in a business setting, a phone charging businesses was the most common (approximately 75% of all SHS business uses we observed), in line with oft-stated expectations that starting a charging businesses would be the most direct way to monetize the ownership of an off-grid solar product (see e.g. Collings, 2011). But even the case of charging phones for others is far more notable for the way in which it is *not* used to generate income rather than the occasional business use. Although nearly one half and one third of SHS adopters in Uganda and Kenya, respectively, reported using their SHS to charge phones belonging to people not living in their house, only about 10% earned any money from this service. And even that small minority mostly charged nominal fees to friends and family rather than setting up a business intended to earn meaningful sums (Table 8).

These results challenge the common assumptions that there is a direct path between off-grid solar energy access and increasing incomes.[12] But our results are consistent with the findings of the IDInsight (2015) study that also took place in Uganda at around the same time as our research, tracked a set of smaller SHS products (from another manufacturer), and also did not observe short-term "productive" uses. Our findings are also in line with the comprehensive literature review by Rahman and Ahmad (2013) of SHS programs in Bangladesh – a much more developed market for these products than East Africa – which also concluded that SHSs do not meaningfully contribute to income generation, employment, or entrepreneurship. This topic is worthy of much more detailed research, as we are not currently aware of research that validates the direct income-generation or poverty-alleviation potential of off-grid solar in Africa.

Challenges to realizing the broader energy access benefits of solar home systems

Questions of whether and how SHSs can promote broader energy access beyond household lighting and phone charging patterns are not well understood. In this respect, our research reveals three important insights. First, it is not just mobile phones that are bought before a household has electricity in their house; many solar adopters buy other key electricity-using appliances *before* purchasing a solar PV product (as shown in Fig. 6 below). Second, unlike with telephones, this pattern of pre-solar investment in electronics complicates the ability to power such electronics with a SHS. As a result, the development of a "plug and play" SHS-compatible market for electronics that is independent of

Table 6
Reported purpose of SHS use (% SHS users).

	Uganda	Kenya
Exclusively domestic	96%	92%
Exclusively business	1%	1%
Both domestic and business	3%	8%

Table 7
Self-reported utility of a SHS.

"My SHS is most useful for":	Uganda (N = 149)	Kenya (N = 79)
Comfort/improving the house	91%	91%
Saving money	2%	5%
Earning more money	2%	0%
Social status/respect	1%	1%
All of the above	4%	3%

[11] We cannot say, however, whether such mobile charging benefits would extend to solar units smaller than the SHS ones we studied. As in the case of kerosene lights replacement, it could be that the relative large capacity of the systems we examined is a key to enabling households to change their overall patterns of phone use and charging.

[12] Harrison et al. (2016) summarizes the (mostly non-academic) literature on this topic.

Table 8
Use of SHS to charge phones for people that do not live in the adopting household.

	Uganda	Kenya
% SHS users that charge phones for others at least occasionally	49%	30%
% SHS users who earn money from charging phones for others	10%	12%
Average weekly revenue of those earning any money (in USD)	$1.25	$2.55

the solar companies could be key to unlocking the benefits of broader electrification through SHS market growth. These insights are explored in more detail directly below.

Disposable batteries

Like kerosene, disposable dry-cell batteries are a leading energy source for rural African households, including for our sample of SHS adopters. And, as with kerosene, the mass use of disposable batteries presents serious local environmental problems – improper disposal of used batteries can result in significant soil and groundwater pollution (Yabe et al., 2010).[13] In addition, our data indicate that the typical monthly expenditures on batteries is comparable with reported spending on charging phones outside the home. Small batteries are primarily used to power radios and flashlights, which are generally low power appliances that a SHS could also charge.

Our data present a mixed picture when it comes to SHSs and battery use in the initial months after adoption. Only 20% (Uganda) and 36% (Kenya) of households that reported regularly using batteries at the time of the SHS purchase did not report doing so during the endline survey, which is far below the kerosene and phone charging displacement rates we observed. In addition, 10% of households (in both countries) that reported purchasing batteries at endline did not do so at the time of SHS adoption, further diluting the overall drop in the total number of households using batteries after SHS adoption (Table 9). Nevertheless, respondents that do buy batteries did report spending significantly less during endline than at baseline – drops of 26% and 46% in Uganda and Kenya, respectively. Battery prices were consistently reported to be nearly the same during both surveys, as were the volumes of batteries purchased by each household whenever they would go to buy them. What changed was an overall drop in the frequency of buying batteries after SHS adoption.

We believe that the significant lingering use of batteries after SHS adoption is due to the widespread ownership of radios and flashlights that are *not* "plug and play" compatible with a SHS. In reality, it is usually not possible to power a flashlight with a SHS because rechargeable flashlights are neither common nor cost-competitive in many rural African areas. And while SHSs are often touted as reliable and cost-effective means of powering a household radio, actually doing so in practice is a surprisingly complicated process that we explore in more detail below. The result is that the adoption of a SHS is not associated with as meaningful reductions in the use of disposable batteries as we had expected, especially in Uganda.[14]

[13] While this potential of solar products to replace batteries is often mentioned positively, it is mostly framed as one of convenience rather than a potentially serious environmental issue to be mitigated. Further focused research on the environmental impacts of disposing small batteries in Africa would significantly add to the African energy access literature.

[14] We cannot definitively rule out the possibility that there may have been an overall increase in the rate of disposable battery use in the year 2014 in the regions we studied and that, had it not been for the SHS, households in our sample would have used them even more (in which case we would be underappreciating the battery-displacement impacts of the SHSs we tracked). However, our baseline interviews at time of adoption were spread out over more than a one year (Uganda) and seven months (Kenya), and we did not detect any systematic differences in the rates or patterns of disposable battery use by households who adopted an SHS in different time periods. We therefore do not believe it is likely that the observed change in disposable battery use associated with the SHS adoption was largely confounded by other variables that we fail to account for.

Radios

Pre-solar radio penetration rates among households adopting SHSs is very high. At over 85% in both Kenya and Uganda, it exceeds even the phone penetration rates among the general population in the same areas (USAID, 2014a, 2014b). Radios are not only common, but they are also heavily used. Over half of our baseline radio users reported their radios were on for more than six hours per day, on average, with 17% reporting 10 or more hours of daily use. It is not uncommon to encounter households where the radio is on all day, every day, even if just as background noise when people are sleeping.

In addition, the vast majority (80% in Kenya and 95% in Uganda) of these radios are powered by disposable batteries and over 85% of them are small, transistor-type radios. In theory, these are exactly the radios that a mid-sized or larger SHS should be able to power. However, unlike for mobile phones, SHS manufacturers simply do not include plug adapters and cables that would readily enable customers to connect the locally common radio models to the new SHS. Even if they did, it is not clear that the process of connecting an existing radio to a new SHS would be as straightforward as that of a phone; although we did not collect data on every participant, during field visits we regularly observed a high number of radios that seemed to be designed exclusively for battery power, with no external power input jacks. In addition, end-users may highly value the portability of battery-powered radios, so simply connecting such a radio to a SHS with a cable may mean that it would lose some of its utility. Because no traditional radios include built-in rechargeable batteries, nor are rechargeable dry-cell batteries common, connecting an old radio to a new SHS means that the radio can only be as far away from the SHS as the cable permits.

These entrenched radio ownership and use trends present significant challenges for the off-grid solar industry. First, SHS adopters do not and, for the most part, cannot readily power their existing radios with a SHS. This may be a barrier to broader SHS adoption if households that have already purchased a radio are reluctant to invest in new power sources (like the SHS) that cannot power that radio.[15]

Second, actually powering any radio through a SHS requires the purchase of a new radio, usually from the SHS vendor. Customers may be reluctant to do that if they are satisfied with their existing radio – why invest in a new device if the old one is good enough? Indeed, of the Ugandan households we tracked, only 18% reported owning a new SHS-compatible radio at the time of the endline survey. But 96% of the Kenyan households did. This stark contrast is driven by the decision of the Kenyan shop we studied to bundle a radio with every SHS purchase. The Kenyan customers had no choice – if they wanted the SHS, they had to also buy the SHS-compatible radio. This could therefore account for the much larger drop in disposable battery use we observed in Kenya relative to Uganda. And it suggests that bundling could be an effective strategy to unlock broader benefits of SHS ownership by overcoming the reluctance to buy a new radio. However, bundling is an imperfect solution, as SHS vendors need to balance its benefits with the opportunity costs of not selling to customers who would buy a stand-alone SHS but not one bundled with a radio.

Third, it is not clear that even the new SHS-compatible radios are as useful as traditional battery-powered ones. Although all the Kenyan study participants bought SHS-compatible radios, only 70% regarded them as their household's primary radio. This may be due to the surprisingly high radio use patterns in the region. It takes a large SHS to power a radio for over six hours each day while also providing electricity for lights and phones. Most of the systems we studied were simply unable to do this. As a result, the new SHS-powered radios were generally used far less than those powered by other means, as shown in Fig. 7.

[15] Although 85% of our observed sample did, in fact, purchase a SHS despite this limitation, it is unclear how many of them were aware of this limitation at the time of adoption.

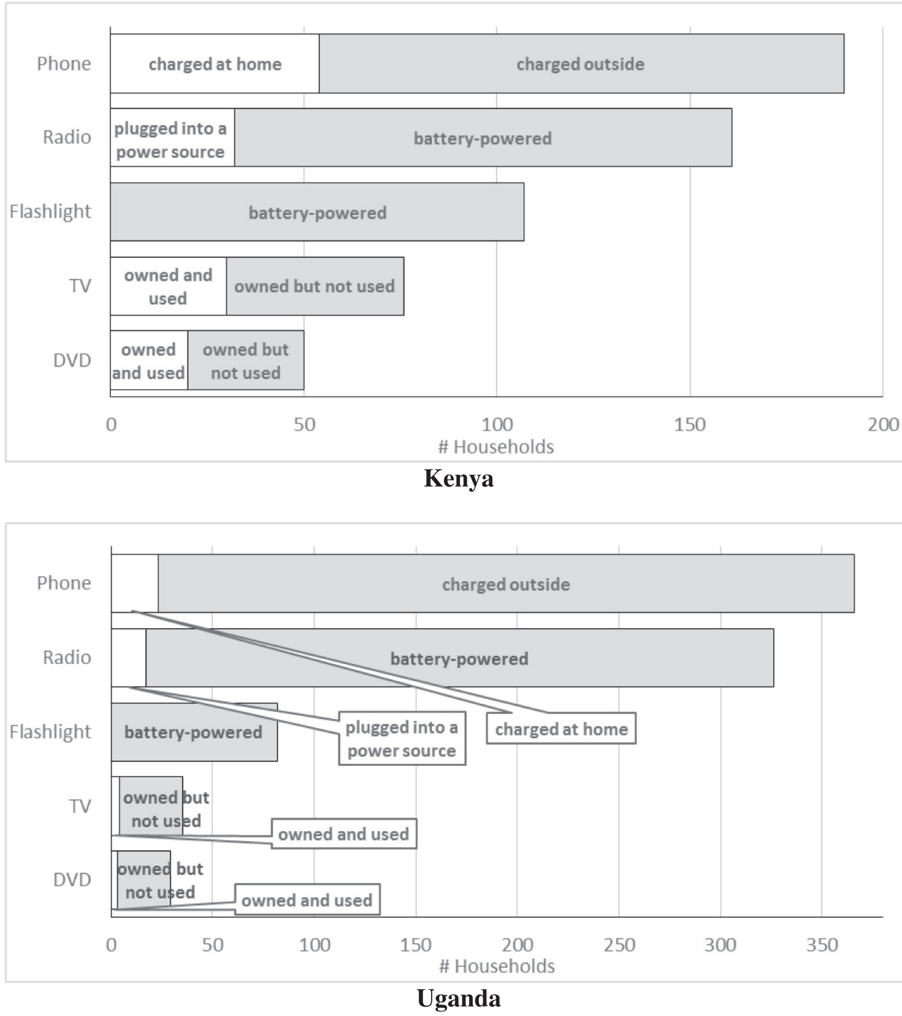


Fig. 6. Pre-SHS household electronics ownership rates.

TVs and video players

Although far less common than radios, a meaningful portion of our study participants also reported owning TVs and/or video players at the time of SHS adoption, especially in Kenya. But unlike the heavily used radios, a large majority of the pre-solar TVs and video players were *not* being used because there was no means to power them (Table 10).

Table 9
Household disposable dry-cell battery use.

	Uganda (N = 255)	Kenya (N = 176)
# using batteries pre-SHS	230	145
(% participants)	(90%)	(82%)
# using batteries post-SHS	205	103
(% participant)	(80%)	(59%)
Disadopters: # using pre-SHS but not post-SHS	45	52
(% participant)	(18%)	(30%)
New adopters: # using post-SHS but not pre-SHS	20	10
(% participant)	(8%)	(6%)
Median monthly spending pre-SHS	2400 USh	225 KSh
Median monthly spending post-SHS	1770 USh	120 KSh

Regardless of the underlying reasons why[16], it is important to recognize the reality that some SHS adopters own mostly unusable TVs and video players. Owning such electronics could be an indication that someone is a “gadget enthusiast” and therefore a good candidate to be an early adopter of a SHS – if you are willing to buy a TV you cannot use, perhaps you are also the type that is willing to try out a new off-grid power solution. But it could also be the case that other TV-owning households would be reluctant to buy a SHS that could not power that specific TV. Traditional CRT TVs, which comprised nearly the entire pre-solar TV stock we observed, are highly energy inefficient and cannot be powered by most SHSs. So there may be many households that own TVs who would otherwise be interested in buying a SHS, but fail to do so because they have already invested in an incompatible TV.

As with radios, bundling could be an effective strategy of getting consumers to adopt new SHS-compatible TVs. Although not all customers were forced to buy a TV, the Kenyan shop we studied did

[16] It is somewhat puzzling that some households buy electronic devices that they have no ability to use – this pattern was also detected by Lee et al. (2016) in Kenya. It could be that these are aspirational purchases and mere ownership of the device provides the household with some utility or social status. And it appears that a number of these consumers genuinely believed at the time of the TV purchase that the national electric grid would soon be extended to their communities, despite no realistic prospects for it.

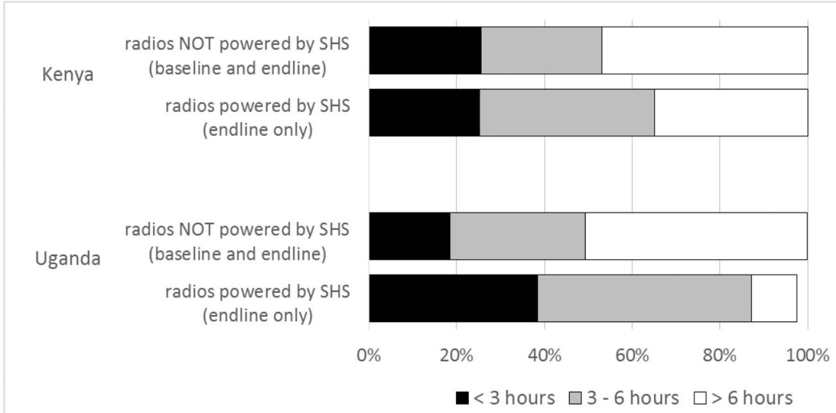


Fig. 7. Daily use of SHS-powered vs. other radios.

offer a number of SHS bundles that included a TV; in contrast, the Ugandan one sold TVs strictly as an add-on item with a clearer breakdown of the costs between the SHS and the TV. Once again, we observed stark differences in the outcomes between the shops. Whereas TV ownership rates at baseline and endline remained flat in Uganda at 9%, they jumped from 40% to 61% in Kenya, driven by the sales of TVs by the SHS vendor. Importantly, 80% of the SHS-compatible TVs were reported as being regularly used, in sharp contrast to other TVs, the large majority of which were unusable at endline just as during baseline.

Moreover, we did not observe evidence that SHS-powered TVs are used less than those that are usable and powered by other means. To the contrary, SHS-powered TV use patterns look quite similar to *usable* non-SHS powered TVs at both baseline and endline, as shown in Fig. 8. This suggests that SHS ownership can, in fact, result in greater adoption and use of TVs. But selling the SHS-compatible TVs in the first place remains a significant challenge, especially if the only source of such TVs is the particular SHS seller through a product bundle.

Improving the potential for SHSs to provide broader energy access

Unlocking the broader energy access benefits of SHS ownership is entirely dependent on SHS adopters' abilities and willingness to purchase SHS-compatible electronics that are as “plug and play” compatible with the SHS as their mobile phones. Basic bundling strategies may be a first step but they come with opportunity costs (losing SHS sales to those not interested in the particular bundle), timing problems (the electronics must be bought at the time of SHS adoption or after, in contrast with the realities on the ground of widespread pre-solar ownership of electronics), and potentially inefficient integrated operations (as a solar energy social enterprise is forced to also become an electronics supplier). To effectively realize the full potential of SHSs may well require the development of a diverse and competitive local market for readily-compatible radios, TVs, flashlights, and rechargeable dry-cell batteries.

To date, SHS manufacturers tend to sell a limited set of their own branded electronics compatible with their particular solar products. These are usually not interchangeable between different solar solutions, as companies tend to view their radios and, to an even greater extent, their TVs as a competitive advantage helping to drive sales of the SHSs. However, given the realities of near-universal pre-solar radio ownership and a surprisingly common tendency to buy TVs before obtaining an energy solution, the industry may want to rethink this approach.

A new generation of DC-powered, energy efficient radios and TVs of various brands and models, manufactured by electronics companies rather than solar PV ones, using standardized plugs, and distributed through channels beyond solar product sales points could help the entire off-grid energy access industry grow. It would also enable solar companies to focus on their core competency of competing on their solar solution rather than appliances. After all, there was no need for solar companies to sell their own branded mobile telephones in order to gain a competitive advantage by unlocking the benefits of using a SHS to power a telephone.

There are encouraging signs that some development support is already being directed towards the creation of a market for SHS plug-and-play compatible radios and TVs, including programs to help create standards and quality assurance for efficient, DC-powered appliances (see e.g. Global LEAP, 2016). But more work is needed – developing

Table 10
Ownership and (lack of) use of TVs and video players at time of SHS adoption.

		Uganda	Kenya
TV	Baseline # households that own a TV	37	76
	(% of baseline respondents)	(9.8%)	(40%)
	# households that do NOT use their TV	33	46
	(% of those who own a TV)	(89%)	(61%)
	Reason TVs are not used		
	–No means to power the TV	33	43
	–TV is broken	0	1
	–other reason	0	2
Video player	Baseline # households that own a video player	34	50
	(% of baseline respondents)	(9%)	(26%)
	# households that do NOT use their video players (% of those who own one)	30 (88%)	30 (60%)
	Reason video players are not used		
	–No means to power the player	25	25
	Video player is broken	1	0
	–Other reason	1	5

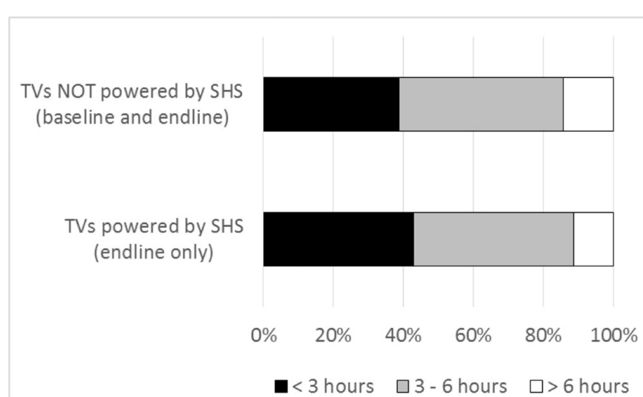


Fig. 8. Daily use of SHS-powered vs. other TVs.

standardized rechargeable flashlights or SHS-compatible means to recharge small batteries are potential areas of focus. Very few companies have introduced such products in the market, even though they could play an important role in unlocking the battery-displacement potential of SHSs. Similarly, a broader set of electric appliances that can be powered by an SHS would be needed to promote any income-generating uses of an SHS, which at the moment seems limited solely to phone charging and possibly working an existing job later in the evenings.

Establishing this market for a readily-available, diverse stock of SHS-compatible electronics that are independent of the solar vendors will undoubtedly be difficult and take more time than simply growing the customer base for the more basic solar PV products. But it is hard to imagine how the off-grid industry will move closer to providing meaningful energy access beyond lighting and charging phones absent such a market.

Conclusion

This research focused on uncovering insights into the roles that solar home systems play at the household level in rural areas in East Africa. We conclude this paper by examining the extent to which our results of actual use patterns are consistent with the broader expectations for solar PV products and the development roles they could play.

At the most basic level, nearly all off-grid solar PV products are promoted as sources of clean, modern lighting. Household-level solar lighting has been especially favored by the development community, with an oft-cited rationale being that it improves health and safety by eliminating kerosene lamps, the entrenched dominant lighting source for many off-grid populations that is associated with many adverse effects (Lam et al., 2012a). The argument is also made that – at scale – mass solar PV deployment may even put a dent in the surprisingly large climate impacts of black carbon emissions from kerosene-fueled lighting (Lam et al., 2012b). Our research supports the view that large solar products like the SHSs we studied are, indeed, associated with significant kerosene displacement and a transition to modern, high-quality lighting. It is also possible that such displacement could be a first step in achieving the positive health and climate outcomes from phasing out kerosene.

Many solar products are also designed to easily connect to and charge mobile phones, ranging from just one phone per day for some picoPV products to up to 30 or more basic phones daily for larger SHSs. The goal is to readily meet the phone charging needs of adopters and thereby provide a vital connectivity service for off-grid populations, as suggested by Harsdorff and Bamanyaki (2009) in Uganda and Urmee and Harries (2011) in Bangladesh. Our results are in line with such hopes, as the SHSs we studied were easily able to power the phone use needs of end-users. It is also worth noting that despite their limited availability relative to other solar products, SHSs may actually account for the bulk of sales of solar products capable of charging phones (as documented by Turman-Bryant et al. (2015) in rural Kenyan markets at approximately the same time as this research). So customers may be quite adept at recognizing the much greater ability of SHSs to charge phones relative to other solar PV products, which is why they might have purchased the large products we were studying in the first place.

The types of improvements in lighting and phone charging that we observed are, in turn, often used to advocate for a rapid scale-up in the deployment of solar PV products to rural populations. That is because such benefits are expected to increase household productivity and income, thereby alleviating poverty. Although there is little systematic research on the topic, the existing literature (summarized by Harrison et al. (2016)) and most common assumptions are that adopters of solar products of all sizes will, in addition to saving money by no longer buying kerosene and charging phones outside the house, improve existing small businesses by using solar lights to enable work after dark and/or use solar energy to start new businesses, most notably phone charging kiosks. We fail to find broad evidence in support of these assumptions despite the fact that the relatively large SHSs we studied should fill the theoretical role of increasing productivity more readily than the more commonly sold picoPV products. This does not, however, mean that SHSs fail to promote positive social spillovers; having a more comfortable home that is conducive to relaxing and socializing may well fulfill a valuable development role. Or it could be the case that even without increasing income-generating activities and household budgets, people could be more productive simply by doing their everyday activities "better" under higher quality solar-powered lights as compared to traditional lights (as assumed by Grimm et al. (2015)). We recommend more thorough investigations of those benefits and urge caution in relying on the direct poverty alleviation potential of SHSs in Africa as a primary rationale for scaling-up adoption.

In addition to high-quality, affordable, healthy, and environmentally-friendly solar lighting, it is hoped that larger solar products could also provide additional basic electrification benefits. After all, improved electricity access should be used for more than just electric lighting. SHSs, in particular, are expected to result in increased adoption and use of mobile phones, radios, and televisions (as reportedly observed in the Bangladesh national SHS program by Urmee and Harries (2011)). These are all electronics that should, in theory, be readily powered by a SHS, with TV use having been reported as a primary driver of SHS adoption in rural Kenya a decade ago (Jacobson, 2007).[17] This, in turn, should promote the broader development benefits of electrification (IEA and World Bank, 2015).

However, our results suggest that unlocking such benefits is not a simple matter of "plug and play", as a number of barriers remain to SHSs becoming more effective tools for basic electrification. Potential strategies to overcome them range from relatively minor design improvements, such as longer cables so that women can use solar lights in food preparation areas, to business model adjustments (like ones that may discourage frequent battery draining or encourage appliance bundling), through more fundamental sector-wide initiatives, such as the development of an independent market for electronics compatible with a variety of solar products.

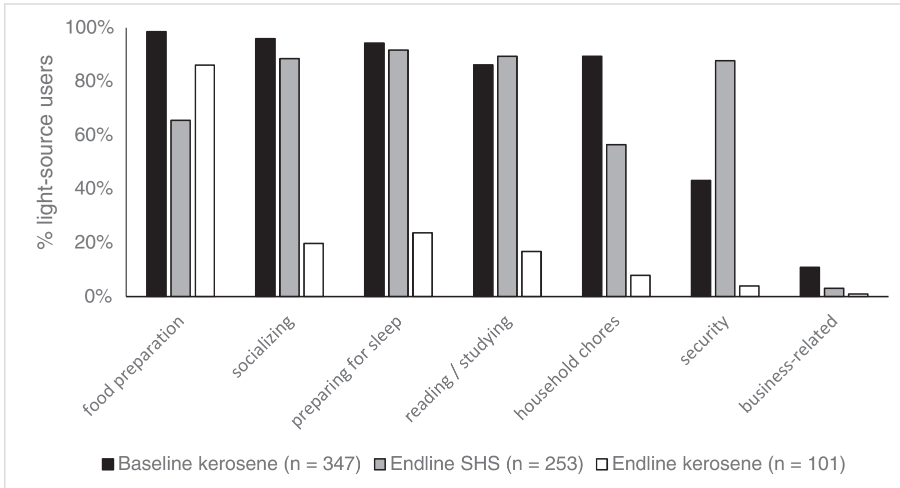
As the African solar market transitions from a focus on picoPV products to a more targeted effort to scale the adoption and impact of SHSs, it is our hope that this paper could contribute to improving the allocation of scarce resources towards more efficient development of the market and lead to better products that more fully meet the needs of end-users.

Acknowledgments

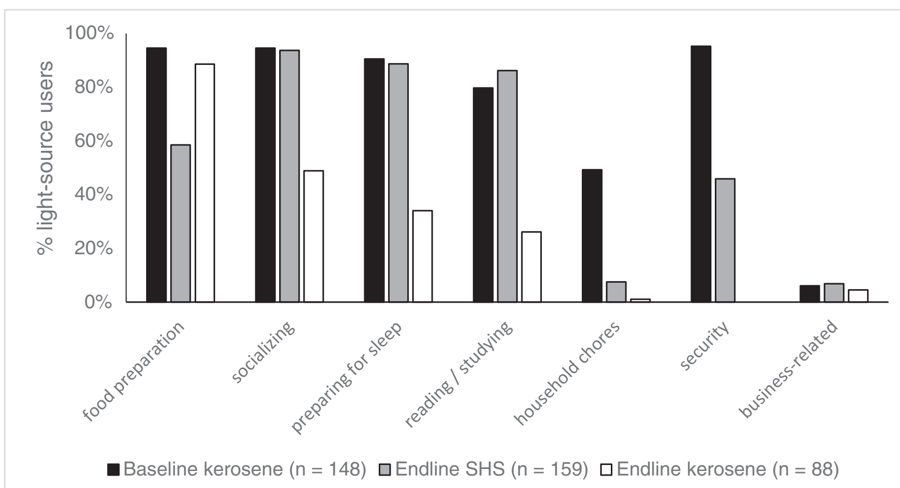
Michael Miller and Brian Kooiman provided exceptional research assistance during the more than 3 years that it took to design and implement this project, as well as to clean and analyze the data. We are also grateful for the hard work and resourcefulness of our on-the-ground data collection teams, ably led by Juliet Kyayesimira and Joseph Arineitwe (CIRCODU – Uganda), and Faith Manywali (Ipsos – Kenya). This primary research was generously funded by grants from the Stanford Institute for Innovation in Developing Economies (SEED), the Freeman Spogli Institute for International Studies (FSI), and the Precourt Institute for Energy (PIE).

[17] Although refrigerators, irons, vacuum cleaners, and – in some cases – electric cooking appliances (stoves, ovens, microwaves) are household appliances in high demand and have the potential to transform a family's daily routines, they all consume much more electricity than can be generated by most solar solutions in the African market. This may change as larger systems enter the marketplace, especially with respect to refrigeration, as considerable efforts have been made to develop highly-efficient DC refrigerators. As of 2016, however, deploying such domestic appliances on a mass scale and powering them through off-grid solar remains only a long-term prospect and is not a key focus of the industry or other stakeholders.

Appendix 1



Uganda



Kenya

Fig. A1. Applications of use for kerosene lights and solar home system bulbs.

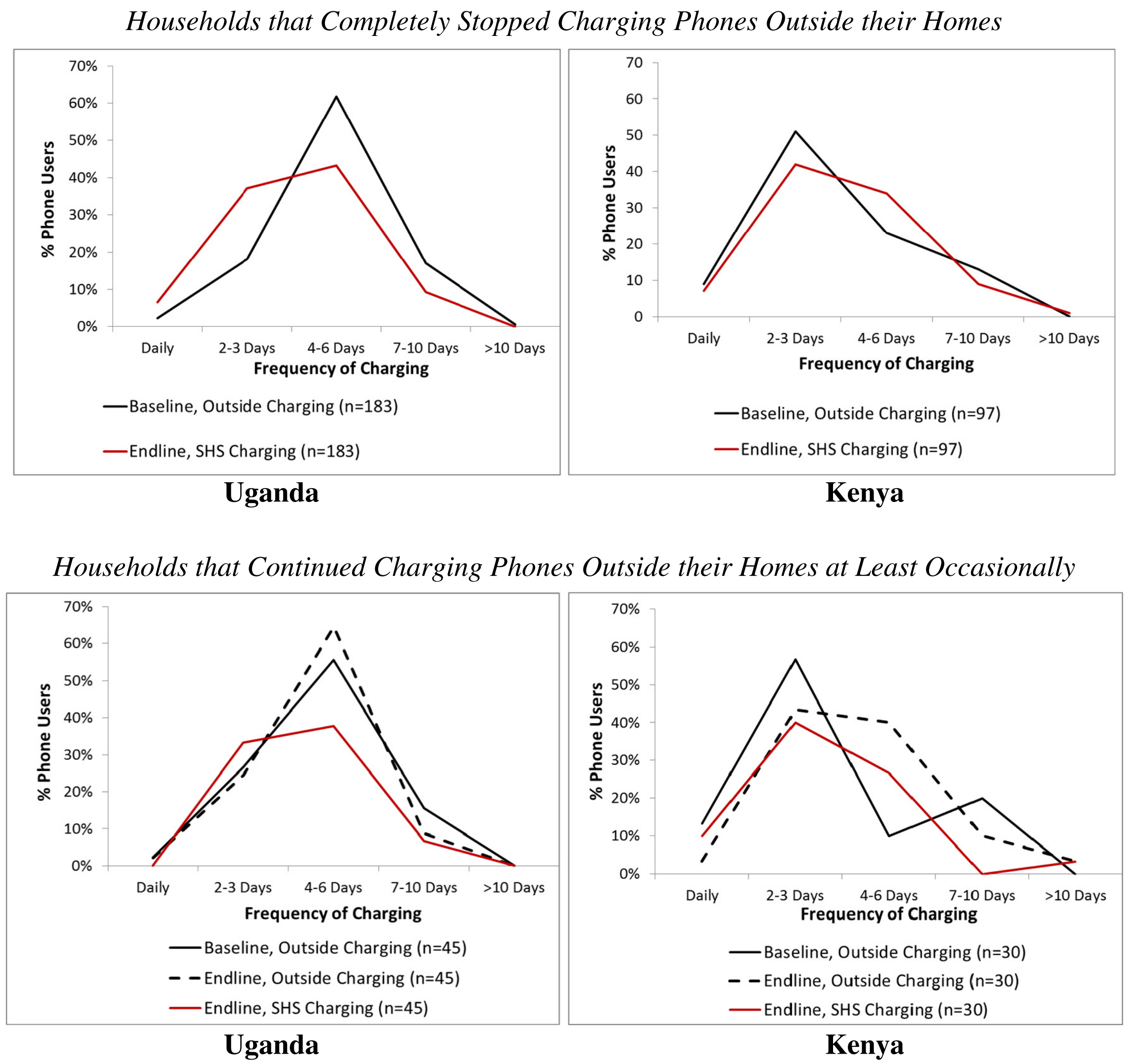


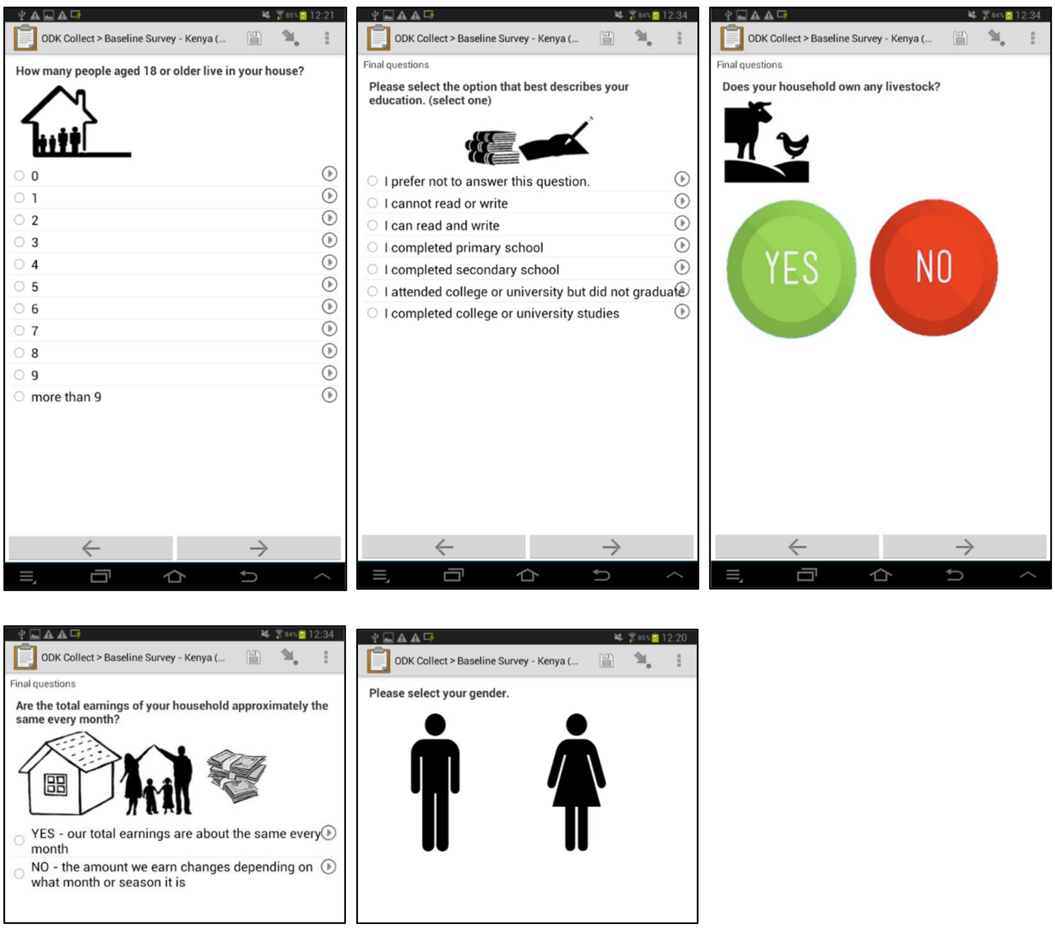
Fig. A2. Change in phone charging habits among households that charged phones outside their homes at baseline

Appendix 2 Survey instrument details

The baseline and endline surveys were conducted using tablet computers with a highly-visual interface. Respondents were encouraged to hold the tablet and select their own answers. An enumerator hired by the research team guided the respondents by reading out and explaining the questions. Respondents were generally engaged, active, and vocal during interviews.

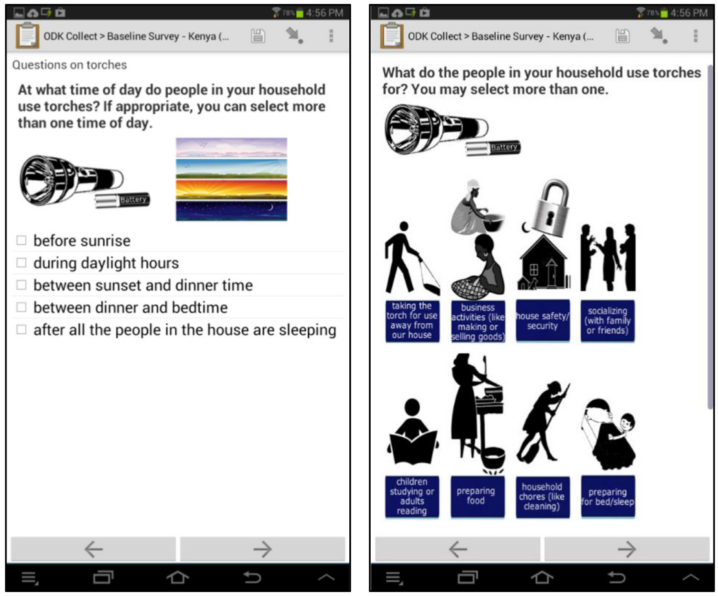
The software used logical routing (only relevant questions were asked, as determined by the answers to prior questions; non-applicable questions were skipped), piping (the text of some questions used responses to previous questions), and consistency checks (requesting the respondents and enumerators to verify or change answers that were inconsistent or unlikely).

Sample demographic questions

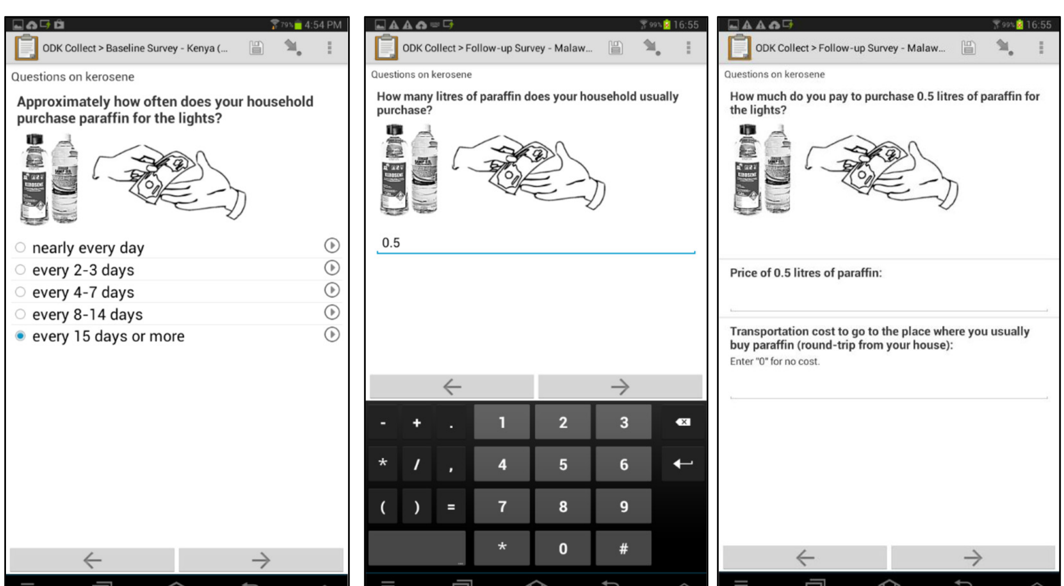


Sample questions on household lighting and energy stock

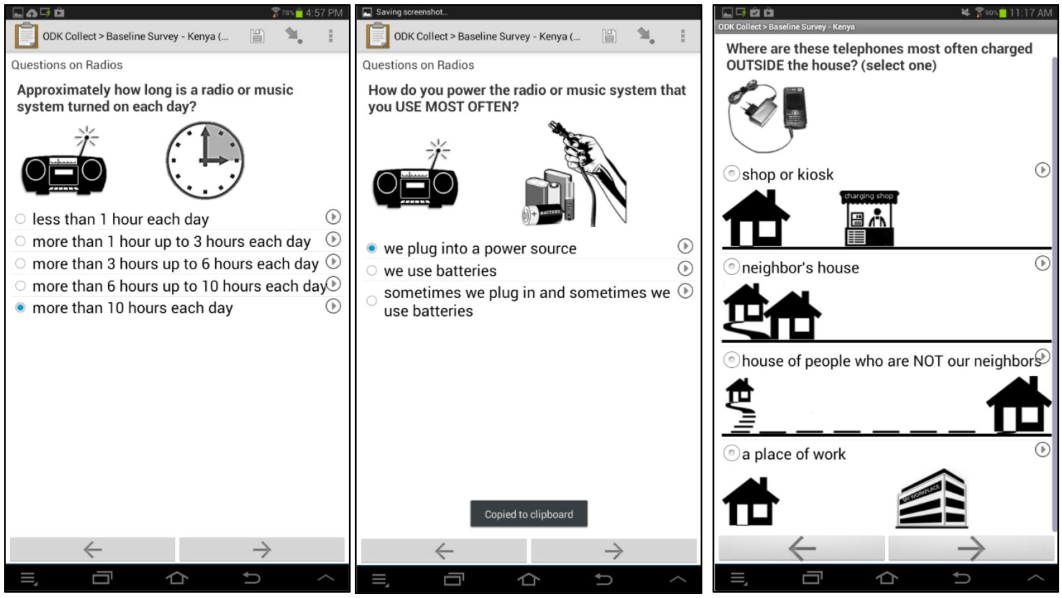
Sample questions on detailed use of lighting sources (in this case flashlights)



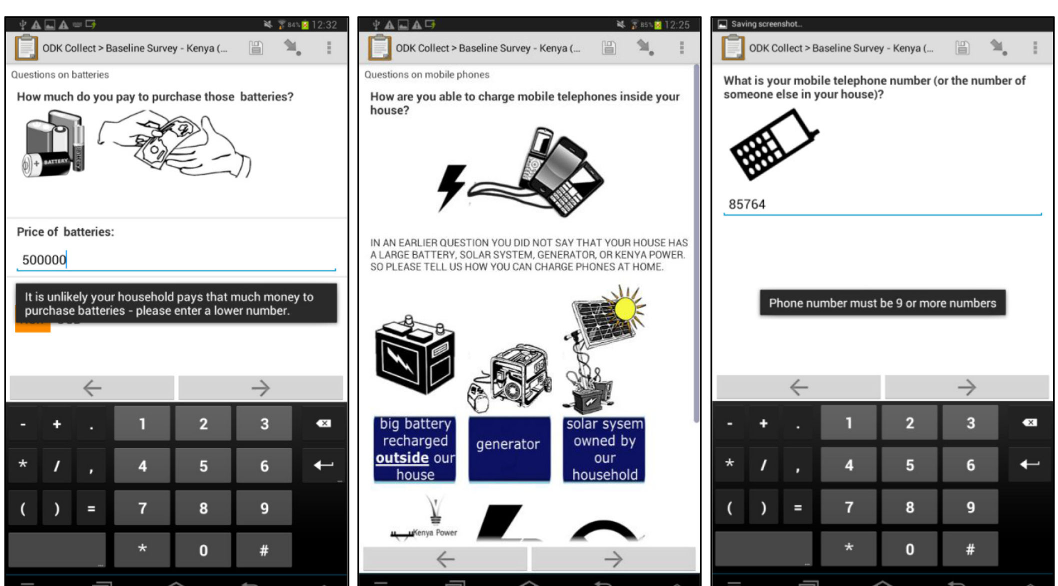
Sample questions on spending for energy (in this case kerosene)



Sample questions on detailed use of electronics (in this case radios and phones)



Sample consistency checks



References

Adkins E, Eapen S, Kaluwile F, Nair G, Modi V. Off-grid energy services for the poor: introducing LED lighting in the millennium villages project in Malawi. Energy Policy 2010;38(2):1087–97. http://dx.doi.org/10.1016/j.enpol.2009.10.061.

Brüderle A. Solar lamps field test Uganda. Research report. GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH); 2011. (available at https://energypedia.info/images/7/72/GIZ_Solar_Lamps_field_Report_Uganda_Webversion.pdf).

Chattopadhyay D, Bazilian M, Lilienthal P. More power, less cost: transitioning up the solar energy ladder from home systems to mini-grids. Electr J 2015;28(3):41–50.

Collings S. Phone charging micro-businesses in Tanzania and Uganda. Research report. GVEP (Global Village Energy Partnership) International; 2011. (available at http://www.energy4impact.org/sites/default/files/phone_charging_businesses_report_with_gsma_final_for_web_0.pdf).

Global LEAP website. available at http://globalleap.org/, 2016. (accessed November 1, 2016).

GOGLA (Global Off-Grid Lighting Association) and Lighting Global. Global off-grid solar market report: semi-annual sales and impact data, January–June 2016. Research report; 2016l. (available at https://www.lightingglobal.org/wp-content/uploads/2016/10/global_off-grid_solar_market_report_jan-june_2016_public.pdf).

Grimm M, Munyehirwe A, Peters J, Sievert M. A first step up the energy ladder? Low cost solar kits and Household's welfare in rural Rwanda. Ruhr economic papers #554; 2015. (available at https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2618446).

GSMA (GSM Association). The mobile economy: sub-Saharan Africa 2015. Research report; 2015. (available at https://www.gsmaintelligence.com/research/?file=721eb3d4b80a36451202d0473b3c4a63&download).

Harrison K, Scott A, Hogarth R. Accelerating access to electricity in Africa with off-grid solar: the impact of solar household solutions. Research report. Overseas Development Institute; 2016. (available at https://www.odi.org/sites/odi.org.uk/files/odi-assets/publications-opinion-files/10229.pdf).

Harsdorff M, Bamanyaki P. Impact assessment of the solar electrification of micro enterprises, households and the development of the rural solar market. Research report. PREEP (Promotion of Renewable Energy and Energy Efficiency Programme) and GTZ (Gesellschaft für Technische Zusammenarbeit); 2009. (available at https://energypedia.info/images/d/d4/Impact_assessment_shs_preeep_uganda_2009.pdf).

IDInsight. d.light solar home system impact evaluation. Research report; 2015. (available at http://idinsight.org/wp-content/uploads/2015/01/d.light-Solar-Home-System-Impact-Evaluation.pdf).

IEA (International Energy Agency). Africa energy outlook: a focus on energy prospects in sub-Saharan Africa. Research report; 2014. (available at https://www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf).

IEA (International Energy Agency), the World Bank. Sustainable energy for all 2015 - progress toward sustainable energy. Washington, DC: World Bank; 2015. http://dx.doi.org/10.1596/978-1-4648-0690-2 (available at http://www.se4all.org/sites/default/files/GTF-2105-Full-Report.pdf).

Jacobson A. Connective power: solar electrification and social change in Kenya. World Dev 2007;35(1):144–62. http://dx.doi.org/10.1016/j.worlddev.2006.10.001.

Kowsari R, Zerriffi H. Three dimensional energy profile: a conceptual framework for assessing household energy use. Energy Policy 2011;39(12):7505–17. http://dx.doi.org/10.1016/j.enpol.2011.06.030.

Lam N, Chen Y, Weyant C, Venkataraman C, Sadavarte P, Johnson MA, et al. Household light makes global heat: high black carbon emissions from kerosene wick lamps. Environ Sci Technol 2012a;46(24):13531–8. http://dx.doi.org/10.1021/es302697h.

Lam N, Smith K, Gauthier A, Bates M. Kerosene: a review of household uses and their hazards in low- and middle-income countries. J Toxicol Environ Health B 2012b;15(6):396–432.

Lee K, Miguel E, Wolfram C. Appliance ownership and aspirations among electric grid and home solar households in rural Kenya. CEGA working paper series no. WPS-057. UC Berkeley: Center for Effective Global Action; 2016. (available at http://escholarship.org/uc/item/1zv1p589.pdf).

Lighting Global. "Lighting Africa: moving consumers up the energy ladder", press release article. available at https://www.lightingafrica.org/lighting-africa-moving-consumers-up-the-energy-ladder/, 2014.

Lighting Global. Lighting Africa off-grid solar market trends report 2016. Research report; 2016. (available at https://www.lightingglobal.org/wp-content/uploads/2016/03/20160301_OffGridSolarTrendsReport.pdf).

Rahman SM, Ahmad MM. Solar Home System (SHS) in rural Bangladesh: ornamentation or fact of development? Energy Policy 2013;63:348–54.

RMI (Rocky Mountain Institute). Building and climbing the solar energy ladder, blog post. available at http://blog.rmi.org/blog_2015_05_12_building_and_climbing_the_solar_energy_ladder, 2015.

Turman-Bryant N, Alstone P, Gershenson D, Kammen DM, Jacobson A. The rise of solar: market evolution of off-grid lighting in three Kenyan towns. Research report. Lighting Global; 2015. (available at https://www.lightingglobal.org/wp-content/uploads/2015/10/2015-RiseOfSolar-10182015-withSurvey.pdf).

Urmee T, Harries D. Determinants of the success and sustainability of Bangladesh's SHS program. Renew Energy 2011;36(11):2822–30. http://dx.doi.org/10.1016/j.renene.2011.04.021.

USAID (United States Agency for International Development). "Kenya: standard DHS", demographic and health surveys program, raw dataset. available at http://dhsprogram.com/what-we-do/survey/survey-display-451.cfm, 2014.

USAID (United States Agency for International Development). "Uganda: MIS", demographic and health surveys program, raw dataset. available at http://dhsprogram.com/what-we-do/survey/survey-display-484.cfm, 2014.

Yabe J, Ishizuka M, Umemura T. Current levels of heavy metal pollution in Africa. J Vet Med Sci 2010;72(10):1257–63. http://dx.doi.org/10.1292/jvms.10-0058.