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Renewables in the Energy Transition: Evidence on Solar Home Systems and Lighting-Fuel Choice in Kenya

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Abstract

We study the determinants of households' choices of lighting fuels in Kenya, including the option of using solar home systems (SHSs). The paper adds new evidence on the factors that influence the introduction and adoption of decentralized and less carbon-intensive energy sources in developing countries. We capitalize on a unique representative survey on energy use and sources from Kenya, one of the few relatively well-established SHSs markets in the world. Our results reveal some very interesting patterns in the fuel transition in the context of lighting-fuel choices. While we find clear evidence for a cross-sectional energy ladder, the income threshold for modern fuel use – including solar energy use – is very high. Income and education turn out to be key determinants of SHSs adoption, but we also find a very pronounced effect of SHSs clustering. In addition, we do not find a negative correlation between grid access and SHSs use.

Keywords: renewable energy, household fuel choice, lighting-fuel choice, solar power use, solar home systems, Kenya, energy ladder, KIHBS

JEL Codes: D12, O12, Q42

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Article Outline

1 Introduction

The fuel choices of developing country households are a crucial factor for the adoption of modern energy services and the introduction of decentralized and less carbon-intensive energy systems. In order to increase the use of renewable energy sources, one has to understand how households decide on which fuels to consume. This paper therefore aims to identify the determinants of households' choices of lighting fuels. Our analysis focuses on the use of solar home systems (SHSs) in developing countries, as these are a major (off-grid) non-fossil fuel option for lighting.

Since households' energy demand is an important part of overall energy demand, particularly in poorer countries with large rural populations, the choices households make about cooking and lighting fuels have a major impact on the shape of energy systems in those countries. In Kenya, for instance, the majority of households rely on biomass energy for their cooking, lighting and heating needs (Murphy 2001), with the result that biomass accounted for 74 percent of Kenya's total primary energy supply (PES) in 2007 (IEA 2010). Kenya's energy system is typical of many developing countries in that it is very dependent on traditional fuels. These traditional fuels are not able to support modern economic activities and, hence, act as impediments to more rapid economic and social development. In addition, their use raises issues such as indoor air pollution and deforestation (Ekholm et al. 2010).

Moving away from traditional biomass to modern energy services may thus foster economic and social development. Furthermore, it is often argued that modern energy services should be based on the clean and renewable sources of energy that are abundant in Africa (Brew-Hammond and Kemausuor 2009), in order to ensure that development will be sustainable. Yet so far renewables such as geothermal, wind and solar have played only a minor role in the provision of developing countries' PES, including that of Kenya, where these energy sources accounted for some 6.4 percent of the total PES in 2007 (IEA 2010). SHSs nevertheless constitute a major source of electricity for lighting and other applications in rural Kenya. An estimated 320,000 SHSs had been installed in the country by 2010, implying that 4.4 percent of rural households owned such a system. These systems typically consist of a small solar module of 14 to 20 Watt peak, some wiring, a rechargeable battery and in some cases a charge-controller. The Kenyan SHSs market, which developed largely without the support of the government or donors, is one of the leading off-grid solar markets in the world and the biggest on the African continent. This makes Kenya an ideal case study for the analysis of the adoption of SHSs, which are used primarily for lighting, the operation of TVs and radios, and the charging of mobile phones (Jacobson 2006).

Approximately one-fifth of the world's final energy is consumed by electrical appliances, including lighting (World Bank 2010), and lighting alone accounts for 19 percent of global electricity demand (IEA 2006). In developing countries, lighting is generally thought to rank among the top three uses of energy,[1] with cooking and sometimes space heating being of even greater importance (ibid.). While cooking-fuel choices have been examined in a number of empirical studies, lighting-fuel choices have received less attention. In addition, the adoption of renewable energy sources is typically not placed in the context of a specific fuel choice. Yet only in this specific context can renewables adoption or fuel switching be adequately understood. In Kenya, SHSs seem to be used to a significant extent for lighting (Jacobson 2006). The lack of studies on the adoption of renewables in a particular fuel-choice context can be partly explained by a lack of data. Adoption tends to be negligible in most de-

1 However, a precise estimate of the role of lighting in household energy consumption is generally difficult to obtain (IEA 2006).

veloping countries, and nationally representative data on renewables use at the household level is virtually nonexistent.

Using data from the Kenya Integrated Household Budget Survey (KIHBS), this paper builds upon a unique dataset to investigate the determinants of the adoption of SHSs for lighting in Kenya. The dataset allows for the analysis of the adoption of SHSs in the context of fuel choice for a particular activity, in this case lighting. Conceptually, our study builds on the energy-ladder concept, and we draw on the literature on household fuel choice for cooking. We first review the corresponding theoretical and empirical literature below. Then, we present the results of our empirical analysis. We conclude with a summary of our main results and some policy implications.

2 Renewables Adoption and Fuel Choices: Conceptual Framework and Previous Evidence

One important element of our conceptual framework is the energy-ladder hypothesis. This hypothesis assumes that a household's fuel (or energy source) choice depends crucially on the household's income level. As income rises, households move first from using traditional fuels, such as wood, to transitional fuels, like kerosene, and then to modern fuels, such as electricity from the grid (Leach 1992). Modern fuels are generally perceived to be superior to traditional or transitional fuels in efficiency, comfort and ease of use (Farsi et al. 2007). The concept can thus be seen as a (stylized) extension of the economic theory of the consumer: as income rises, consumers not only demand a larger amount of the good but also change their consumption pattern in favor of higher quality goods (Hosier and Dowd 1987).[2] The stark differences observed in energy-use patterns between poor and rich countries (e.g. Leach 1992) as well as between households with differing income levels within many (developing) countries motivated the energy-ladder hypothesis, which has since served as the basis for many empirical applications in the literature (e.g. Heltberg 2004; Gebreegziabher et al. 2011). Indeed, the empirical literature has confirmed that income is one of the main demand-side factors determining household fuel choice. This can be partly explained by the fact that modern fuels often involve a relatively large upfront investment in equipment, which hinders credit-constrained poorer households from using it. In addition, the adoption of modern fuels may require knowledge and a certain level of education as demand-side factors. On the supply side, there is often a lack of access to markets for modern fuels and the required equipment may not be supplied. All these factors together may explain why so many poor households are prevented from climbing up the energy ladder.

2 Masera et al. (2000) point out that more expensive technologies are also often perceived to signal higher social status so that one additional aim of moving up the energy ladder is to demonstrate an increase in social status.

Our empirical analysis of the determinants for the adoption of SHSs for lighting builds on two strands of empirical literature that are both related to the energy-ladder hypothesis. We aim to combine these two strands, namely, the literature on household fuel choice for a particular activity and the studies that focus on the adoption of SHSs.

To our knowledge, empirical analyses of household fuel choice for a particular activity almost exclusively investigate cooking fuels.[3] For this household activity the majority of households use firewood, charcoal, kerosene or electricity, with the specific mix varying depending on the setting (e.g. Heltberg 2004; Hosier and Dowd 1987; Farsi et al., 2007; Njong and Johannes 2011). Each household faces a number of mutually exclusive options for cooking fuels and chooses the fuel that maximizes its utility. So-called *fuel stacking* – that is, a household's combining of different fuels for one purpose (in this case cooking) – is an aspect that is often discussed in the literature (e.g. Acker and Kammen 1996).[4] In this case, a single option can be a combination of different fuels. Fuel stacking is therefore addressed in some cases by using typical fuel combinations as choices (e.g. Heltberg 2004) and ignored in other cases by considering only the main fuel used by the household (e.g. Farsi et al. 2007).

The data used in the literature on cooking-fuel choice often stem from national household surveys and typically do not include a time dimension. The studies therefore investigate a kind of "cross-sectional energy ladder," as they do not discuss economic development over time, but rather variations in cross-sectional data – that is, between rich and poor households. While this cross-sectional (co-)variation is likely to provide useful insights into what happens to poorer households when they become richer, this caveat of former work and the present study should be borne in mind. In the following, we review some evidence on the determinants of fuel choices for cooking fuels in developing-country contexts.

Heltberg (2004), for example, investigates fuel switching in urban areas for eight developing countries. He finds a strong link between electrification and the uptake of modern cooking fuels. Other factors that are associated with an increased likelihood of choosing modern fuels are consumption expenditure and education, as well as, in some specifications, the size of the household. In a similar investigation in Guatemala, Heltberg (2005) confirms the relevance of income for fuel choice. He also emphasizes the importance of non-income factors, such as the cost of firewood (as firewood is a widely used cooking fuel in Guatemala). The study shows the widespread prevalence of fuel stacking for cooking purposes in Guatemala and therefore explicitly incorporates two-fuel options into the empirical analysis (for example, joint wood-liquefied petroleum gas (LPG) use).

Farsi et al. (2007) take a slightly different approach and also find that income is one of the main factors that prevent households from using modern and cleaner fuels in an application

3 See for example Foell et al. (2011).

4 Another definition of fuel stacking is that households use more than one fuel in their energy consumption (Ngui et al. 2011) without a differentiating according to the purpose it is used for. However, this fact alone is not sufficient for fuel stacking in our context.

for India based on a household expenditure survey. Additionally, they find that the education level and gender of the household head as well as LPG prices impact fuel choice. In contrast to Heltberg (2004, 2005) the authors use the fuel that provides the highest share of total useful cooking energy as the dependent variable and order the fuels in terms of efficiency, comfort and ease of use, strictly in line with the energy ladder.

Gebreegziabher et al. (2011) assess the determinants of the adoption of electric *mitad* cooking appliances for baking bread, among other energy uses, in Northern Ethiopia and the effects of this adoption on urban energy transition. The authors analyze the factors that explain urban households' choice of fuel among five options: wood, charcoal, dung, kerosene, and electricity. Based on survey data the paper finds that the likelihood of the electric *mitad* adoption increases with household expenditure, age of household head and family size. Furthermore, fuel choices more generally are found to be determined by the prices of substitutes, household expenditure, age and education of household head, and family size, with the probability of using transitional and modern fuels (such as kerosene and electricity) positively correlated with the price of wood and charcoal, household expenditure, and the age and education of the household head.

All of the studies presented above find income or household expenditure to be a key determinant of cooking-fuel choice, in line with the energy-ladder hypothesis. Most authors additionally stress the importance of non-income factors, which vary slightly from case to case but typically include both socioeconomic demand-side factors and supply-side factors, such as fuel prices or electrification rates. While some of these factors are specific to cooking (for example, gender of household head), most are likely to affect lighting-fuel choices as well (for example, education).

The above literature on the determinants of cooking-fuel choices is closely linked to empirical studies that analyze SHS adoption. The factors that are of special relevance to SHS uptake should also be included in our lighting-fuel choice analysis, in addition to the more general fuel-choice determinants.

Due to its early development, quite a number of studies have examined adoption in the case of the Kenyan consumer market for SHSs. Acker and Kammen (1996) track the emergence of the Kenyan SHSs market from the 1980s to the mid-1990s. They also report results from a (not representative) survey of approximately 40 SHSs users interviewed near urban centers. This initial analysis of the Kenyan SHSs market finds that SHSs are purchased by affluent households with above-average income that are located near the electricity grid. The authors admit that this counterintuitive finding may be due to a selection bias given that they largely surveyed households in the vicinity of urban centers and hence near the grid.

A more thorough quantitative analysis of the Kenyan SHSs market was carried out by Jacobson (2006), who describes various aspects of the Kenyan SHSs market and presents analyses based on two cross-sectional surveys among rural Kenyan households which were conducted in 2000 and 2001. Jacobson finds that the benefits of solar electrification are captured primarily by the rural middle class, that solar plays only a modest role in supporting productive activities and education, and that solar electrification is more related to general market forces than to poverty alleviation and sustainable development. Based on the 2000 survey, Jacobson further finds that most SHSs are owned by households in the first three wealth deciles. He characterizes these households as belonging to the rural middle class, with annual household incomes well above USD 2,000 (in current USD). In the paper he further argues that the data suggests a trend towards a deepening of access beyond the middle class, with smaller systems becoming affordable for lower-income households as well.

Rebane and Barham (2011) analyze the determinants of SHSs awareness and adoption in Nicaragua. They identify the determinants of four measures of SHSs knowledge. This is followed by an investigation of factors that predict SHSs adoption conditional upon sufficient awareness about SHSs. They use survey data from 158 households in rural Nicaragua, 40 of which had adopted SHSs. Knowledge is predicted most strongly by the presence of other installed SHSs, being male, being young and having a high-quality residence (as a proxy for wealth). Income, having learned about SHSs from a business or NGO and not living in the Caribbean lowlands (where SHSs were very rare at the time the survey was carried out) are all positive determinants of SHSs adoption, while living near a dealer reduces the likelihood of adoption. The authors presume that the latter is due to the proximity of dealers to urban areas, which would suggest that the households near a dealer might have higher expectations of grid extension in the near future. Rebane and Barham (ibid.) argue that knowledge about SHSs is important in the adoption process, that the presence of other SHSs is a very important educational tool, and that women should be included in education about SHSs.

Komatsu et al. (2011) also assess the determining characteristics for household purchases of SHSS in a case study for three regions in rural Bangladesh that comprises around 600 households. They model a two-step decision, where the household first faces the (binary) decision of whether to purchase a system and then in a second step decides on the size of the panel. The authors find household income, ownership of rechargeable batteries, kerosene consumption, and the number of mobile phones to be key determinants of SHSs purchases. They especially highlight the level of kerosene consumption as a key determinant.

It is worth noting that while the studies on cooking-fuel choice mostly draw on national household surveys, the SHSs adoption literature cited above typically uses smaller surveys, often tailored to one specific research question (e.g. Jacobson 2006; Komatsu et al. 2011). By using the KIHBS household budget survey we thus try to achieve convergence between both strands of literature.

In summary, most insights on fuel choice stem from the empirical analysis of cooking-fuel choices. In addition, the determinants for the adoption of solar energy technologies are typically examined without putting them into the context of a particular fuel choice and often based on nonrepresentative samples and case studies. As lighting-fuel choices and the role of lighting in energy use in developing countries have not been investigated as thoroughly as cooking-fuel choices,[5] we focus our analysis on the fraction of household energy consumption that goes to lighting. This investigation is important not only due to the role of lighting in household energy use, but also as increased access to lighting is expected to contribute to the achievement of the UN's Millennium Development Goals (IEA 2008).

3 Solar Energy and Lighting-Fuel Choice in Kenya

In our empirical analysis, we first assess the patterns of energy use in Kenyan households. Then, we investigate lighting-fuel choices and, afterwards, specifically discuss the use of SHSs in Kenya. We use data from the Kenyan Integrated Household Budget Survey (KIHBS) 2005/2006 provided by the Kenya National Bureau of Statistics (KNBS). The sample consists of 13,430 households – with 10 households randomly drawn from each of the 1,343 clusters – stratified into 136 strata, according to Kenya's 69 districts.[6] The clusters are drawn from a pool of 1,800 clusters with a probability proportional to their size, based on data from the 1999 Population and Housing Census. Item nonresponse is virtually nonexistent (less than 1 percent).[7] The KIHBS dataset contains a unique set of information for our purposes, since it includes very detailed questions about households' energy consumption and, furthermore, specifically asks for details on households' ownership and use of SHSs.

3.1 Solar Home Systems, Energy Use, and Lighting-Fuel Choices: Descriptives

Each household's costs for energy use over the preceding month are directly reported for purchased firewood, charcoal, kerosene, gas and electricity.[8] Table 1 provides descriptive statistics on household energy expenditure by source.[9] By far the most important energy source that Kenyan households purchase is paraffin/kerosene (hereafter referred to simply as kerosene). More than 80 percent of all Kenyan households have some expenditure for this type of energy source and (non-zero) median expenditure amounts to 160 Kenyan shillings (KES) per household.[10] Traditional fuels, more specifically firewood and charcoal, also account for a

5 While the discussion of cooking-fuel choices often focuses on the use of firewood (for example, in the discussions on indoor air pollution and on deforestation), this source is unlikely to be of equal importance in the discussion on lighting-fuel choice.

6 An urban and a rural region of each district, with two districts being fully urban.

7 For more information on the survey and dataset see CBS (2004/2005), KNBS (2005/2006) and KNBS (2007).

8 Due to the lack of market prices, the energy sources collected firewood, animal waste and straw/stalk are excluded from this part of our analysis.

9 On average, Kenyan households spend approximately 5 percent of their budgets on energy (authors' calculations based on KNBS [2005/2006]). This share varies little across the expenditure distribution. As we will illustrate below, the expenditure share also depends on the composition of fuels.

10 The USD–KES exchange rate in 2005/2006 stood at 1:74; that is, KES 160 was equivalent to 2.16 current 2005/2006 USD.

considerable portion of household fuel expenditure. Approximately 15 percent of Kenyan households have non-zero expenditure for firewood, and 36 percent for charcoal. With non-zero median expenditures even higher than those for kerosene (KES 200 and KES 250, respectively), these traditional sources are generally still used to a significant extent. Modern fuels are used by a smaller part of the population, 6 percent in the case of gas/LPG and 12 percent in the case of electricity. If households use these sources, their expenditure for them is much higher than for traditional or transitional fuels, with KES 780 for gas/LPG and KES 350 for electricity. Of course, these much higher costs reflect much greater energy consumption.

Table 1 also illustrates the pronounced differences between Kenyan regions. The poorest parts of the country, the Eastern, North Eastern and Western provinces, typically exhibit energy expenditure patterns that are inclined towards the use of traditional fuels. The use of modern fuels is most common in Nairobi, where approximately 50 percent of households have some expenditure for electricity, as well as in the richer provinces of Central, Coast and the Rift Valley, where more than 10 percent of households use (or rather pay for) electricity.

Table 1: Median Energy Expenditure per Month of Non-Zero Observations (in KES) and Share of Non-Zero Observations (in Percent), by Fuel and Province

Province	Purchased Firewood		Charcoal		Kerosene		Gas/LPG		Electricity		Total
	Median	Non-zero (%)	Median	Non-zero (%)	Median	Non-zero (%)	Median	Non-zero (%)	Median	Non-zero (%)	Median
Nairobi	200	2.8	200	38.8	400	63.8	1050	40.5	1500	47.8	1050
Central	300	21.5	300	42.6	200	91.1	691.5	8.5	265	19.8	400
Coast	200	7.2	250	32.0	200	68.2	750	6.1	500	14.1	200
Eastern	300	10.7	200	28.6	150	85.3	650	3.0	300	6.2	168
North Eastern	180	27.7	300	17.7	150	48.7		0.0	200	8.1	150
Nyanza	150	17.7	250	48.8	150	94.6	800	3.9	380	8.2	250
Rift Valley	250	10.8	300	36.2	180	80.5	900	4.0	250	10.7	250
Western	200	22.2	225	34.2	120	95.0	700	2.3	300	5.5	200
Total	200	14.3	250	36.4	160	83.2	780	6.0	350	12.0	250

Source: Authors' calculations based on KNBS (2005/2006).

The potential for substitution among energy sources is restricted to fuels used for the same purpose – for example, dry cells and solar, which are used for lighting but not for cooking. Fortunately, the survey allows for the relation of each energy source to one main use. While firewood, charcoal and gas/LPG are mainly used for cooking, kerosene and electricity are mainly used for lighting.

This pattern is mirrored by questions regarding whether the main fuel is used for a specific purpose. Here, the households are asked which two fuels they use most frequently for cooking and lighting, respectively. For lighting the options are collected firewood, purchased firewood, grass, kerosene, electricity, gas/LPG, solar, dry cell (torch), candles and biogas (KNBS [2005/2006]). For cooking, charcoal and biomass residue are further options, while solar, dry cells, and candles can only be used for lighting.

Table 2: Main Sources of Cooking and Lighting Fuel (in Percent)

Purpose of Use	Cooking		Lighting	
Fuel	Fuel 1	Fuel 2	Fuel 1	Fuel 2
Collected Firewood	54.9	8.8	6.4	12.3
Purchased Firewood	9.8	13.3	0.2	1.1
Grass	0.2	0.3	0.2	0.2
Kerosene	10.9	27.4	73.5	20.8
Electricity	0.8	2.0	16.4	2.0
Gas/LPG	4.2	4.4	0.2	0.9
Charcoal	18.2	41.5	.	.
Biomass Residue	0.3	1.7	.	.
Solar	.	.	1.4	1.4
Dry Cell (Torch)	.	.	1.4	48.3
Candles	.	.	0.2	12.6
Biogas	0.1	0.2	.	0.1
Other	0.8	0.4	0.2	0.5
N	12,988	4,188	12,989	4,479

Source: Authors' calculations based on KNBS (2005/2006).

Table 2 shows that fuel choices between cooking and lighting differ considerably. For both uses, only about a third of the households also name a second source of fuel. Collected and purchased firewood, charcoal and kerosene are the most important cooking fuels, with the fuel choice being fairly diversified. For lighting, this is different. Here, kerosene is clearly the dominant source, followed by electricity and collected firewood. Solar and dry cells (torches) are less common but are still used by a number of households as the main source. The typical combination of lighting fuel for households that use more than one fuel is kerosene with dry cells as the first fuel and all other sources with kerosene as the second fuel.

As income levels as well as access to modern fuels are very likely to be among the key determinants of fuel use, we now briefly examine lighting-fuel choices by income quartiles as well as household location (urban/rural). The differentiation of fuel use by quartiles of total household income (Table 3) suggests that the energy-ladder concept may indeed hold true for lighting-fuel choice: While the use of firewood and dry cells decreases with rising income, the use of electricity, solar and gas increases. The use of the transitional fuel kerosene first increases and at a higher income level decreases again. The distribution of SHSs by income quartile is in line with Jacobson's (2006) observation that households using solar tend to be rich but not the richest.

Table 3: Main Source of Lighting Fuel (in Percent), by Household Expenditure (Quartiles) and by Rural/Urban

	Overall	Q1	Q2	Q3	Q4	Rural	Urban
Collected Firewood	6.4	17.2	5.4	2.5	0.7	9.4	0.9
Purchased Firewood	0.2	0.5	0.2	0.1	0.2	0.3	0.2
Grass	0.2	0.2	0.2	0.1	0.1	0.1	0.2
Kerosene	73.5	76.1	84.6	80.3	53.0	83.3	55.7
Electricity	16.4	2.3	6.6	14.2	42.1	2.8	41.1
Solar	1.4	0.3	0.7	1.5	3.2	1.8	0.7
Gas	0.2	0.1	0.1	0.3	0.4	0.2	0.3
Dry Cell (Torch)	1.4	2.7	1.9	0.7	0.1	1.9	0.4
Candles	0.2	0.3	0.2	0.2	0.2	0.1	0.6
Other	0.2	0.4	0.0	0.1	0.1	0.2	0.1

Source: Authors' calculations based on KNBS (2005/2006).

Table 4: Share of Energy Expenditure in Total Household Expenditure, by Lighting Fuel (in Percent)

Lighting Fuel	Mean	Median	N
Collected Firewood	1.3	0.0	831
Purchased Firewood	5.0	3.5	30
Grass	4.5	3.7	20
Kerosene	5.1	3.9	9,543
Electricity	6.6	5.6	2,113
Solar	4.5	2.9	185
Gas	6.4	4.3	27
Dry Cell (Torch)	3.1	2.0	176
Candles	4.6	3.5	29
Other	2.0	0.0	21
Total	5.1	3.9	12,975

Source: Authors' calculations based on KNBS (2005/2006).

There are pronounced differences between rural and urban households regarding their main lighting fuel: While most rural households mainly use kerosene, approximately 10 percent mainly use firewood. A small number of households primarily use electricity, dry cells or solar energy. In contrast, urban households tend to choose between kerosene and electricity, and rarely use other fuels.

We have indicated above that overall energy expenditure accounts on average for approximately 5 percent of household expenditure and that this share may be affected by the lighting-fuel choice. Table 4 makes an attempt to find out whether this is the case. It compares energy expenditure shares between households with different main lighting sources (only for sources that are mainly used by more than 50 households in the sample). The table illustrates that energy expenditure shares are indeed lower in households that use solar power for lighting. While households that mainly use electricity (kerosene) for lighting spend 6.6 (5.1) percent of their budgets on energy, this share is only 4.5 percent for households using solar. This is despite the fact that electricity-using households have a median household expenditure that is approximately 20 percent higher than that of solar users. Only dry cell–using households spend less than solar-using ones. The above descriptive statistics illustrate that solar energy can be seen as one of the potential clean substitutes for kerosene as a lighting source.[11] The fact that households with solar as the main lighting fuel tend to spend less on energy overall can be taken as a sign that this choice might even result in welfare gains at the household level – though this is not the focus of this paper and would have to be investigated more thoroughly.

The survey provides some more insights into the adoption of solar power. The question "Does HH have installed solar panels in the dwelling?" was posed to those households that had chosen the answer "electricity" or "solar" in the preceding lighting-fuel question (2,409 or approximately 19 percent of the total sample). Among these households, approximately 11 percent reported having a solar panel installed in their dwelling (see Table 5). These represented 2 percent of the sampled households. With nearly 80 percent of SHSs situated in rural areas, solar panels are more common in, but not restricted to, rural areas. The size of the panels recorded in our dataset varies considerably, with panel sizes of 12, 14, 20, 24 and 40 Watt peak (Wp) being the most common, and with a median size of 21 Wp.

Table 5: Solar Panels Installed, Overall and by Province

		Frequency	Percent
HH Installed Solar Panel	Total	2,409	100.00
	No	2,148	89.17
	Yes	261	10.83
of which			
	Nairobi	19	3.78
	Central	51	12.94
	Coast	14	5.09
	Eastern	77	23.33
	North Eastern	0	0.00
	Nyanza	15	6.36
	Rift Valley	67	13.24
	Western	18	15.38

Source: Authors' calculations based on KNBS (2005/2006).

Note: The question was only posed to households that reported the use of electricity or solar for lighting.

The distribution of solar panels across the provinces is similarly diverse and regionally clustered, ranging from none in the North Eastern Province to over 23 percent in the Eastern Province (see Table 5). The household's location may play a role in the choice to use solar due to the availability of specific (market) infrastructure as well as to awareness of and

11 Despite the widespread interest in solar cookers among development agencies, NGOs and academics (Karekezi 2002), these solar appliances generally have not taken hold among Kenyan households.

knowledge about the technology. Climatic conditions for the use of solar energy, on the other hand, vary only moderately throughout the country.[12]

Most of the electrified households without solar panels have grid access either in their dwelling or within 100 meters (see Table 6). Approximately one-third of the households that report owning a solar panel actually have grid access in their dwelling or in their neighborhood – that is, they have the option of being connected to the grid.[13] This contradicts the common notion that households only decide on solar energy systems when grid access is not available. A similarly counterintuitive observation has also been reported by Acker and Kammen (1996). Whereas they attribute this observation to their sample selection, this cannot be the reason in our case.[14] Households may choose solar energy, rather, as a complementary – possibly less costly, and sometimes more reliable – energy source.

Table 6: Household Installed Solar Panel, by Grid Access or Access within <100 m

	Grid Access <100 m	Yes	No	Total
Solar	Yes	89	171	260
	No	2,122	25	2,147
	Total	2,211	196	2,407

Source: Authors' calculations based on KNBS (2005/2006).

3.2 Determinants of Household Lighting-Fuel Choice

We now examine the determinants of households' lighting-fuel choices using a multinomial logit model. Households face the choice between wood, kerosene, electricity, solar and dry cells for lighting purposes. These choices are unordered in the sense that they cannot be ranked unambiguously, which is why we opt for the multinomial logit. Some of the literature reviewed above follows a similar approach to analyzing household cooking-fuel choice (e.g. Heltberg 2004, 2005; Hosier and Dowd 1987). The choice variable is constructed from the main lighting-fuel choice and therefore does not take into account the option of fuel stacking.[15]

The selection of covariates follows the empirical literature on cooking-fuel choices and so we test for the existence of a cross-sectional energy ladder. In addition, we consider variables

12 In Kenya, annual irradiation estimates range from approximately 1,460 to 2,190 kWh/m², which suggests that solar technologies can be used even at the lower end of this range (Ministry of Energy 2010).

13 See Ondraczek (2011) for further details on electricity prices and the cost of connecting to the grid in Kenya, which tends to be prohibitively expensive for many Kenyan households.

14 This finding may be partly due to the lack of a time dimension in our dataset. We cannot observe whether the household had grid access at the time the solar panels were bought. Yet, it seems unlikely that getting connected after buying solar drives this result, as grid access had not been extended rapidly in Kenya in the years preceding the survey.

15 As all typical combinations in our case include kerosene as the second lighting fuel (except for kerosene, of course), the approach using typical combinations does not yield different results.

that explain the adoption of specific fuel types. The household's fuel decision for lighting is in many respects comparable to the decision regarding cooking fuels. Similar mechanisms should prevail for income, education level, fuel prices, and rural/urban differences. These differences influence, among other things, the local availability and accessibility of fuels. In rural areas households may be constrained by a lack of access to markets for modern fuels (especially for fuels where special equipment/appliances are needed). This implies a greater potential for lighting-fuel switching in urban areas than in rural areas.

The covariates hence include (log) household expenditure and the achieved education level of the household head as a dummy (primary, secondary, tertiary education, with the base category "no primary education completed"). The location of the household is captured by a set of regional dummies for the provinces and an urban dummy (Table 7).

Table 7: Summary Statistics of Variables Used in Estimation

Variable Name	Description	Min.	Max.	Median	Expected Sign for SHSs
Household expenditure	Total annual household food and nonfood consumption expenditure, in Kenyan shilling	1,163	6,649,317	93,610	
Log household expenditure		7.06	15.71	11.45	+
*_ education	Highest education level of household head, dummy. Base category: no formal education	0	1	.	+
Rural/urban	Area of the household's residence, dummy = 1 for urban area	0	1	.	-
Province _*	Dummy = 1 if household lives in province _*	0	1	.	
Kerosene price	Median price of kerosene in the household's district	50	150	56	
Log kerosene price		3.91	5.01	4.03	+
Flat	Dummy = 1 if household lives in a flat	0	1	.	-
Ownership of dwelling	Dummy = 1 if household owns its dwelling	0	1	.	+
Potential grid access	Dummy = 1 if household is either connected to the grid or has neighbors connected to the grid within 100 m	0	1	.	-
Prevalence of SHSs	Share of households with SHSs installed in the district	0	0.09	0.02	+

Source: Authors' calculations based on KNBS (2005/2006).

In addition, we explain household lighting-fuel choice by technology-specific variables. Prices of kerosene are computed as median prices at the district level. The dummy variable "flat" captures whether the household lives in a flat, as this form of housing may prevent the household from using either wood or solar power for lighting. Additionally, we include a dummy for house ownership, as a household may be more likely to invest in grid access or solar panels in this case. As a proxy for "potential grid access" a dummy variable is included and set to 1 if the household is either connected to the grid or has grid access within the neighborhood (<100 m).[16] The use of modern sources of energy, in particular solar power, requires a certain level of locally available knowledge about and awareness of the technology, as well as the availability of (solar) components. To proxy for these effects and to capture possible locally concentrated knowledge spillovers, we introduce the prevalence of SHSs in the district into the regression.[17]

Table 8 shows the average marginal effects – that is, the sample average of the effects of partial or discrete changes in the explanatory variables. It therefore shows the marginal effects on the probability of choosing alternative fuel *i* for an individual with mean characteristics.[18]

The results support the expected income effect explained by the energy-ladder model: that households switch from wood to kerosene to electricity or solar with rising income.[19] Note that Table 8 shows average marginal effects of an increase in log income – that is, the probability of choosing wood (kerosene) as the main lighting fuel decreases by about 4.5 (4.3) percentage points with a unit increase in log household expenditure. This means that an increase of 10 percent in household expenditure decreases the probability of using wood by slightly less than half a percentage point (at median household expenditure). For solar and electricity this 10 percent increase in income would be associated with an increase in the fuel choice probabilities of about 0.8 and 0.1 percentage points, respectively.

16 Actual grid access is also included in a robustness check at a later stage.

17 According to the Hausman test on the independence of irrelevant alternatives (IIA) assumption, H0 cannot be rejected and there is therefore no evidence of a violation of the IIA assumption in our setup. The Small-Hsiao test on the other hand leads to opposite results in some specifications. Since the sample is randomly divided into two subsets each time the latter test is conducted, the results vary. Therefore, we additionally test if fuel choices (outcomes) should be combined to larger categories. This is not the case according to Wald and LR test results.

18 The model is relevant, as the test if all coefficients associated with given variables are 0 is rejected for each variable in the Wald test as well as in the LR test. Neither a high correlation between explaining variables and potential resulting problems of multicollinearity nor empty or small cells seem to be present in our sample.

19 For dry cells we find no effect of income and generally relatively small effects for all other covariates. This can be explained by the small number of observations for this choice.

Table 8: Determinants of Household Fuel Choice for Lighting, Average Marginal Effects

	Wood	Kerosene	Electricity	Solar	Dry Cell (Torch)
Log household expenditure	-0.045***	-0.043***	0.077***	0.012***	-0.001
	(0.003)	(0.004)	(0.003)	(0.002)	(0.001)
Primary education of household head	-0.066***	0.049***	0.002	0.013*	-0.005*
	(0.004)	(0.010)	(0.009)	(0.006)	(0.002)
Secondary education of household head	-0.058***	-0.031*	0.054***	0.033***	-0.002
	(0.004)	(0.013)	(0.009)	(0.009)	(0.003)
Tertiary education of household head	-0.035	-0.175***	0.123***	0.056	-0.014***
	(0.024)	(0.044)	(0.016)	(0.031)	(0.001)
Urban dummy	-0.032***	0.008	0.037***	-0.008**	-0.010***
	(0.005)	(0.009)	(0.006)	(0.003)	(0.002)
Provinces					
Nairobi	-0.067***	0.016	0.056	0.003	-0.014***
	(0.002)	(0.014)	(6.238)	(0.009)	(0.001)
Central	-0.062***	0.038**	0.023**	0.002	0.001
	(0.004)	(0.012)	(0.007)	(0.003)	(0.009)
Coast	-0.051***	0.023	0.025**	0.006	0.001
	(0.004)	(0.012)	(0.008)	(0.006)	(0.007)
Eastern	-0.027***	-0.003	0.006	0.001	0.023***
	(0.004)	(0.010)	(0.008)	(0.003)	(0.005)
North Eastern	-0.008	-0.260***	-0.014	-0.015***	0.297***
	(0.011)	(0.054)	(0.023)	(0.001)	(0.059)
Nyanza	-0.063***	0.116***	-0.050***	-0.007*	0.002
	(0.004)	(0.011)	(0.007)	(0.003)	(0.008)
Western	-0.056***	0.121***	-0.047***	-0.003	-0.014***
	(0.004)	(0.010)	(0.008)	(0.004)	(0.001)
Log kerosene price	-0.001***	0.001	0.001	0.000	-0.000***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Flat	-0.067***	-0.055*	0.084	0.004	0.027
	(0.002)	(0.027)	(3.934)	(0.012)	(0.021)
Ownership of dwelling	-0.031***	0.092***	-0.055***	0.015***	-0.019***
	(0.005)	(0.008)	(0.006)	(0.002)	(0.003)
Potential grid access	-0.043***	-0.158***	0.214***	-0.002	-0.007*
	(0.005)	(0.009)	(0.006)	(0.004)	(0.003)
Prevalence of SHSs	-0.883***	-0.161	0.613***	0.374***	0.013
	(0.123)	(0.196)	(0.149)	(0.048)	(0.063)
Observations: 12,878					

Source: Authors' calculations based on KNBS (2005/2006).

Notes: Multinomial logit, incl. constant; excludes "other." Significance levels: ***: 1%; **: 5%; *:10%; dy/dx for factor levels is the discrete change from the base level. Standard errors in parenthesis. Reference province for the regional dummy is "Rift Valley." Base category for education is "no primary education completed."

The estimated marginal effects of log household expenditure on choice probabilities are negative coefficients for the use of wood and kerosene and positive for modern fuels. We will illustrate the economic importance of these results in more detail below. Higher educational levels are also associated with a higher probability of using modern fuels. Interestingly, the marginal effect of primary education – with no schooling as reference group – is negative for traditional fuels, but positive for kerosene, the only transitional fuel. Secondary education is associated with a lower probability of using kerosene, but this marginal effect is much stronger for wood. These effects of education are exerted on fuel choice in addition to the positive effect that education is likely to have on household income and hence expenditure. Thus, we find evidence of an "educational energy ladder." On this educational energy ladder, solar appears to be an option that medium-educated households prefer. The marginal effect of tertiary education is much lower for solar than for electricity, but we should note that the point estimate of this effect is not very precise for solar.

The location variables all have the expected effects. Households in urban areas are more likely to have access to electricity. This effect, however, is fairly small: compared to a rural household with country-wide average characteristics, the same urban household has an increased probability of using electricity as the main source of lighting of only 3.7 percentage points.[20] The effect of being located in an urban area is even smaller for solar. The regional effects are very much in line with the above descriptive statistics. Richer regions, such as Central, Coast or Nairobi, have better infrastructure and hence provide easier access to modern fuels.

The price of kerosene does not seem to have a large impact on fuel choice. This finding, however, should be treated with caution, as the estimations rely on cross-sectional price variation between districts only. Such variation may well capture omitted factors at this level of aggregation. The effects of the housing variables are perfectly in line with expectations in the case of the dummy for flats: living in a flat decreases the probability of using wood or kerosene. Yet, house ownership – while increasing the use of kerosene and solar – decreases the use of electricity as well as of traditional fuels. We attribute this counterintuitive effect to the significant number of smallholders in our sample who, while they own their houses, predominantly live in rural areas with no access to the electricity grid.

Potential grid access has the expected large positive effect on using electricity. It does not, however, significantly affect the household's choice of using solar, while it is associated with a lower probability of using wood or kerosene. This implies that households choose to use solar power for lighting despite grid availability in their neighborhood.[21] Finally, the largest average marginal effect on the use of solar can be found for the prevalence of SHSs in the district, which suggests that the accessibility of and local knowledge about SHSs are of signifi-

20 Note that most of the location-induced effect is probably captured by the potential grid access variable that is 1 for most urban households.

21 This may be explained to a certain extent by the fact that connecting to the grid might not be possible due to financial or administrative reasons.

cant importance in the decision to install SHSs. Since it can be assumed that systems are cheaper to purchase and install when the necessary infrastructure is at hand, the prevalence of solar may also lead to lower prices for SHSs.

As income, proxied here by total household expenditure, is confirmed by these results to be of crucial importance for lighting-fuel choice, Figure 1 depicts the predicted probabilities with respect to the income level – holding all other characteristics of the households constant at average values.[22] The graphs for the different fuel choices illustrate the energy ladder very nicely. For the interpretation of the graph it is useful to keep in mind that the parts of the graph supported by data are those in a range of approximately log household expenditure of 7 and 16 (the minimum and maximum values for total annual household expenditure).[23] Only at very low levels of income would households have a high probability of using the traditional fuel "wood" for lighting. As income increases, this probability starts to fall very quickly. Kerosene shows a typical transitional fuel pattern, with an increase at low levels, followed by a peak and a lower predicted probability of use at incomes above a certain level. The threshold for modern fuels – electricity and solar – to replace transitional fuels can be found somewhere around 11, or an income of KES 60,000 (approximately USD 800). Many households in Kenya have expenditure levels below this threshold. We find that while electricity takes off rapidly once this threshold has been passed, the probability of using solar increases much more slowly. Yet, what appears to be a steep increase in modern fuel use has to be put into perspective: only at log expenditure levels of 14.5 (approximately USD 27,000) are modern fuels more likely to be chosen than traditional and transitional fuels.

Of course, this is an illustrative ceteris paribus exercise that assumes many other factors to be constant that are unlikely to remain constant with rising incomes. To illustrate this point and to further scrutinize the determinants of SHSs use, we repeat the above exercise for the relationship between the prevalence of SHSs in the district and the predicted probabilities of choosing solar.

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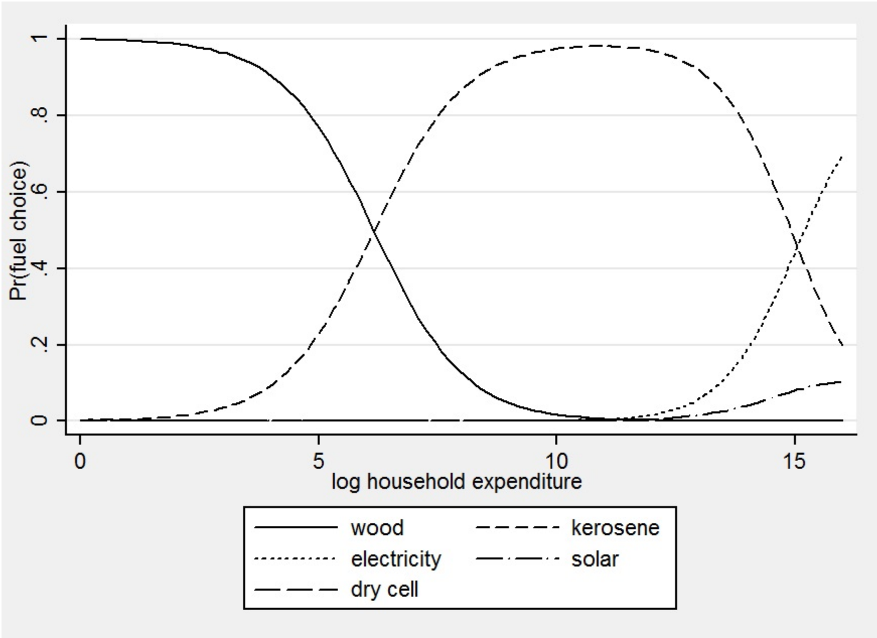
22 Note that the probabilities can be interpreted as incidence – that is, the share of households that use a specific energy source.

23 Subsistence household expenditures of approximately USD 450 per year (USD 1.25 per day) would correspond to a log value of approximately 6. Remember that median expenditure in the KIBHS is approximately KES 90,000 (USD 1,200).

Figure 1: The Effect of Income on Fuel Choice



Source: Authors' calculations based on KNBS (2005/2006).

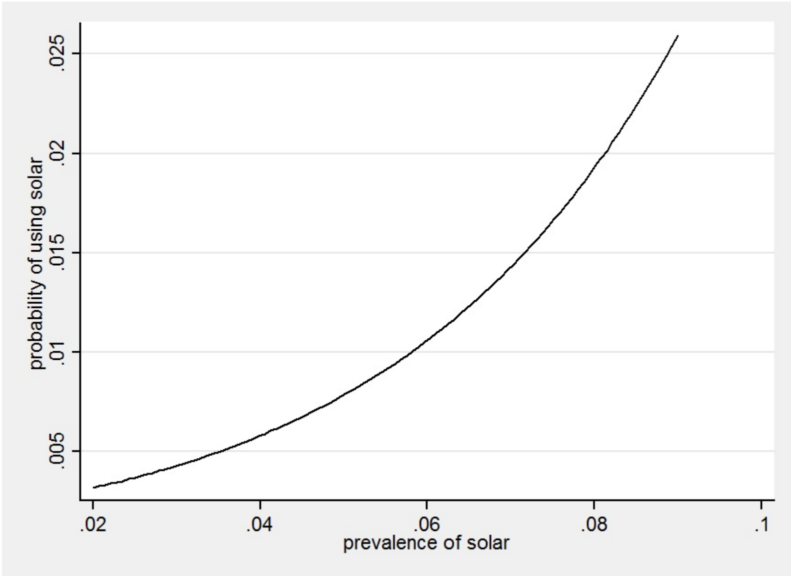
Figure 2 shows that the predicted probability of using solar power increases exponentially as the prevalence of SHSs in the district rises. At low levels, the probability of using solar is relatively low. The more SHSs are already present in the district, the faster the probability of using it increases. This supports the notion of the potential importance of knowledge spillovers as well as awareness and accessibility. However, there are two important caveats which call for some caution with the interpretation. Firstly, since no prices for SHSs are included in the analysis, the strong effect of prevalence of SHSs may partly suffer from an omitted variables bias. Secondly, as the prediction is only meaningful for the range where the probabilities are supported by actual data, the figure presents probabilities for a prevalence ranging from 0.02 to 0.1.

As a variation of the model specification, we test the effects of the inclusion of actual grid access and household size, as these are two determinants frequently used in other applications. Including actual grid access in addition to or instead of potential grid access yields positive effects for electricity and solar and no statistically significant effects for wood and dry cells.[24] Our results on grid access hence remain robust to these changes. The results also do not change much when household size is included as an additional control variable, as is done in some applications for cooking-fuel choice. The coefficient for household size is positive and statistically significant for wood and negative for electricity and solar. We find no statistically significant effect for dry cells.[25]

24 Kerosene is used as the base category in the regression.

25 We also tested the ordered approach used by Farsi et al. (2007). Our results (using the fuels in the order in which they are presented in Table 8 show that all coefficients are positive and statistically significant at the

Figure 2: The Effect of the Prevalence of SHSs on the Choice of SHSs



Source: Authors' calculations based on KNBS (2005/2006).

The above analysis provides some new evidence on the microeconomics of the energy transition when renewable energy options are available. Yet, there are some important limitations to our empirical analysis. The major caveat of this study is its use of a cross-sectional dataset for a study that intends to analyze a transition process. We have stressed above that we are aware of the fact that we are testing a dynamic theory, the energy-ladder concept, with static data. This is not because of bad intentions or misinterpretations, but rather because micro-panel data on the use of renewables is not available. In addition to this fundamental problem, which we share with many other studies, our econometric analysis also suffers from some problems that we do not intend to conceal. First, some important determinants of fuel choices cannot be operationalized empirically with the data at hand. Most importantly, these are the prices for wood and solar. This implies that our estimates suffer from omitted variable bias. However, this bias should be mitigated somewhat by the inclusion of regional dummies. Reverse causality may plague one of our main results, the effects of household expenditure on fuel choices, as fuel choices may influence the income of the household and hence consumption. At the household or individual level, omitted variables, for example, preferences for "modern lifestyles" that would be correlated with both income and fuel choice, may additionally bias these results. As all these biases are likely to upwardly bias our estimates of the effect of household expenditure on fuel choice, these should be considered an upper bound of the actual parameters.

1 percent level, except for household size (negative), kerosene prices (which are positive and significant at the 5 percent level) and ownership (which is not significant at the 10 percent level).

4 Summary and Conclusions

In this paper we have analyzed the determinants of lighting-fuel choices in a developing country with a focus on the adoption of solar energy technologies. We have capitalized on a unique representative survey on energy use and fuel sources from Kenya, one of the few relatively well-established SHSs markets in the world. Our results reveal some very interesting patterns of the fuel transition in the context of lighting-fuel choices and add new evidence on the role of renewable energy sources in this transition.

We find clear evidence for a cross-sectional energy ladder: Poor households use traditional fuels, in particular wood, for lighting. With rising incomes, households switch relatively quickly to transitional fuels, in this case kerosene. In a fairly extended income range, households keep using kerosene, and only start using modern energy sources, that is, electricity and solar energy, at relatively high levels of income. Our estimates put this "takeoff" for modern energy sources at an income level of approximately USD 800 (current 2005 USD) per year per household, but it is only at income levels of approximately USD 27,000 that the probability of using modern energy sources exceeds that of using traditional and transitional fuels. This quantitative insight on energy-ladder thresholds is one of this paper's key findings.

The second set of key findings regards the determinants of SHSs adoption in a relatively established developing-country market. Income again plays a key role. The probability of choosing solar energy as the main source of lighting fuel increases with income. Yet, at least in the cross-section, the use of conventional electricity from the grid increases much more quickly with income than the adoption of SHSs – beyond the above-mentioned threshold. If trends in time followed the pattern detected in the cross-section, the use of SHSs for lighting purposes would level out at an incidence of not even 20 percent – with everything else assumed to be constant. However, the assumption that everything else would remain constant may be too pessimistic if one shares the view that the widespread adoption of renewable energy sources is in principle desirable. We also find a very pronounced effect of clustering; that is, the prevalence of SHSs in the proximity of a potential user increases the likelihood of adoption. This finding supports the idea that the availability of components as well as the knowledge of and openness towards a new technology – and possibly learning-by-doing effects – may play a major role in further increasing the uptake of SHSs. Finally, the lack of correlation between the adoption of solar and access to the electricity grid may be counterintuitive, as SHSs are often perceived only as an off-grid option. Yet, this unanticipated result can easily be rationalized by the advantages that SHSs apparently offer to their users. They may be more reliable, depending on weather conditions, and possibly less costly in the long run. Unfortunately, our data does not allow for the disentangling of these two effects.

The relatively slow transition to modern fuels and the persistence of transitional fuels suggested by the above results show that the "decarbonization" of economic development is no trivial task. Even under conditions that are perceived by many as ideal for the adoption of renewable energy sources, the pace of adoption, at least for SHSs in Kenya, is fairly slow.

Thus, making households switch to SHSs or possibly to other renewable energy technologies is likely to require deliberate, concerted efforts and context-specific policies. Some insights on the features of such policies can be inferred from our analysis. First, it appears that grid extension does not hamper the adoption of SHSs. It may hence be useful to think of SHSs as a complementary and not a substitute fuel source. In this context, it remains to be seen what impact Kenya's ongoing rural electrification program will have on the long-term demand for off-grid solar power. Taken at face value, our results imply that households would still opt for SHSs even if the grid becomes more widely available. However, it seems likely that the overall potential market for SHSs would be significantly smaller if affordable grid access was offered to rural households on a larger scale and on a predictable and more reliable basis. At the same time, the rapid increase in the number of mobile phone users (and to some extent the increased number of TV sets and radios) is likely to serve as an additional driver for the spread of SHSs.

Furthermore, policies that support adoption should take into account possible spillover effects, which appear to be fairly strong in our case study. This may also mean that raising awareness and knowledge about SHSs may be a useful element of such policies. Despite our weak results on price effects, we think that price policies, including subsidies for clean and modern energy sources and higher taxes on carbon-intensive fuels, are likely to be the most powerful instruments for developing countries' governments to shape the evolution of their energy systems. Finally, prices for SHSs are much lower today than they were at the time of the survey, meaning that they have become more competitive alternatives to traditional and transitional fuels even without any government intervention. This trend seems likely to persist in the future as developments on the world market and innovative business models (such as pay-as-you-go payment schemes) continue to lower SHSs prices for consumers in developing countries.

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