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Essays on the Economics of Rural Electrification in Western Kenya

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by

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Abstract

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In Sub-Saharan Africa, 600 million people live without electricity. Despite the ambitions of governments and donors to invest in rural electrification, decisions about how to extend electricity access are being made in the absence of rigorous evidence. This dissertation combines four papers that address various aspects of the economics of rural electrification in Western Kenya.

Chapter 1, which is based on joint work with Eric Brewer, Carson Christiano, Francis Meyo, Edward Miguel, Matthew Podolsky, Javier Rosa, and Catherine Wolfram, presents high-resolution spatial data on electrification rates in rural Kenya in order to quantify and visualize energy poverty in a novel way. Using a dataset of 20,000 geo-tagged structures in Western Kenya, the chapter provides descriptive evidence that electrification rates remain very low despite significant investments in nearby grid infrastructure. The implication is that a substantial portion of the 600 million people without electricity may be “under grid” (as opposed to “off grid”), meaning that they are close enough to connect to a low-voltage line at a relatively low cost. This distinction is important because the policy implications for off grid and under grid communities are different. In under grid communities, it may be preferable to support policies that leverage existing infrastructure with the goal of increasing “last-mile” grid connectivity.

There are active debates about whether increases in energy access should be driven by investments in electric grid infrastructure or small-scale “home solar” systems (e.g., solar lanterns and solar home systems). Chapter 2, which is based on joint work with Edward Miguel and Catherine Wolfram, summarizes the results of a household electrical appliance survey and describes how households in rural Kenya differ in terms of appliance ownership and aspirations. The data suggest that home solar is not a substitute for grid power. Furthermore, the environmental advantages of home solar are likely to be relatively small in countries like Kenya, where grid power is primarily derived from non-fossil fuel sources.

Chapter 3, which is based on joint work with Edward Miguel and Catherine Wolfram, presents results from a field experiment that randomized the expansion of electric grid infrastructure to under grid households in rural Kenya. Electricity distribution is the canonical example of a natural monopoly. Randomized price offers show that demand for electricity connections falls sharply with price. Experimental variation in the number of connections combined with administrative cost data reveals considerable scale economies, as hypothesized. However, consumer surplus is far less than total costs at all price levels, suggesting that residential electrification may reduce social welfare. The chapter discusses how leakage, reduced demand (due to red tape, low reliability, and credit constraints), and spillovers may impact this conclusion.

Based on the findings presented in Chapter 3, a question that follows is whether the gains from extending the grid to rural public facilities, such as secondary schools, are large enough to offset the costs of rural electrification. Chapter 4 presents an analysis on the impact of the rapid rollout of secondary school electricity connections in Western Kenya on the number of students writing the Kenya Certificate of Secondary Education examination ("KCSE"), an important indicator for school completion in Kenya. The chapter presents some evidence that school electrification increases the number of KCSE examinees at boarding schools. In contrast, the effect at day schools is much smaller and is not statistically significant. The result suggests that school electrification may have a larger impact at schools where students are more likely to use electric lighting at night.

For Zakariya Daeho.

Contents

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Chapter 1

Electrification for “Under Grid” Households

Kenneth Lee, Eric Brewer, Carson Christiano, Francis Meyo, Edward Miguel, Matthew Podolsky, Javier Rosa, and Catherine Wolfram

July 2014[1]

1.1 Introduction

In Sub-Saharan Africa nearly 600 million people—or 70% of the population—live without electricity (IEA 2013). This region contains nearly half of the unelectrified households in the world and decisions about how to increase energy access will have major implications for poverty alleviation and global climate change. Yet there is limited evidence on even the most basic patterns of energy demand and the socio-economic impacts of electrification in Africa.

Policy makers, non-governmental organizations, and donors often assume that the majority of the unelectrified are “off grid,” or too far away to realistically connect to a national electricity network. The International Energy Agency constructs its World Energy Outlook forecasts using an assumption that mini-grids and small, stand-alone off-grid solutions will be required for 70% of all rural areas in developing countries (IEA 2012). As a result, there is growing support for off-grid, distributed energy approaches, most of which are best suited for regions without access to grid power. At the same time, the cost-benefit calculations driving large-scale energy infrastructure investments tend to be based on the assumption that “if you build it, they will come.” In this view, expanding high voltage distribution networks and building out greater generation capabilities should translate into increased connectivity for rural households and businesses.

In this paper, we present novel descriptive evidence to address both of these assumptions using an original dataset of over 20,000 geo-tagged structures located across 150 rural communities in Western Kenya. Our study focuses on a region in which we would expect to find evidence of rapid growth in rural connectivity. Since 2007, Kenya has experienced a period of economic growth. In addition, the recent push to expand rural grid coverage nationwide has resulted in higher levels of electricity access, particularly in the densely populated counties of Western Kenya. Keeping these factors in mind, we collected rich spatial and economic data in

[1] The material in this chapter appeared in *Development Engineering* 1 (2016) under the title, “Electrification for “Under Grid” Households in Rural Kenya”, and was first published online in December 2015.

each of our sample communities on the universe of rural structures, including households, businesses, and public facilities, to produce a unique high-resolution dataset illustrating local electrification rates in this region. We are not aware of any other comparable dataset with a similar level of detail in a low-income setting.

Using our high-resolution data, we estimate local household and business electrification rates and identify the correlates of household connectivity. We also combine our household-level data with detailed geo-coded information on the local distribution network, in terms of transformers and connection points (i.e., connected structures), to generate relevant statistics on the location or households with respect to the grid. In addition, we create a new distinction between households that are “off grid,” meaning that they are too far away to connect to the national electrical grid without significant additional investments, and households that are “under grid,” meaning that they are close enough to connect to a low-voltage line at a relatively low cost.

We demonstrate that even in a seemingly ideal setting, where there is high population density and extensive grid coverage, electrification rates remain very low, averaging 5% for rural households and 22% for rural businesses. This pattern holds across time and is observed for both poor and relatively well-off households and businesses. Furthermore, we find that half of the unconnected households in our sample are “under grid,” or clustered within just 200 meters of a low-voltage power line. These results may hold across many countries in Sub-Saharan Africa. Citing a working version of this paper, the Center for Global Development estimates that there may be up to 95 million people living in “under grid” areas in Nigeria, Kenya, Tanzania, Ghana, and Liberia.[2] We argue that if governments wish to leverage existing grid infrastructure, subsidies and new approaches to financing are necessary. In regions that have yet to build out grid or off-grid infrastructure, we highlight the need for forward-looking policies that consider household and business demand for connections, as well as potential economies of scale in costs.

Our work is related to the literature that estimates the impact of electrification on development outcomes. Several studies suggest that rural electrification drives improvements in employment, health, agricultural productivity, and education (see, e.g., Dinkelman 2011; Lipscomb et al. 2013; Khandker et al. 2014; Barron and Torero 2014; Kitchens and Fishback 2015). Additionally, most of the growth in energy demand over the coming decade is predicted to come from low-income countries (Wolfram et al. 2012). For these reasons, policy makers have begun to view energy poverty with an increasing sense of urgency. The challenge to electrify Africa rapidly while minimizing environmental impacts has led to the formation of high profile efforts to achieve universal energy access, including Sustainable Energy for All, a joint venture of the United Nations and the World Bank, and President Obama’s Power Africa initiative. Similarly, there is increasing momentum in the private sector to finance and commercialize off-grid solutions that can provide rural households with enough renewable power to light a room or charge a mobile phone.

While academics and policymakers agree that modern energy is a key input to development, there are fundamental disagreements concerning how best to expand energy access

[2] Leo, Ben, Vijaya Ramachandran, and Robert Morello. 2014. Shedding New Light on the Off-Grid Debate in Power Africa Countries. *Center for Global Development*. Available at: http://www.cgdev.org/blog/shedding-new-light-grid-debate-power-africa-countries.

in rural areas. A number of organizations promote off-grid solutions—such as solar lanterns, solar home systems, and microgrids—over the alternative of existing grid infrastructure under the presumption that these alternatives would be less environmentally damaging.[3] Others remain critical of this approach. For example, The Breakthrough Institute describes it as, "a vision of, at best, charity for the world's poor, not the kind of economic development that results in longer lives, higher standards of living, and stronger and more inclusive socioeconomic institutions."[4]

These debates, however, take place in a data vacuum that this paper seeks to fill. We document that there are a number of households in Western Kenya that remain unconnected, even though there are electricity lines nearby. Moreover, the presumption that increasing the number of grid-connected households would lead to environmental damage may not necessarily hold in Kenya, where over 60% of current installed generation capacity (roughly 1,700 MW) comes from non-fossil fuel sources such as hydro and geothermal. Furthermore, there are plans to build an additional 5,000 MW of capacity by 2017 of which more than 50% will be comprised of geothermal and wind sources. With its relatively "green grid," it may be possible for Kenya to substantially raise rural energy access without leaning too heavily on increases in fossil fuel consumption.

Our findings also relate to existing work on technology adoption that highlights the importance of social, behavioral, and other factors in influencing take-up of new technologies in Africa (see, e.g., Kremer and Miguel 2007; Duflo, Kremer and Robinson 2011; Jack and Suri 2011). However, grid electricity differs from previously studied technologies such as deworming, fertilizers and perhaps even mobile phones in that physical structures must be individually integrated into a wider network—in order to connect to power, there must be an electric line nearby. Furthermore, the interconnected physical electrical network has important economies of scale in terms of cost. When one household connects, it becomes far cheaper for neighboring households to connect, pointing to the existence of a positive externality associated with each new connection. In standard economic theory, externalities provide a rationale for providing public subsidies to achieve socially desirable outcomes.

This paper is organized as follows. Section 2 provides a brief background on rural electrification in Kenya. Section 3 describes our data collection strategy. Section 4 provides a summary of the leading patterns that emerge from our dataset. Section 5 discusses the implications of our results.

1.2 Background

In Kenya, rural electrification first became a public priority in 1973 with the establishment of the Rural Electrification Programme, a government plan to subsidize the cost of electricity supply in rural areas. Under this initial setup, rural electrification was the joint responsibility of the Ministry of Energy and its implementing partner, Kenya Power (KPLC), the country's regulated monopoly transmission, distribution, and retail company.[5] Over the next few decades,

[3] Examples of organizations promoting off-grid solutions include the IEA and the Sierra Club.

[4] Trembath, Alex. 2014. The Low-Energy Club. *The Breakthrough Institute*. Available at http://thebreakthrough.org.

[5] Initially, KPLC was also the largest power-producing company in Kenya. The Kenya Electricity Generating Company (KenGen), the country's main power producer, was established in 1998 in a spin-off of KPLC.

however, the pace of rural electrification remained stagnant. The cost of grid expansion was prohibitively high and there was a general perception that demand for energy in rural areas was too low to be financially viable.

In recent years, there has been a dramatic increase in the coverage of the national electricity grid. In 2003, a mere 285 public secondary schools across the country were connected to electricity. By November 2012, Kenyan newspapers were projecting that 100% of the country's 8,436 secondary schools would soon be connected. This recent big push to electrify rural Kenya began with the ratification of the Energy Act of 2006, which restructured the country's electricity sector and created the Rural Electrification Authority (REA), an agency that would operate independently of Kenya Power, and would be in charge of accelerating the pace of rural electrification. Almost immediately, REA announced a strategy to prioritize the connection of three major types of rural public facilities—markets, secondary schools and health clinics. In the densely populated regions of Central and Western Kenya, where the majority of the population lives, it is widely believed that households are within walking distance of multiple public facilities, although detailed data verifying these claims are lacking. By following this strategy, public facilities would not only benefit from electricity but could also serve as community connection points, bringing previously off-grid homes and businesses within reach of the grid.

By 2013, REA announced that 90% of the country's public facilities had been electrified suggesting that a large share of the population had access to the electricity grid. Despite this success, estimates of the national household electrification rate remain just between 18 and 26%.[6] This gap—between those who are believed to live within range of power and those who are connected to power—suggests that "last-mile" grid connections could be important moving forward.

1.3 Methods

Estimates of grid coverage and grid connectivity in developing countries suffer from uncertainty and measurement error. There is a need for better data on the extent to which unelectrified rural households and businesses are truly "off grid," and the barriers to last-mile electrification where grid infrastructure is already present. We examine these questions by first defining a basic spatial unit—what we refer to as a "transformer community"—to include all buildings within 600 meters of a transformer (the distance at which the utilities deem a building eligible to apply for a grid connection). Our analysis focuses on 150 transformer communities that had transformers installed by REA between 2008 and 2013. All of these communities are located in Busia and Siaya, two Western counties that are broadly representative of rural Kenya in terms of electrification rates and socio-economic development. Given the high population density in this region, the potential for rapid rural electrification is high. After defining our transformer communities, we conducted a census of all households, businesses and public facilities to determine electrification status and collect data on observable attributes of each building.

[6] The 18% figure comes from The World Bank Databank (available at: http://data.worldbank.org/); the 26% figure comes from REA (available at: http://www.rea.co.ke/).

1.3.1 Community selection

In August 2013 local representatives of REA provided us with a master list of 241 unique REA projects, consisting of roughly 370 individual transformers spread across the ten constituencies of Busia and Siaya.[7] Each project featured the electrification of a major public facility (market, secondary school, or health clinic), and involved a different combination of high and low voltage lines and transformers. Projects that were either too recent, or not commissioned, were not included in this master list.[8]

In September 2013 we randomly selected 150 transformers using the following procedure: 1) in each constituency, individual transformers were listed in a random order, 2) the transformer with the highest ranking in each constituency was then selected into the study, and 3) any remaining transformers located less than 1.6 km (or 1 mile) from, or belonging to the same REA project as one of the selected transformers, were then dropped from the remaining list. We repeated this procedure, cycling through all ten constituencies, until we were left with a sample of 150 transformers for which: 1) the distance between any two transformers was at least 1.6 km, and 2) each transformer represented a unique REA project. We limited our sample to 150 communities due to budgetary constraints. In our final sample, there are 85 and 65 transformers in Busia and Siaya counties, respectively, with the number of transformers in each of the ten constituencies ranging from 8 to 23.[9]

1.3.2 Sample representativeness

Table 1.1 utilizes national census data to present a basic comparison between the sample region (i.e., Busia and Siaya counties), and all other counties in Kenya, excluding Nairobi and Mombasa, which are entirely urban. In general, counties in Western Kenya tend to have higher population densities with a higher share of rural homes. For example, the population per square kilometer in the sample region is 375.4 compared to the nationwide county-level median of 183.2. The population density of the 150 transformer communities in our sample, however, is lower, averaging 238.1 people per square kilometer.

Although population and household density are relatively high, Busia and Siaya are broadly representative of—or lag just behind—other parts of rural Kenya in terms of basic education and income indicators. For example, the proportion of people with a secondary school education is 10.4% in our sample region, just below the nationwide county-level median, and the proportion of buildings with high quality walls (i.e. those made of brick, cement, or stone) is 32.5%, just above the nationwide county-level median. With respect to the number of public facilities (i.e. secondary schools, markets, and health clinics), the sample region has 0.81 public facilities per 1,000 people, which is slightly above the nationwide county-level median of 0.75.

[7] Since REA has been the main driver of rural electrification in Kenya, the master list of projects reflects the universe of rural areas in which there is a possibility of connecting to the national grid.
[8] Since the primary objective of the study is to estimate local electrification rates, projects that were funded after February 2013 were excluded to ensure that each community had reached a stable point in terms of electricity take-up.
[9] This variation can be attributed to differences across constituencies in land size and population density. In smaller constituencies, or constituencies where transformers were bundled closely together, our list of potential sites was exhausted before the selection process was complete.

Even though the sample region is highly populated, there is a similar density of public facilities compared to the rest of Kenya.

Based on the 2009 Kenya Population and Housing Census, rural and urban electrification rates in Busia and Siaya are low compared to other parts of Kenya, perhaps because these are relatively rural counties. A more appropriate question would address whether our sample is representative in terms of grid penetration. Would the “under grid” observation apply to other parts of the country? By July 2013, REA had identified 26,070 rural public facilities, located across the 46 non-Nairobi counties in Kenya, of which 22,860 were deemed to be electrified. This translates into national public facility electrification rate of 87.7% and a median county-level rate of 88.2%. In comparison, public facility connectivity in our sample region was 84.1%. Levels of grid penetration in Busia and Siaya are therefore similar to those found in other parts of the country.

1.3.3 Data collection

Between September and December 2013, teams of Innovations for Poverty Action (IPA) surveyors visited each of the 150 transformer communities to geotag each structure within 600 meters of the central transformer and to determine whether the structure had a visible electricity connection at the time of the visit.[10] All data was collected using Open Data Kit (ODK) on Android tablets. Households were identified at the level of the residential compound, which is a unit known locally as a *boma*. In Western Kenya, it is common for related families to live in different households but share the same compound. In our sample of 13,107 compounds, 29% consist of multiple households. Throughout this paper, we refer to these types of compounds as households.

In each community, we were assisted by local guides to quickly capture basic socio-economic indicators for each structure, such as building quality, household size, and whether there was a known business operating inside the household. Using the GPS coordinates, we calculated straight-line distances to the central transformer (and any other transformers in the community), as well as the nearest distance to any type of connected structure. The shortest distance to any of these points is an upper bound on the distance to a low-voltage line.

1.3.4 Data visualization

We create a series of maps, presented in Figure 1.1 (and Appendix Figures A1 to A3 in the Appendix), to illustrate the degree to which rural Kenyans are living close to existing national grid infrastructure. The maps illustrate the large proportion of unconnected households (green circles) that are located near existing connection points (yellow circles, squares, and triangles). The transformer on the left-hand side of the figure was funded/installed in 2008-09 at a

[10] In rural Kenya, households are typically connected to the national grid through drop-down cables and are therefore visible from the road. In a very small number of cases, businesses in market centers are connected through underground cables. In these situations, enumerators verified whether a business was connected to power by looking inside the business. There is a possibility, however, that we underestimate business electrification rates due to measurement error.

secondary school (although the school itself is unconnected). Connectivity is 14% for households and 53% for businesses, and 84% of all unconnected households in this community are “under grid,” or within 200 meters of a connection point. The transformer on the right-hand side of the figure was funded/installed in 2012-13 and located in a market center. The dark region in the upper left of the figure is Lake Victoria. Connectivity is 8% for households and 45% for businesses, and 75% of all unconnected households are “under grid.”

Our maps depict several patterns. For example, businesses and public facilities (squares and triangles) appear to be located along the roads, while households (circles) tend to be scattered across the countryside. Also, across the communities depicted in Figures 1.1 (and Appendix Figures A1 to A3), it is readily apparent that a large proportion of unconnected households (green circles) are located near existing connection points (yellow circles, squares, and triangles).

1.4 Results

In this section, we discuss three leading patterns that emerge from our data. We focus on community electrification rates over time, the predictors of connectivity, and the proximity of unconnected structures to the electricity network.

1.4.1 Despite large investments in grid infrastructure, electrification rates remain low even up to five years after infrastructure has been built.

Extending the grid across rural Kenya has been costly. A typical REA project involves the construction of 11,000 V (11 kV) high-voltage lines, secondary distribution transformers, single and three-phase low-voltage lines, and drop-down lines for last-mile connections. Since these projects are implemented in remote areas, additional costs associated with transportation, surveying and design, and temporary shutdowns tend to be high. In our sample, the median cost of a single REA project is KSh 2.5 million, or $29,548.[11] If we divide the cost of each REA project by the number of transformers in the project, the estimated median cost of each deployed transformer in our sample is $21,820.[12]

This high cost could potentially be justified if many of the surrounding households and businesses were connected to the grid.[13] The majority of households in our sample region are willing to pay for an electricity connection. Based on a random sub-sample of 265 unconnected households, 55% state that they would connect if the connection price were just 30% lower. Nonetheless, local electrification rates remain low, averaging 5.5% and 22.3% for households and businesses in our sample of transformer communities, respectively.[14] By dividing the

[11] For all currency conversions, we assume an exchange rate of 85 KSh per U.S. dollar.

[12] These estimates are based on actual cost data supplied by REA. We were provided with budgetary estimates for 127 projects and actual expenditures for 121 projects in our sample. Most of the projects with missing data were funded in 2008-09 and the data were not recorded in the latest database.

[13] In our sample, there are an average of 85 households and 19 businesses in each transformer community.

[14] We estimate local electrification rates by dividing the total number of structures with a visible electricity connection by the total number of structures observed within the boundaries of the transformer community. Household electrification refers to connectivity at the compound level.

estimated cost of each transformer by the total number of observed connections—including households, businesses and public facilities—we highlight the degree to which this infrastructure is currently underutilized. In our sample, the median infrastructure investment per connection is $2,427. Yet if every structure within each transformer community were to connect, this figure would drop to $210.

It is possible that electrification rates are low because the communities we analyze were electrified only recently; connectivity may naturally increase over time. In order to assess whether electrification rates remain low over time, we categorize our sample of transformers by REA project year and compare electrification rates. The REA project year is the fiscal year in which each project was nominated for electrification by the local Constituency Development Fund and funded in the REA system. Typically, transformers are commissioned within several months of being funded.[15]

In Figure 1.2, we plot average rates for communities grouped by year and type (e.g., businesses and households), with the most recently connected group appearing on the left. Transformer communities are grouped by REA project year. The REA project year is the fiscal year in which each project was nominated and funded for electrification. There are 12, 37, 22, 58, and 21 projects in the 1 Year (2012-13), 2 Years (2011-12), 3 Years (2010-11), 4 Years (2009-10), and 5 Years (2008-09) groups, respectively. We separate households and businesses into those with either low-quality walls (made of mud, reeds, wood, or iron) or high-quality walls (made of brick, cement, or stone). In our setting, wall quality is a proxy for wealth. The figure illustrates that electrification rates have steadily increased over time for both households and businesses but remain at relatively low levels, even after five years. Even for the oldest transformers in our sample, those funded during 2008-09, the average household electrification rate is 8.9%. Selection issues, however, may confound our interpretation of these results. Communities with higher take-up potential may have been electrified first, resulting in upward sloping curves. Yet even if we acknowledge this selection issue, electrification rates remain low.

In our sample of 2,824 businesses, 33.6% are visibly connected to power. In Table 1.2, we report the average electrification rate and number of observations for the ten most commonly observed types of rural businesses. There is considerable variation across types. Connectivity is the lowest for small food stands at 5.7% and the highest for barbershops and salons at 63.2%. These differences form a snapshot of the demand for business electrification in rural areas. Barbershops and hair salons cannot operate effectively without power, and given the relatively low cost of related electrical appliances, connectivity is quite high. Surprisingly, connectivity is low for the more energy-intensive business types. Only 13.3% of cornmeal “posho” mills—the business type that is found across the largest number of communities—are visibly connected, suggesting that the majority of millers are still operating diesel motors. Similarly, connectivity for welding, carpentry and workshops is relatively low at 39.2%.[16]

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[15] There is no reliable data on precise transformer commissioning dates in Western Kenya.

[16] Businesses that require but are without electricity primarily rely on portable sources (such as car batteries) that are capable of powering basic functions such as lighting and mobile phone charging. In some cases, businesses without a grid connection rely on diesel generators.

1.4.2 Connectivity is low even for relatively well-off rural households and businesses.

Should low levels of connectivity be attributed to a technical or an economic constraint? On the one hand, since it is technically easier to supply a connection to a building that is close to a transformer, connectivity should be lower for households that are further away from a transformer. On the other hand, the current connection price of KSh 35,000, or $412, may not be affordable for poor, rural households in a country where the GNI per capita (PPP) is $1,730.[17] Connectivity should be lower for households with visible markers of poverty, such as low-quality building materials.

In our dataset of over 13,000 households, 76.4% have low-quality walls and 23.6% have high-quality walls. For each structure, we use the GPS coordinates to calculate straight-line distances to the central transformer, as well as the nearest distance to any type of connected structure. We take the shorter of the two distances to approximate distances to low-voltage lines. In Figure 1.3, we plot locally weighted regressions of connection status on distance to the central transformer for businesses and households with high and low-quality walls. The figure illustrates that the likelihood of being connected improves slightly with proximity to the transformer, and the improvement is much larger for households with higher-quality walls. However, even for relatively well-off households, connectivity remains low.

In Table 1.3, we report ordinary least squares regression results using connection status as the outcome variable, and distance, years since transformer installation, wall quality, and interaction terms as the explanatory variables. We report the results for households and businesses separately. These coefficients are estimated using the regression model

$$y_{ic} = \beta_1 d_{ic} + \beta_2 t_c + \beta_3 w_{ic} + \beta_4 w_{ic} \times d_{ic} + \beta_5 w_{ic} \times t_c + \lambda_c + \varepsilon_{ic} \quad (1.1)$$

where y_{ic} is an indicator variable for whether or not structure i in community c was visibly connected to electricity, d_{ic} is the straight line distance between the structure and the central transformer (in 100 meter units), t_c is the approximate number of years (ranging from 1 to 5) since the transformer was first installed in the community, w_{ic} is an indicator variable for whether or not the structure had high-quality walls (e.g., brick, cement, or stone), and λ_c captures community fixed effects to account for site-level differences in market status or geography.

The coefficients in column 2 suggest that, holding years constant, a household with high-quality walls is 3% more likely to be connected if it is 20 meters away than if it is 200 meters away. In comparison, at 200 meters, a household with high-quality walls is 16% more likely to be connected compared to a household with low-quality walls. These results suggest that households further away from centrally located transformers are poorer and less likely to connect to power. Similarly, holding distance constant, a household with high-quality walls is 3% more likely to be connected in communities where the transformer had been installed one year earlier, suggesting that richer households are able to accumulate resources over time to obtain electricity connections. Wall quality is also an important predictor in the sample of businesses.

Nonetheless, connectivity is under 30% for these relatively well-off households, most

[17] In March 2014, Kenya Power, the national utility, stated that it will continue to charge eligible customers $412 for single-phase power connections, as long as the cost of connection does not exceed $1,588, inclusive of VAT.

likely because the majority of these households are still poor. While high-quality walls correlate with being better off, the difference in primary economic activity between households with high and low-quality walls in our sample is not large. Based on a sub-sample of 1,737 households in our transformer communities, 70% of households with high-quality walls list small-scale farming as a primary economic activity, compared to 77% of households with low-quality walls. Taken together, the above patterns suggest that the current connection price is simply too high for rural households and businesses.[18]

1.4.3 Half of the unconnected households in our sample are "under grid," or clustered within 200 meters of a low-voltage line, and could be connected at a relatively low-cost.

Taking advantage of the spatial nature of our data, we calculate the shortest distance between unconnected households and the nearest connection point or transformer to approximate the extent to which each household is "under grid." These estimates are conservative. Since our data are limited to the 600-meter circles drawn around each transformer, these are upper bounds on the actual distance because there may be other low-voltage lines immediately beyond our mapped boundaries. In Figure 1.4, we plot the density of the 12,001 unconnected households and 1,875 unconnected businesses in our data set using this metric along the horizontal axis. The figure illustrates that the mass of unconnected households is within 100 and 200 meters of a low-voltage line, and the mass of unconnected businesses is within 50 meters of a low-voltage line (since businesses tend to be clustered in market centers).

Although every structure within a transformer community is eligible to apply for a connection, this is not enough to guarantee that an application will be immediately fulfilled by the local utilities. From the supplier's perspective, it is preferable to connect buildings that are no more than a few service poles away from a low-voltage line because the installation costs associated with single, distant connections are much higher.[19]

According to REA, service poles are required for every 50 meters of line; three or four service poles would therefore imply a maximum distance of 150 to 200 meters. We conservatively estimate the incremental cost of supplying an electricity connection to a single household 200 and 100 meters away from a low-voltage line to be $1,940 and $1,058, respectively, inclusive of material and transportation costs, as well as a 25% contractor markup.[20] Once connected, households pay the utility an electricity tariff that is structured to cover the cost of additional power generation.

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[18] In a related project, we are experimentally varying the connection cost to assess this hypothesis directly.

[19] This is based on multiple discussions with REA and Kenya Power representatives that took place between July 2013 and March 2014.

[20] This excludes additional last-mile costs of household wiring and the meter deposit that households pay to the utility. We conservatively estimate the physical cost of supplying last-mile connection costs, as well as potential economies of scale, using the following assumptions provided by REA: (a) low-voltage single-phase two-wire overhead lines costing $7.06 per meter; (b) single-phase service lines costing $81.92 per connection; (c) transportation costing $1.18 per kilometer for a single lorry traveling over an average distance of 50 km; and (d) contractor costs equal to 25% of all material and transportation costs. Since each truck can carry a maximum of 30 poles, a single vehicle would be sufficient to transport the materials for small groups of neighboring households 600 meters away from a transformer.

These cost estimates, however, do not account for the significant economies of scale that could be achieved by connecting multiple households along the same length of line at the same time. In Figure 1.5, we plot the cost of supplying a single-phase connection as a function of distance and the number of neighboring households connecting to the same length of low-voltage line. The assumptions driving these cost estimates were provided by REA. For example, if two neighboring households were to connect, the above per household costs would fall by roughly 47%, to $1,021 and $580 for distances of 200 and 100 meters, respectively. These neighboring households can be located as far as 30 meters away from either side of the line. The average cost does not decrease by 50% because each household would still require its own service line. If six households were to connect, these estimates would drop to $409 and $262, respectively. While we do not have adequate data to estimate marginal costs in a mass connection program, the costs would presumably be much lower. For instance, if we ignore transportation costs and assume that there is no need to build any additional distribution lines, the marginal cost of a single connection would theoretically fall to $80, the cost of a single-service line. Our cost estimates are in line with previous work on the costs of rural electrification in Kenya (see, e.g., Parshall et al. 2009), illustrating that the cost per household drops dramatically when multiple structures are connected simultaneously due to the fact that they can share some of the infrastructure.

There are no precise estimates of the overall value of electricity to a household. However, if we assume that a connection generates benefits well into the future and apply an annualized interest rate of 12%, then an $80 cost of connection need only generate the equivalent of $10 per household per year in monetary and non-monetary benefits—or 0.6% of the GNI per capita—to be welfare improving.[21] For instance, these benefits could come in the form of higher net profits for household businesses or improved educational outcomes for children. Applying a 200-meter threshold, we find that 47.2% of the 12,386 unconnected households in our sample could be deemed “under grid.” These households are clustered together and are, on average, 115 meters away from a connection point. Based on our data, this represents 36,800 individuals who lack modern energy yet live within range of connecting to the grid at a relatively low cost.

1.5 Conclusions

We demonstrate that even in a seemingly ideal setting, where there is high population density and extensive grid coverage, electrification rates for rural households and businesses remain very low. This pattern holds across time and is observed for both poor and relatively well-off households and businesses. Clearly, under the status quo pricing policies, significant investments in grid infrastructure in Western Kenya have not translated into equally high rates of rural electrification. Our data does however highlight an opportunity that may inform future policies. Half of the unconnected households in our sample are “under grid,” or clustered within 200 meters of a low-voltage line, and could potentially be connected at relatively low marginal cost. If this pattern were to hold across transformer communities nationwide, then given that over 90% of Kenya’s major public facilities (i.e. markets, secondary schools and health clinics) are now electrified, and that these structures are spatially distributed across the country, there is a

[21] The Kenya Government Bond 10 year rate was 11.44% in March 2014. Alternatively, if we assume an interest rate of 30%, the required benefits would be $24 per household per year.

potential opportunity for millions of new connections.[22]

There are at least three ways in which our results could be useful in designing future electrification strategies. First, governments may wish to subsidize mass connection programs. There may be a natural redistributive motive behind this strategy. The fact that connectivity remains so low in “under grid” Kenyan communities indicates that a $412 connection price is too high for poor, rural households to face alone.[23] Furthermore, each new connection expands the geographic reach of the electricity network bringing more and more structures “under grid.” In theory, subsidies can be useful in the presence of these types of externalities. The idea of subsidizing last-mile electricity connections to households is, of course, nothing new. Between 1935 and 1939 the United States implemented its own rural electrification program, issuing roughly 0.3% of GDP—or $16 billion in chained 2009 dollars—in government subsidized loans for rural electrification. Within two decades the proportion of electrified farms in the U.S. increased from 10% to over 90% (Kitchens and Fishback 2015). Similarly, the Tennessee Valley Authority Program, which featured major public investments in a series of hydroelectric dams, has been attributed to persistent growth in regional manufacturing (Kline and Moretti 2014).

Second, governments may wish to support innovative financing and payment approaches to raising connectivity. The lack of a vibrant credit sector serving poor, rural households in developing countries is well documented (see, e.g., Karlan et al. 2014). Providing access to credit or financing options could help rural households meet the up-front cost associated with electrification. Third, governments may wish to support group-based subsidies that are tied to the number of applicants. When take-up is higher, it is cheaper for utilities to connect households because transportation costs are lower and it is possible to design lower-cost local distribution networks. This strategy would therefore take advantage of existing infrastructure and economies of scale. Coordinating household connections, however, poses a collective action problem that would need to be solved through government policies such as mass connection programs.

Our results highlight an opportunity to greatly reduce energy poverty in Sub-Saharan Africa by targeting last-mile connections in “under grid” communities. In regions that have yet to build out grid or off-grid infrastructure, we highlight the need for forward-looking policies that take into account household and business demand for connectivity, as well as potential economies of scale in costs. In Sub-Saharan Africa, there has been a growing focus on expanding renewable generation capacity. In countries like Kenya, where there is a relatively “green grid,” the usual tradeoff between energy access and environmental damage is not as salient. As governments and donors embark on the ambitious task of electrifying millions of households over the coming years, the novel results in this paper call for further research on the demand for and impacts of electrification as well as the potential of various financing mechanisms.

[22] For example, based on REA’s estimates of 8.8 million households and 26% household electrification, then the 50% “under grid” result would point to an opportunity for 3.3 million new connections

[23] It is possible that connectivity is low due to bureaucratic red tape, low grid reliability, credit constraints, as well as the necessity to invest in complementary appliances, as well.

Table 1.1—Comparison of socio-economic indicators between sample region and nationwide counties.

		Nationwide county percentiles		
	Sample region	25th	50th	75th
Total population	1,586,250	528,054	724,186	958,791
per square kilometer	375.4	39.5	183.2	332.9
% rural	85.7	71.6	79.5	84.4
% at school	44.7	37.0	42.4	45.2
% in school with secondary education	10.3	9.7	11.0	13.4
Total households	353,259	103,114	154,073	202,291
per square kilometer	83.6	7.9	44.3	78.7
% with high quality roof	59.7	49.2	78.5	88.2
% with high quality floor	27.7	20.6	29.7	40.0
% with high quality walls	32.2	20.3	28.0	41.7
% with piped water	6.3	6.9	14.2	30.6
Total public facilities	1,288	356	521	813
per capita (000s)	0.81	0.59	0.75	0.98
Electrification rates				
Rural (%)	2.3	1.5	3.1	5.3
Urban (%)	21.8	20.2	27.2	43.2
Public facilities (%)	84.1	79.9	88.1	92.6

Note: Sample region column presents aggregate and weighted-average statistics (where applicable) for Busia and Siaya counties. Demographic and socio-economic data obtained from 2009 Kenya Population and Housing Census. Public facility electrification data obtained from the Rural Electrification Authority (REA). Rural and urban electrification rates represent the proportion of households who stated that electricity was their main source of lighting during the 2009 census. National county percentiles exclude the urban counties of Nairobi and Mombasa.

Table 1.2—Electrification rates for businesses of various types.

	%	N
	(1)	(2)
All businesses	33.6	2,824
Small retail	36.2	1,163
Posho mill	13.3	294
Barber shop / salon	63.2	209
Restaurant	31.3	182
Tailor	26.5	162
Guesthouse	14.2	155
Food stand	5.7	140
Bar / cinema / television hall	62.9	105
Butcher	29.7	91
Welding / carpentry / workshop	39.2	74
Other	42.2	249

Note: Column (1) reports the average electrification rate; (2) reports the total number of observations.

Table 1.3—Predictors of electrification

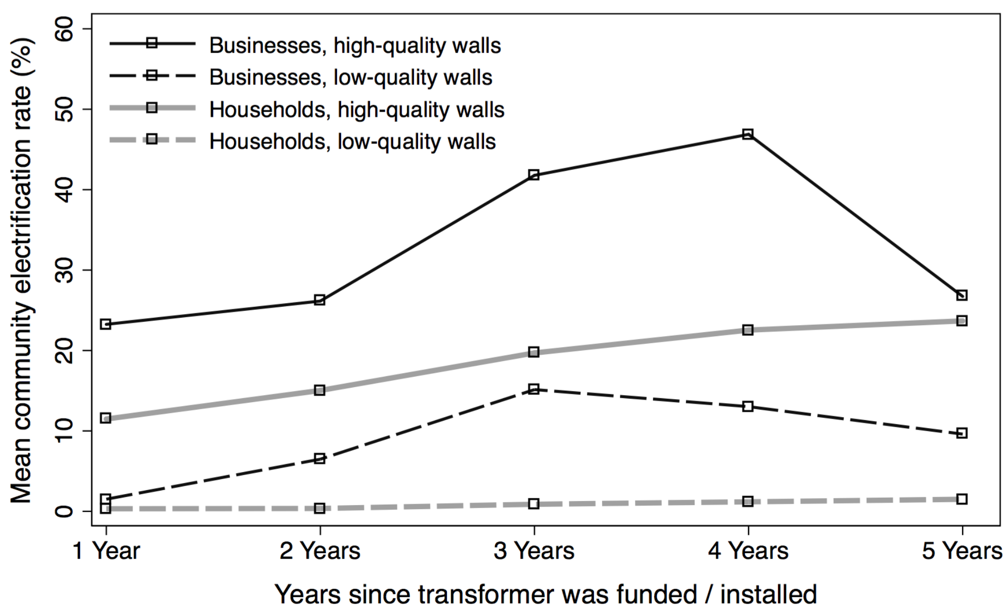
	Households			Businesses		
	(1)	(2)	(3)	(4)	(5)	(6)
Distance	-0.69***	-0.14*	-0.19**	-2.71***	-2.08**	-1.37
	(0.18)	(0.08)	(0.09)	(0.91)	(0.93)	(1.41)
Years		0.34***			0.82	
		(0.08)			(1.23)	
Walls		16.51***	16.70***		18.31	22.25*
		(3.87)	(3.73)		(11.53)	(11.57)
Walls*Distance		-1.60***	-1.56***		0.47	0.04
		(0.57)	(0.57)		(1.10)	(1.29)
Walls*Years		2.56***	2.44***		3.18	1.60
		(0.88)	(0.83)		(3.01)	(2.92)
Community fixed effects	No	No	Yes	No	No	Yes
Mean of dep. var.	5.47	5.47	5.47	33.58	33.58	33.58
Observations	12,666	12,666	12,666	2,823	2,823	2,823
R-squared	0.00	0.14	0.16	0.01	0.10	0.20

Note: All columns report OLS regressions. Robust standard errors clustered at the community level in parentheses. The dependent variable is an indicator variable (multiplied by 100) for household connection status. Columns (1) to (3) report results for households; Columns (4) to (6) report results for businesses. Definitions: (a) Distance is the straight line distance to the central transformer (in 100 meter units), (b) Years is the approximate number of years (ranging from 1 to 5) since the transformer was first installed in the community, (c) Walls is equal to 1 for buildings with high-quality walls (e.g. brick, cement, or stone) and is equal to 0 otherwise, (d) Walls Distance is the interaction between Walls and Distance, and (e) Years Walls is the interaction between Years and Walls. Columns (3) and (6) report community fixed effects regressions. Asterisks indicate coefficient significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

Figure 1.1—Visualizing the proportion of households and businesses that are “under grid.”

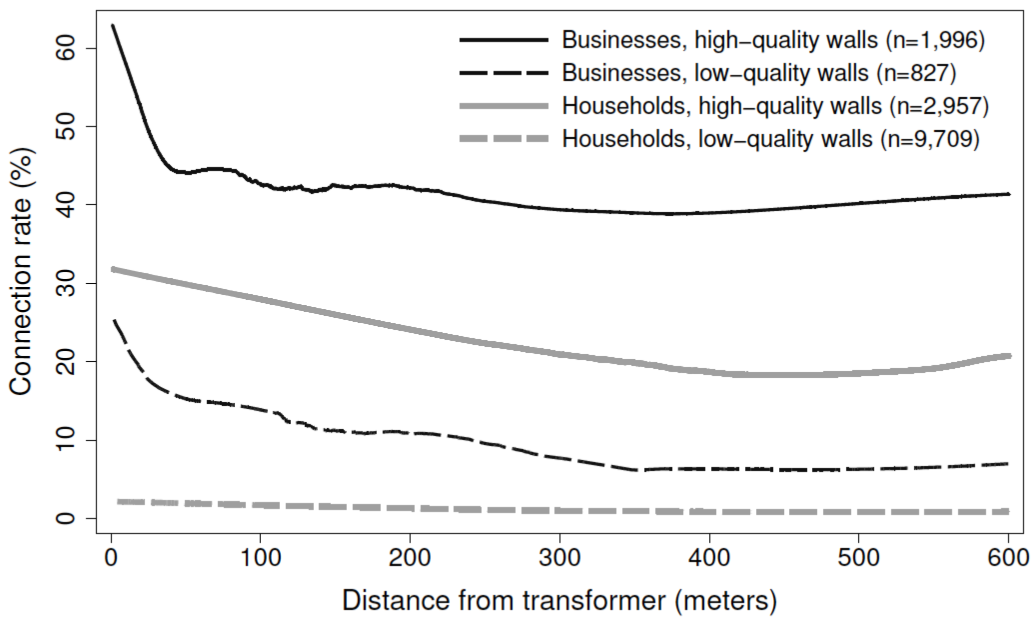
Note: In these maps, the white circle labeled “T” in the center identifies the location of the REA transformer. The larger white outline demarcates the 600-meter radius boundary. Green circles represent unconnected households; purple squares represent unconnected businesses; and blue triangles represent unconnected public facilities. Yellow circles, squares, and triangles indicate households, businesses, and public facilities with visible electricity connections, respectively. Household markers are scaled by household size, with the largest indicating households with more than ten members, and the smallest indicating single-member households. Residential rental units are categorized as households. The figures illustrate the large proportion of unconnected households (green circles) that are located near existing connection points (yellow circles, squares, and triangles). (*Left*) The transformer was funded/installed in 2008-09 at a secondary school (although the school itself is unconnected). Connectivity is 14% for households and 53% for businesses, and 84% of all unconnected households in this community are “under grid,” or within 200 meters of a connection point. (*Right*) The transformer was funded/installed in 2012-13 and located in a market center. The dark region in the upper left of the figure is Lake Victoria. Connectivity is 8% for households and 45% for businesses, and 75% of all unconnected households are “under grid.” Maps of 18 additional transformer communities are presented in Appendix Figures A1 to A3.

Figure 1.2—Median transformer community electrification rates by structure type and funding/installation year.



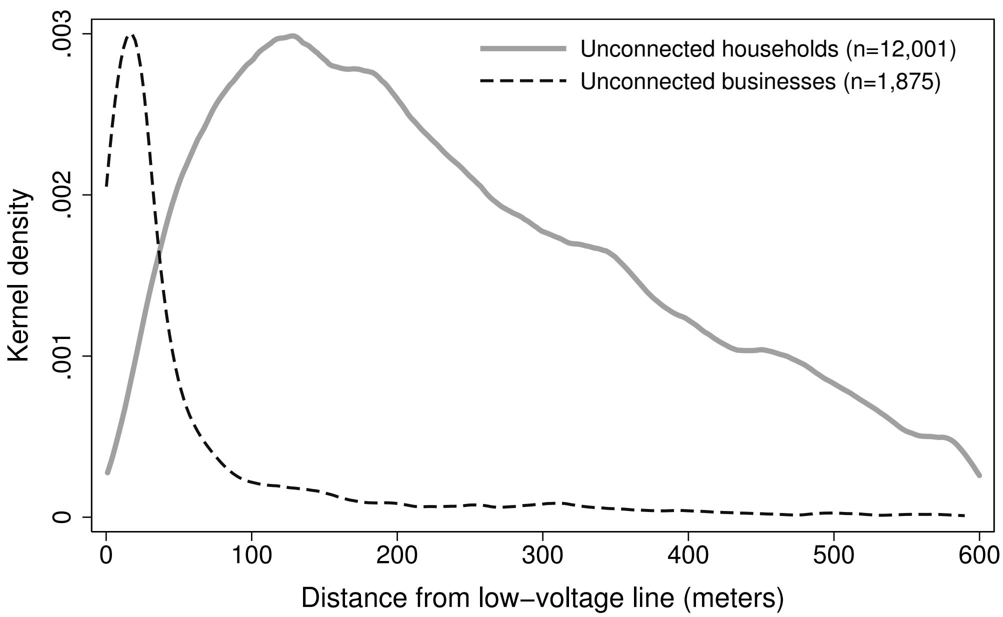
Note: Transformer communities are grouped by REA project year. The REA project year is the fiscal year in which each project was nominated and funded for electrification. There are 12, 37, 22, 58, and 21 projects in the 1 Year (2012-13), 2 Years (2011-12), 3 Years (2010-11), 4 Years (2009-10), and 5 Years (2008-09) groups, respectively. Structures with high-quality walls are defined as those made of brick, cement, or stone. Structures with low-quality walls are defined as those made of mud, reeds, wood, or iron. The figure illustrates that electrification rates have steadily increased over time for both households and businesses but remain at relatively low levels, even after five years.

Figure 1.3—Connection rates by distance to the central transformer.



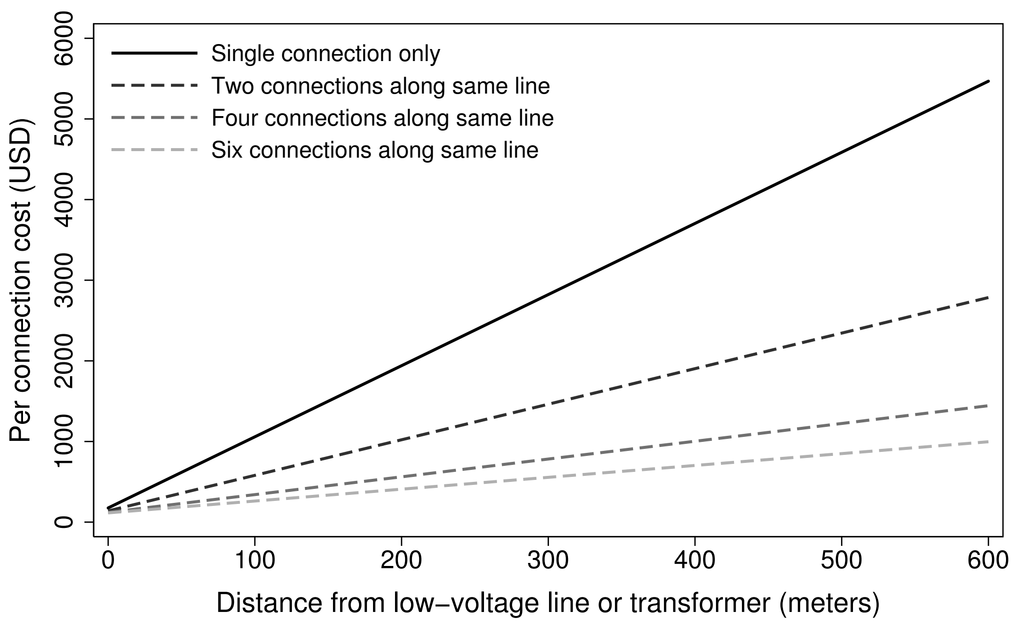
Note: In this figure, we plot locally weighted regressions (bandwidth 5) of the connection status on the distance to the transformer for businesses and households with high and low-quality walls. As in Fig. 1.2, high-quality walls are defined as those made of brick, cement, or stone. Low-quality walls are defined as those made of mud, reeds, wood, or iron.

Figure 1.4—Kernel densities of unconnected households and businesses by distance from low-voltage line.



Note: We plot Epanechnikov kernels (bandwidth 12). The horizontal axis represent the distance of the unconnected household or business to nearest connection point or transformer. The vertical axis scale applies to household density only. The peak density for businesses is 0.016.

Figure 1.5—Economies of scale in the cost of providing household electricity connections.



Note: Cost estimates are based on actual assumptions used by REA for budgetary purposes. The horizontal axis can be interpreted as either the distance to the nearest low-voltage line or the distance to the central transformer.

Chapter 2

Appliance Ownership and Aspirations

Kenneth Lee, Edward Miguel, and Catherine Wolfram

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2.1 Introduction

Universal energy access has emerged as a major policy goal in Sub-Saharan Africa. However, there are active debates about the extent to which energy access should be driven by investments in large-scale infrastructure, such as grid connections, or small-scale decentralized solutions, such as solar lanterns and solar home systems. Recently, both the US Agency for International Development (USAID) and the UK Department for International Development (DFID) have announced high profile energy initiatives—named *Power Africa* and *Energy Africa*, respectively—targeting the 70 percent of Sub-Saharan Africans who are believed to be living off of the electric grid. At the heart of both policies is a focus on expanding the market for solar lanterns and solar home systems, which we refer to collectively as "home solar."

Several factors have contributed to the enthusiasm for home solar. With energy-related emissions of greenhouse gases accounting for over three-quarters of worldwide emissions, politicians, international donors, and non-governmental organizations have been quick to highlight the renewable nature of home solar, particularly in developing countries that are still building out their electricity systems. In addition, technological innovations have increased the affordability of these products by reducing solar prices and decreasing the power requirements for a variety of end uses (e.g., connectivity and computing through smartphones and tablets). Furthermore, by integrating mobile money payment technologies into their products, companies such as M-KOPA in Kenya have addressed the financing challenge and are providing poor, rural households with previously unaffordable solar products that can be paid for gradually over time.[2]

Not everyone, however, shares this enthusiasm for home solar. On the cost side, Deichmann et al. (2010) propose that decentralized renewable energy will be the lowest cost

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[1] The material in this chapter appeared in *American Economic Review: Papers & Proceedings* 106(5) (2016) under the title, "Appliance Ownership and Aspirations among Electric Grid and Home Solar Households in Rural Kenya", and was published in May 2016.

[2] In addition to these factors, Jacobsen (2007) points to the private sector appeal of home solar, noting how decentralized solar first emerged during the late-1980s and 1990s, a period in which mainstream development policies emphasized economic liberalization, privatization, and market-based approaches to service provision.

option for just a minority of households in Africa, even when taking into consideration the likely reductions in costs over the next 20 years. On the demand side, a recent household survey in Tanzania, conducted by the Center for Global Development, revealed that nearly 90 percent of households who already had "access to electricity outside of the national grid, such as solar power" still wanted a connection to the national grid.[3] Writing at The Breakthrough Institute, Caine et al. (2014) caution that, "whatever the short-term benefit, a narrow focus on household energy and the advocacy of small-scale energy sources like solar home systems can, in fact, make it more difficult to meet the soaring increase in energy demand associated with moving out of extreme poverty." Broadly, policymakers have begun to move away from binary definitions of energy access to recognize variation in the service levels provided by home solar and grid connections with different levels of reliability (see, e.g., ESMAP 2015).

While there is a small but growing research literature on the economic impacts of electrification (see, e.g., Barron and Torero 2015), there is minimal data and evidence on how electricity is consumed in the developing world, and how electricity use relates to the type of energy supplied. In this paper, we summarize the results of a recent household appliance survey conducted in Western Kenya to provide descriptive evidence on how rural households with and without grid connections, and those with home solar systems, compare in terms of the appliances they own and the appliances they aspire to own.

Our data indicate that home solar users own quite different appliances compared to grid-connected households, and suggest that home solar systems do not satisfy the full range of household energy needs, given current appliance technologies. We also document planned expansions in centralized electricity generating capacity in a number of Sub-Saharan African countries, including Kenya. We find that the environmental advantages of decentralized solar are likely to be relatively small in countries like Kenya, where a large proportion of existing and planned grid electricity is generated without fossil fuels. This paper is organized as follows: Section 2.2 describes the data and setting, Section 2.3 presents the results, and Section 2.4 concludes.

2.2 Data and setting

We analyze household survey data collected between February and August 2014 from 2,504 rural households in 150 communities in Busia and Siaya, two counties that are broadly representative of rural Kenya in terms of electrification rates and economic development. Our sample consists of 2,289 households that are not connected to the grid and 215 households that are connected to the grid. In each community, field enumerators sampled 15 unconnected households, and up to 4 connected households wherever possible, using a comprehensive census of residential structures conducted in 2013. At the time of the census, community electrification rates were low, averaging 5 percent for rural households. The sampling procedure—which is described in detail in Lee, Miguel, and Wolfram (2016b)—ensured that the data are largely representative of the rural population in Western Kenya.

We collected data on the different types of energy used in each household. In our setting, home solar penetration is low despite low grid electrification rates. For unconnected households,

[3] See http://www.cgdev.org/blog/dfid-solar-only-approach-rural-electricity-africans-want-on-grid.

the most common primary sources of energy are kerosene (92.4 percent), solar lanterns (3.6 percent), and solar home systems (2.2 percent). Only 8.7 percent of unconnected households use either a solar lantern or a solar home system as a primary or secondary source of energy.[4]

Based on this data, we divide our sample into three categories: (1) households that are connected to the national electric grid (n=215), (2) households that are not connected to the grid but use home solar systems (i.e., solar lanterns or solar home systems) (n=198), and (3) households that are not connected to the grid and rely primarily on kerosene energy (n=2,091).

There is a wide range of products in the home solar market. Solar lanterns, which typically cost $10 to 100, offer less than 10 watts of power and are limited to lighting and mobile charging services. In contrast, solar home systems, which cost anywhere from $75 to $2,000, offer up to 1,000 watts of power and can power televisions, fans, and limited motive and heating power. The most popular solar home system in Kenya, M-KOPA, currently costs over $200 and provides an 8 watt panel, two LED bulbs, an LED flashlight, a rechargeable radio and mobile charging adaptors.[5] In comparison, residential grid connections support the full range of potential applications. Higher-end systems, accommodating the use of high-wattage appliances, are rare in Western Kenya and none of the households in our sample have such a system. In our data, the mean price paid for solar lanterns and solar home systems is $54.27 and $234.37, respectively.[6] Most of the systems documented are used solely to power low-wattage appliances. For this reason, we group solar lanterns and solar home systems together in our analysis.

We asked household respondents to list all of the electrical appliances they own. We then asked respondents to name the appliances that they would ideally purchase next. After compiling a list of all owned and desired appliances, we divide the list into two categories based on typical required wattages.[7] We define low-wattage appliances, such as mobile phones and radios, as those that can be powered using the most common solar lanterns and basic solar home systems found in the study region. High-wattage appliances are defined as those that require either higher-end solar home systems (which again are largely non-existent in our setting) or connections to the electric grid. Using these data, we present comparisons below across the three categories of households defined above in order to better understand how households compare in terms of appliance ownership and aspirations.

2.3 Patterns of electrical appliance ownership and aspirations

Three patterns emerge in our data. First, home solar households have higher living standards than kerosene households, but differences in appliance ownership are not large. In Appendix Table B1, we summarize the key differences in observed characteristics between kerosene and home solar households. Both types are similar in that the majority of household respondents are primarily farmers by occupation, but home solar users are characterized by higher socioeconomic status across most measures: they are more educated, politically aware, have bank accounts, and live in households characterized by high quality walls (made of brick,

[4] Households were asked to identify their "main" (primary) and "other" (secondary) sources of lighting energy.
[5] Based on Alstone, Gershenson, and Kammen (2015) and M-KOPA (http://www.m-kopa.com/products/).
[6] Mean prices paid for solar lanterns and solar home systems are based on 113 and 51 responses, respectively.
[7] We assume that nearly all households with grid connections or home solar devices have electric lighting.

cement, or stone, rather than the typical mud walls), more land and assets. These higher living standards, however, do not translate into meaningful differences in appliance ownership.

In Figure 2.1, we present a summary of the appliance ownership survey data, grouping appliances into low-wattage (Panel A) and high-wattage appliances (Panel B). Horizontal bars indicate the proportion of households in each category that own (dark grey) and desire (light grey) each appliance type. Connected households clearly own the most appliances, which is expected given that both connectivity and asset ownership are positively correlated with income. The difference between home solar and kerosene households, however, is far more muted; neither type of household owns many appliances. With the exception of mobile phones and televisions, ownership levels for all appliances fall below 6 percent and 15 percent for kerosene and home solar users, respectively.[8]

Second, both home solar and kerosene households reveal a strong desire to own high-wattage appliances. The most desired appliances for kerosene users include televisions (39 percent) and irons (16 percent). Similarly, home solar users desire televisions (37 percent), irons (26 percent), and refrigerators (24 percent). Many of the most commonly desired appliances can only realistically be powered with connections to the electric grid, pointing to the limitations of the home solar systems commonly available in Kenya.

Third, despite having access to electric lighting, both connected and home solar households continue to purchase non-trivial amounts of kerosene. In Appendix Figure B2, we summarize monthly spending for non-charcoal energy sources for each household category.[9] As expected, connected households have the largest total energy budget, spending \$15.68 per month on average. In comparison, kerosene and home solar users spend \$5.42 and \$6.53 per month, respectively. Surprisingly, all three types of households spend a similar amount on kerosene, ranging from \$3.66 for connected households to \$3.90 for kerosene households.

Although mean kerosene spending is similar, there are substantial differences in the proportion of households reporting zero spending on kerosene. For example, 33.4 percent of connected households reported that they did not spend any money on kerosene over the past seven days, compared to 23.7 percent and 2.5 percent of home solar and kerosene households, respectively. These figures suggest that a large proportion of home solar users—and even connected households—are unable to completely eliminate their use of kerosene.[10] For connected households, these spending patterns may indicate underlying problems with the grid, such as blackouts and other forms of poor reliability, highlighting the need for an increased focus on improving the service quality of the electric grid. For home solar households, these patterns suggest that the current range of solar products do not provide sufficient lighting points within the home and must be complemented with kerosene lanterns.

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[8] A number of households own appliances that they appear unable to use regularly. For example, 16 percent of kerosene households own televisions, which may be powered with car batteries. Electric iron ownership is likely to be largely "aspirational" among home solar consumers, as conventional irons require over 1,000 watts of power, far more than the 8 watts that the most common home solar systems in Kenya can accommodate.

[9] We asked connected households for the amount of the last monthly electricity bill. For kerosene and other sources of energy, we asked for the total amount spent over the past seven days and then estimated monthly amounts.

[10] Note that very few households report using kerosene to cook. Only 0.4 percent and 3.1 percent of unconnected households list kerosene as their primary and secondary source of cooking energy, respectively. In comparison, 94 percent of unconnected households list collected firewood as their primary source of cooking energy.

2.4 Conclusion

Solar lanterns and solar home systems are often framed as an important step up the "modern electricity service ladder" (see, e.g., Alstone, Gershenson, and Kammen 2015). The findings in our data are consistent with this description. Relative to kerosene, home solar users benefit from improvements in basic energy applications, such as lighting and mobile phone charging. Once households have access to these basic end uses, however, the appliances that they aspire to own next tend to require high wattage levels that cannot be accommodated by most home solar systems. The power supplied by home solar simply does not scale with demand. Home solar is not a substitute for grid power. Unless there is a dramatic reduction in the price of high-wattage systems, it is unlikely that households will be able to "leapfrog" the electric grid in the same way that mobile phones allowed people to leapfrog fixed line telecommunications. Of course, decentralized solar may remain the most attractive option for a small number of isolated rural communities located far away from the national power grid.

Home solar still has the potential advantage of being cleaner than fossil fuel based energy alternatives. To evaluate the possible environmental advantages of home solar in Kenya and other countries, we document the existing and planned sources of centralized electricity generating capacity in the region. In Figure 2.2A, we plot installed capacity, and the proportion of non-fossil fuel generation, for the top ten producers of electricity in Sub-Saharan Africa (SSA) and ten Newly Industrialized Countries (NICs) from other regions. Relative to the SSA countries, the NICs have much higher levels of installed capacity. However, the SSA countries generate power that is, on average, half as carbon-intensive as the NICs. In the NICs, non-fossil fuel capacity is 29.4 percent compared to 64.6 percent in the SSA countries.[11]

In the future, countries in Sub-Saharan Africa will continue to expand centralized electricity generating capacity to serve industrial, commercial, and urban customers. This will happen regardless of the proportion of rural households that adopts home solar. In the SSA countries that we examine, a large share of these capacity additions will be tied to non-fossil fuel technologies. Appendix Table B1 summarizes current and future installed capacity in Kenya, where several geothermal and wind projects are already under development. Over the next 15 years, installed capacity is expected to increase dramatically from 2,295 MW to 19,620 MW. Still, the proportion of non-fossil fuel sources will remain constant, at roughly 64 percent.

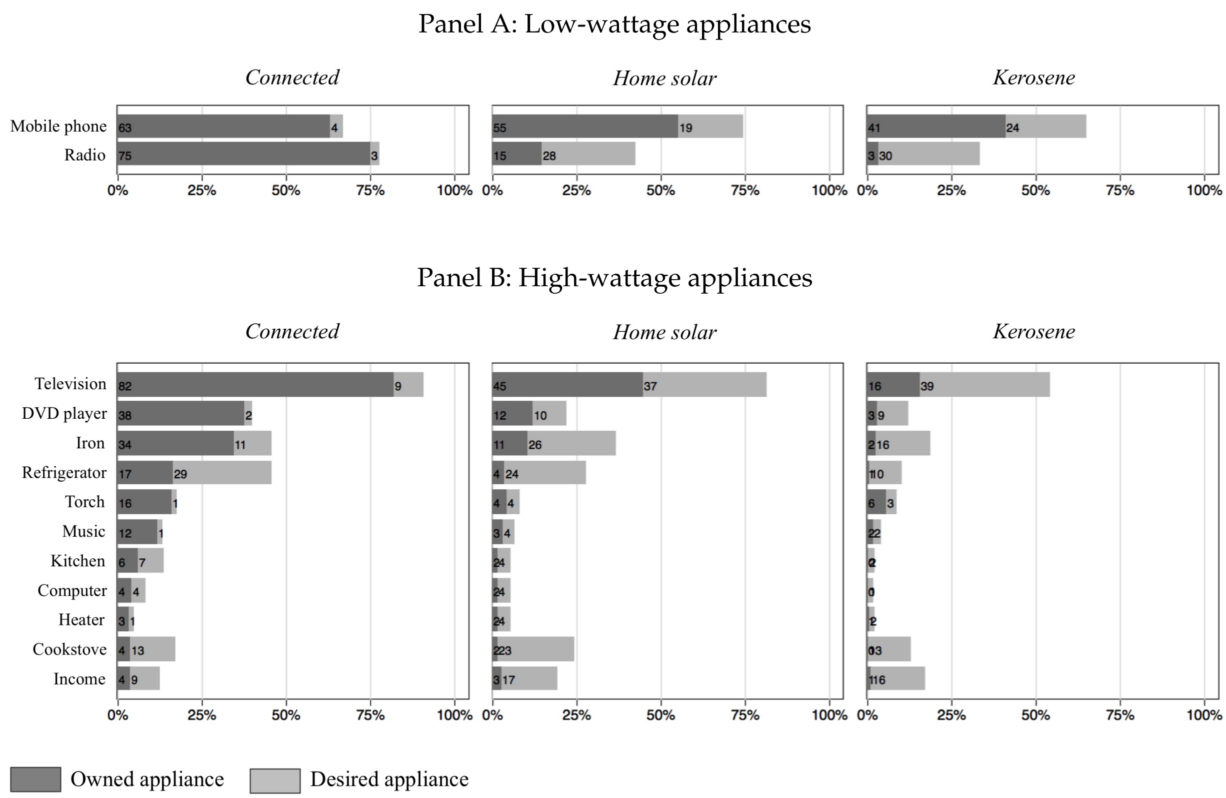
In Figure 2.2B, we plot current and future installed capacity targets for the ten SSA countries, based on publicly available sources. Almost all of the countries plan to increase installed capacity while maintaining or even increasing the share of power derived from non-fossil fuel sources. As countries move to further decarbonize their national grids, the potential environmental advantages of home solar systems will decline.

The energy infrastructure choices that Kenya and other African countries make over the next decade will have major implications for both their economic development and global climate change. Focusing on home solar alone is unlikely to promote economic development. As

[11] Figures 2.2A and 2.2B summarize plant capacities, while environmental emissions will be proportional to the energy produced by different types of plants. Unfortunately, we are unable to obtain predictions of plant capacity factors, although it is not a priori clear that the share of non-fossil fuel production would be lower or higher than the share of non-fossil fuel capacity based on capacity factors of similar types of plants in other countries.

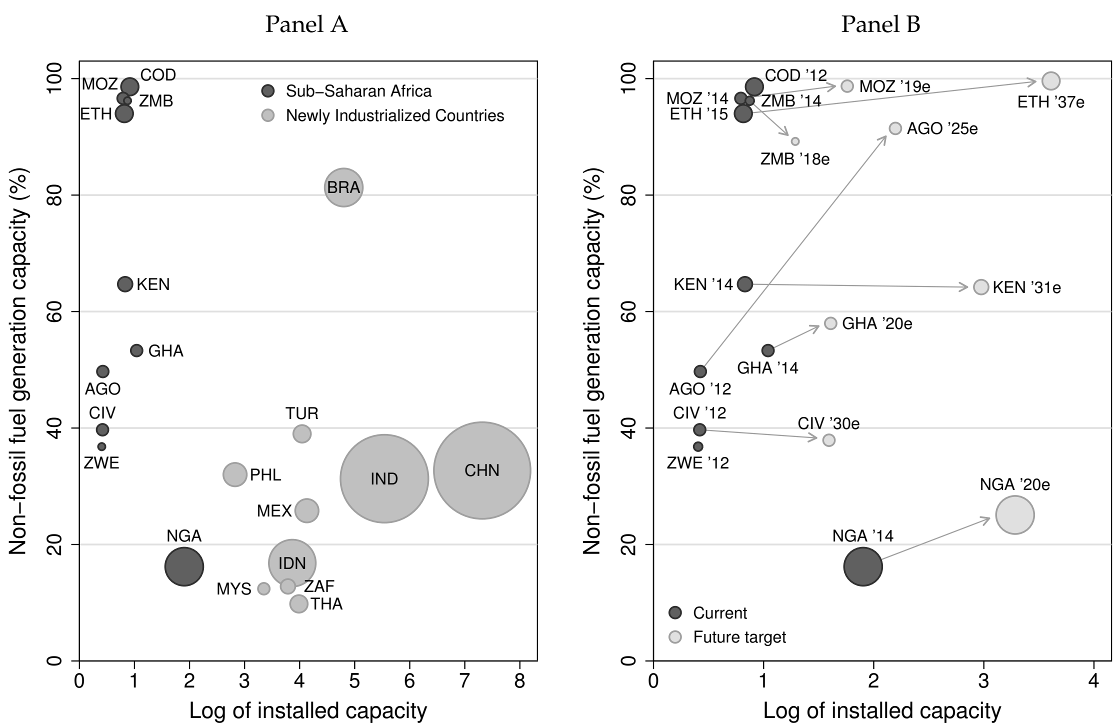
Kremer and Willis (2016) point out, investment choices today will impact the economics (and the politics) of future energy infrastructure investments. In order to understand the economic implications of different approaches to addressing energy poverty, more research is needed on household energy demand in low-income countries, and how improvements in the governance and service quality of electric utilities will influence this demand.

Figure 2.1—Electrical appliances owned and desired by rural households in Kenya



Notes: The label next to each bar indicates the proportion of households that own or desire each appliance. See Appendix Note B1 for additional details on appliance categories.

Figure 2.2—Installed electricity generation capacity: Current and future targets



Notes: In Panel A, average non-fossil fuel generation is 64.6 and 29.4 percent for SSA countries and NICs, respectively. Markers are scaled by population. See Appendix Note B2 for detailed data sources.

Chapter 3

Experimental Evidence on the Demand for and Costs of Rural Electrification

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3.1 Introduction

Investments in infrastructure, including transportation, water and sanitation, telecommunications, and electricity systems, are primary targets for international development assistance. In 2015, for example, the World Bank directed a third of its global lending portfolio to infrastructure.[1] The basic economics of these types of investments—which tend to involve high fixed costs, relatively low marginal costs, and long investment horizons—can justify government investment, ownership, and subsequent regulation. While development economists have recently begun to measure the economic impacts of various types of infrastructure, including transportation (Donaldson 2013; Faber 2014), water and sanitation (Devoto et al. 2012; Patil et al. 2014), telecommunications (Jensen 2007; Aker 2010), and electricity systems (Dinkelman 2011; Lipscomb, Mobarak, and Barham 2013; Barron and Torero 2016; Burlig and Preonas 2016; Chakravorty, Emerick, and Ravago 2016), there remains limited empirical evidence that links the demand-side and supply-side economics of infrastructure investments, in part due to methodological challenges. For instance, in many settings it is not only challenging to identify exogenous sources of variation in the presence of infrastructure, but also difficult to obtain detailed data on particular infrastructure extension projects.

In this paper, we analyze the economics of rural electrification. We present experimental evidence on both the demand-side and supply-side of electrification, specifically, household connections to the electric grid. Our study setting is 150 rural communities in Kenya, a country where grid coverage is rapidly expanding. In partnership with Kenya's Rural Electrification Authority (REA), we provided randomly selected clusters of households with an opportunity to connect to the grid at subsidized prices. The intervention generated exogenous variation both in

[1] Based on *The World Bank Annual Report 2015*, available at: http://www.worldbank.org/en/about/annual-report. During the 2015 fiscal year, the World Bank allocated $14.4 billion (34 percent of total lending) towards its Energy and Mining, Transportation, and Water, Sanitation, and Flood Protection sectors. During the 2014 fiscal year, the comparable figure was even higher, at 44 percent.

the price of a grid connection, and in the scale of each local construction project. As a result, we are able to estimate both the demand curve for grid connections among households and, in a methodological innovation of the current study, the average and marginal cost curves associated with household grid connection projects of varying sizes. We then compare the demand and cost curves to begin to assess the welfare implications of mass rural electrification.

We find that household demand for grid connections in our data is lower than predicted, even at high subsidy rates. For example, lowering the connection price by 57 percent (relative to the prevailing price) increases demand by less than 25 percentage points. The cost of supplying these connections, however, is very high, even at universal community coverage when the benefits of the economies of scale are attained. As a result, the estimated consumer surplus from grid connections is far less than the total connection cost at all coverage levels, amounting to less than one quarter of total costs. These findings point to a perhaps unexpected conclusion, namely, that rural household electrification may reduce welfare in our setting. We then consider a variety of explanations for this finding, and present empirical evidence on the role of excess costs from leakage during construction, and reduced demand due to bureaucratic red tape, low grid reliability, and credit constraints, and more speculatively, any unaccounted for spillovers.

Electricity systems serve as canonical examples of natural monopolies in microeconomics textbooks. Empirical estimates in the literature date back to Christensen and Greene (1976), who examine economies of scale in electricity generation.[2] In recent decades, initiatives to restructure electricity markets around the world have been motivated by the view that while economies of scale are limited in generation, the transmission and distribution of electricity continue to exhibit standard characteristics of natural monopolies (Joskow 2000).

We differentiate between two separate components of electricity distribution. First, there is an access component, which consists of physically extending and connecting households to the grid, and is the subject of this paper. Second, there is a service component, which consists of the ongoing provision of electricity. There is some evidence of economies of scale in both of these areas. Engineering studies, for example, show how the costs of grid extension may vary depending on settlement patterns (Zvoleff et al. 2009) or can be reduced through the application of spatial electricity planning models (Parshall et al. 2009). With regards to electricity services, data from municipal utilities has been used to demonstrate increasing returns to scale, particularly in administrative functions such as maintenance and billing (Yatchew 2000). While recent papers have examined the demand for rural electrification using both survey (Abdullah and Jeanty 2011) and experimental variation (Bernard and Torero 2015; Barron and Torero 2016), our study is the first to our knowledge to combine experimental estimates on both the demand for and costs of grid extensions. By combining these elements, we contribute to ongoing debates regarding the economics of rural household electrification.

In Sub-Saharan Africa, over 600 million people currently live without electricity (IEA 2014). In recent years, achieving universal access to modern energy has become a primary goal for policymakers, non-governmental organizations, and international donors. In 2013, for example, U.S. President Barack Obama launched his signature multi-billion dollar foreign aid initiative, *Power Africa*, announcing the goal of adding 60 million new connections throughout

[2] Christensen and Greene (1976) find that while substantial economies of scale in production existed in 1955, by 1970 most U.S. electricity generation occurred in the “flat” region of the average total cost curve.

Sub-Saharan Africa. The United Nations Sustainable Development Goals include, "access to affordable, reliable, sustainable and modern energy for all."[3] In Kenya, the government has recently invested heavily in expanding the electric grid to rural areas, and even though the rural household electrification rate remains low (at roughly 5 percent), the majority of households are now "under grid," or within connecting distance of a low-voltage line (Lee et al. 2016).[4] As a result, "last-mile" grid connectivity has recently emerged as a political priority in Kenya.

At the macroeconomic level, the correlation between energy consumption and economic development is strong, and it is widely agreed that access to a well-functioning energy sector is critical for sustained economic growth. There is little evidence, however, on how energy drives poverty reduction, and, for example, how investments in industrial energy access compare to the economic impacts of electrifying rural households. For rural communities, there are also active debates about whether increases in energy access should be driven mainly by connections to the grid or via distributed solutions, such as solar lanterns and solar home systems.[5] In this paper, we present some of the first empirical evidence on the economics of, and implementation challenges surrounding, electric grid investments in low-income regions.

Although we find that the estimated consumer surplus from household grid connections is substantially less than the total connection cost at all coverage levels, universal access to electricity may still increase social welfare. For example, mass electrification might transform rural life in several ways: with electricity, individuals may be exposed to more media and information, might participate more actively in public life and generate improvements in the political system or public policy, and children with electricity in their homes could study more and be more likely to obtain work outside of rural subsistence agriculture later in life. However, these types of social, political and long-run economic effects have not been the main focus of electrification impact evaluations to date. Researchers and policymakers might need to focus on such outcomes in order to justify rural electrification as a development policy priority, given the small consumer surplus from electrifying rural households (relative to cost) that we estimate.

The remainder of this paper is organized as follows. Section 3.2 identifies the various natural monopoly scenarios that are empirically tested in our study; Section 3.3 discusses rural electrification in Kenya; Section 3.4 describes the experimental design; Section 3.5 presents the main empirical results; Section 3.6 discusses the institutional and implementation challenges to rural electrification, and their implications; and Section 3.7 concludes.

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[3] See http://www.un.org/sustainabledevelopment/energy/ for further details.

[4] According to the *2009 Kenya Population and Housing Census*, available at http://www.knbs.or.ke, 5.1 percent of rural households in Kenya used electricity as the main type of lighting.

[5] Deichmann et al. (2010), for example, utilize a spatial planning model to suggest that for the majority of households in Sub-Saharan Africa, decentralized solutions are unlikely to be cheaper than the grid. Writing at the Breakthrough Institute, Caine et al. (2014) point out that, "whatever the short-term benefit, a narrow focus on household energy and the advocacy of small-scale energy sources like solar home systems can, in fact, make it more difficult to meet the soaring increase in energy demand associated with moving out of extreme poverty." In contrast, Craine, Mills, and Guay (2014) at the Sierra Club argue that off-grid systems are an important first step up the "energy ladder" and that basic energy services (such as lighting and mobile phone charging) must first be available before households further expand their energy consumption; see Lee, Miguel, and Wolfram (2016a) for a discussion.

3.2 Theoretical Framework

In the classic definition, an industry is a natural monopoly if the production of a particular good or service by a single firm minimizes cost (Viscusi, Vernon, Harrington 2005). More advanced treatments elaborate on the concept of subadditive costs, which extend the definition to multiproduct firms (Baumol 1977). Some textbook treatments point out that real world examples involve physical distribution networks, and specifically cite water, telecommunications and electric power (Samuelson and Nordhaus 1998; Carlton and Perloff 2005; Mankiw 2011).

3.2.1. Standard model

We consider the case of an electric utility that provides communities of households with connections to the grid. In order to supply these connections, the utility incurs a fixed cost to build a low-voltage (LV) trunk network of poles and wires within each community. In the standard model, illustrated in Figure 3.1, Panel A, the electricity distribution utility is a natural monopoly facing high fixed costs, constant or declining marginal costs, and a downward-sloping average total cost curve. As community coverage increases, the marginal cost of connecting an additional household should decrease as the distance to the network declines. At high coverage levels, the marginal cost is essentially the cost of a drop-down service cable that connects each household to the LV network.[6] Household demand for a grid connection reflects expectations about the difference between the consumer surplus from electricity consumption and the price of monthly electricity service.

The social planner's solution is to set the connection price equal to the level where the demand curve intersects the marginal cost curve (p′). Due to the natural monopoly characteristics of the industry, the utility is unable to cover its costs at this price, and the social planner must subsidize the electric utility to make up the difference. In Panel A, total social surplus from the electricity distribution system is positive at price p′ since the area under the demand curve is greater than the total cost, represented by rectangle with height c′ and width d′.

3.2.2. Alternative scenarios and potential externalities from grid connections

We illustrate an alternative scenario in Figure 3.1, Panel B. Here, the natural monopolist faces high costs relative to demand. The marginal cost curve does not intersect the demand curve and a subsidized mass electrification program reduces social welfare. In this case, mass electrification appears unlikely to be an attractive policy.

In Panel C, we maintain the same demand and cost curves as in Panel B, but illustrate a case in which the social demand curve (D′) lies above the private demand curve (D). There may be positive externalities (spillovers) from private grid connections, especially in communities with strong social ties, where connected households share the benefits of power with their neighbors. In rural Kenya, for instance, it is common for people to spend some time in the homes of neighbors who have electricity, watching television, charging mobile phones, and enjoying better quality lighting in the evening. Another factor that could contribute to a gap between D

[6] This is particularly the case if households are sampled randomly and connected, as in the experiment we study.

and D′ is the possibility that households have higher inter-temporal discount rates than government policymakers. For example, if electrification allows children to study more and increases future earnings, there may be a gap if parents discount their children's future earnings more than a social planner. Further, demand may be low due to market failures, such as credit constraints or a lack of information about the long-run private benefits of a connection; the social demand curve would reflect the willingness to pay for grid connections if these issues were resolved. In general, if D′ lies above D, there may be a price at which the consumer surplus (the area underneath D′) will exceed total costs.

Which of these cases best fits the data? In this paper, we trace out the natural monopoly cost curves using experimental variation in the connection price and in the scale of each construction project. The estimated curves correspond to the segments of Figure 3.1 that range between the pre-existing rural household electrification rate level, which is roughly 5 percent at baseline in our data, and full community coverage (d=1). This is the policy relevant range for governments considering subsidized mass rural connection programs.

One type of externality that we do not consider is the negative spillover from greater energy consumption, due to higher CO_2 emissions and other forms of environmental pollution. These would shift the total social cost curve up, making mass electrification less desirable. In the next section, we discuss aspects of electricity generation in Kenya that make these issues less of a concern in our setting than they often are elsewhere.

3.3 Rural Electrification in Kenya

Kenya has a relatively "green" electricity grid, with most energy generated through hydropower and geothermal plants, and with fossil fuels representing just one third of total installed electricity generation capacity, which currently stands at 2,295 megawatts. Installed capacity is projected to increase tenfold by the year 2031, with the proportion of electricity generated using fossil fuels remaining roughly the same over time.[7] Thus Kenya appears poised to substantially increase rural energy access by relying largely on non-fossil fuel energy sources.

In recent years, there has been a dramatic increase in the coverage of the electric grid. For instance, in 2003, a mere 285 public secondary schools across the country had electricity connections, while by November 2012, Kenyan newspapers projected that 100 percent of the country's 8,436 secondary schools would soon be connected. The driving force behind this push was the creation of REA, a government agency established in 2007 to accelerate the pace of rural electrification.[8] REA's strategy has been to prioritize the connection of three major types of rural public facilities, namely, market centers, secondary schools and health clinics. Under this approach, public facilities not only benefited from electricity but also served as community connection points, bringing previously off-grid homes and businesses within close reach of the

[7] Specifically, in 2015, total installed capacity was 2,295 MW and consisted primarily of hydro (36.0 percent), fossil fuels (35.4 percent), and geothermal (25.8 percent) sources. Based on government planning reports (also referred to as "*Vision 2030*"), total installed capacity is expected to reach 21,620 MW by 2031, with fossil fuels (e.g., thermal, medium-speed diesel, and geothermal-natural gas) representing 32.4 percent of the total. Many other African countries generate similar shares of electricity from non-fossil fuel sources (Lee, Miguel, and Wolfram 2016a).

[8] Prior to the creation of REA, rural electrification was the joint responsibility of the Ministry of Energy and Petroleum and Kenya Power, the country's regulated monopoly transmission, distribution and retail company.

grid. In June 2014, REA announced that 89 percent of the country's 23,167 identified public facilities had been electrified. This expansion had come at a substantial cost to the government, at over $100 million per year. The national household electrification rate, however, remained relatively low at 32 percent, with far lower rates in rural areas.[9] Given the widespread grid coverage, the Ministry of Energy and Petroleum identified last-mile connections for "under grid" households as the most promising strategy to reach universal access to power.

During the decade leading up to the period of this study, any household in Kenya within 600 meters of an electric transformer could apply for an electricity connection at a fixed price of $398 (35,000 KES).[10] The fixed price had initially been set in 2004 and was intended to cover the cost of building infrastructure in rural areas. As REA worked to expand grid coverage, the connection price emerged as a major public issue in 2012, appearing with regular frequency in national newspapers and policy discussions. The fixed price seemed "too high" for many if not most poor, rural households to afford. However, Kenya Power, the national electricity utility, estimated the cost of supplying a single connection in a grid-covered area to be $1,435, which vastly exceeded the household charge. After the government rejected its proposal to increase the price to $796 (70,000 KES) in April 2013, Kenya Power initially announced that it would no longer supply grid connections in rural areas at all, limiting supply to households that were a single service cable away from an LV line. As a result, the government agreed to temporarily provide Kenya Power with subsidies to cover any excess costs incurred, allowing the expansion of rural grid connections to continue at the same $398 price as before. In February 2014, the government ended these subsidies to Kenya Power, and it was again reported that the price would increase to $796. Ultimately, the $398 fixed price remained in place for households within 600 meters of a transformer throughout our study period, from late-2013 to early-2015.

The government announced in May 2015 (after our primary data collection activities) that it had secured $364 million—primarily from the African Development Bank and the World Bank—to launch the *Last Mile Connectivity Project* (LMCP), a subsidized mass electrification program that plans to eventually connect four million "under grid" households, and that once launched, the program would lower the fixed price substantially to $171 (15,000 KES). This new price was based on the Ministry of Energy and Petroleum's internal predictions for take-up across all rural areas, and was revealed for the first time to the public in May 2015. For households that were unable to afford this price, a financing plan would also be put in place, allowing households to slowly pay for their connections over time, although few details have been provided.[11] Our study, which is described in the next section, takes place during the tail end of the decade-long $398 price regime, before the announcement of the planned LMCP program.

[9] REA provided us with estimates of the proportion of public facilities electrified (June 2014), the national electrification rate (June 2014), and overall REA investments (between 2012 and June 2015).

[10] All Kenya Shilling (KES) figures are converted into U.S. dollars at the 2014 average exchange rate of 87.94 KES/USD. The fixed price of 35,000 KES was set in 2004 in order to reduce the uncertainty surrounding cost-based pricing. Anecdotally, there were concerns that some staff had lowered the cost-based price in exchange for a bribe.

[11] At the time of writing this paper, the government had not yet begun any LMCP electricity connections.

3.4 Experimental design and data

3.4.1. Sample selection

This field experiment takes place in 150 "transformer communities" in Busia and Siaya, two counties that are broadly representative of rural Kenya in terms of electrification rates and economic development, and where population density is fairly high.[12] Each transformer community is defined as the group of all households located within 600 meters of a secondary electricity distribution (low-voltage, LV) transformer, the official distance threshold that Kenya Power established for connecting buildings to the grid at the standard price.

The list of communities was sampled in close cooperation with REA. In August 2013, local representatives of REA provided us with the master list of all 241 unique REA projects—centered on the electrification of a market, secondary school, or health clinic—consisting of roughly 370 individual transformers spread across Busia and Siaya.[13] Using this list, we randomly selected 150 transformers, subject to the conditions that the distance between any two transformers was at least 1.6 km (1 mile), and each transformer represented a unique REA project. In our final sample, there are 85 and 65 transformers in Busia and Siaya, respectively.[14]

Between September and December 2013, teams of surveyors visited each of the 150 transformer communities to conduct a census of the universe of households within 600 meters of the central transformer. This database, consisting of 12,001 unconnected households in total, served as the sampling frame for our study. At the time of the census, 94.5 percent of households remained unconnected despite being "under grid" (Lee et al. 2016).

We present a map of a fairly typical (in terms of residential density) transformer community in our sample in Figure 3.2, illustrating the degree to which unconnected households are within close proximity of an LV line. Although population density in our setting is high, the average minimum distance between structures is 52.8 meters. These distances make illegal connections quite costly, since local pole infrastructure would need to be built in order to "tap" into nearby lines. In practice, the number of illegal connections is negligible in our sample.

For each unconnected household, we calculated the shortest (straight-line) distance to an LV line, approximated by either a connected structure or a transformer. To limit construction costs, REA requested that we limit our sampling frame to the 84.9 percent of these households that were no more than 400 meters away from a connected structure or a transformer. Applying this threshold, we randomly selected, enrolled, and surveyed 2,289 "under grid" households, or roughly 15 households per community.

[12] In Appendix Table C1, we use national census data to compare Busia and Siaya to all other counties in Kenya. The sample region is more densely populated than most other rural areas, but is broadly representative of—or lags just behind—other regions in terms of basic education, income proxies, and grid coverage.

[13] Since REA has been the main driver of rural electrification, this master list reflects the universe of rural communities in which there is a possibility of connecting to the grid in these two counties.

[14] Appendix Figure C1 maps the communities in our sample. Appendix Note C1 provides further details.

3.4.2. Experimental design and implementation

We illustrate the experimental design in Figure 3.3. Between February and August 2014, we administered a baseline survey to the 2,289 study households. In addition, we collected baseline data for 215 already connected households—or 30.5 percent of the universe of households observed to be connected to the grid at the time of the census—sampling up to four connected households in each community, wherever possible. See Appendix Note C2 for details.

In April 2014, we randomly divided the sample of transformer communities into treatment and control groups of equal size, stratifying the randomization process to ensure balance across county, market status, and whether the transformer installation was funded early on (namely, between 2008 and 2010). The 75 treatment communities were then randomly assigned into one of three subsidy treatment arms of equal size. Following baseline survey activities in each community, between May and August 2014, each treatment household received an official letter from REA describing a time-limited opportunity to connect to the grid at a subsidized price.[15] The treatment and control groups are characterized as follows:

1. High subsidy arm: 380 unconnected households in 25 communities are offered a $398 (100 percent) subsidy, resulting in an effective price of $0.
2. Medium subsidy arm: 379 unconnected households in 25 communities are offered a $227 (57 percent) subsidy, resulting in an effective price of $171.
3. Low subsidy arm: 380 unconnected households in 25 communities are offered a $114 (29 percent) subsidy, resulting in an effective price of $284.
4. Control group: 1,150 unconnected households in 75 communities receive no subsidy and face the regular connection price of $398.

Households were given eight weeks to accept the offer and deposit an amount equal to the effective connection price (i.e., actual price less the subsidy amount) into REA's bank account.[16] In order to prevent transfers of the offer between households, the offer was only valid for the primary residential structure, identified by the GPS coordinates captured during the baseline survey. All treatment households were given a reminder phone call two weeks prior to the expiry date of the offer. At the end of the eight-week period, enumerators visited each household to collect copies of bank receipts to verify that payments had been made.

Treatment households also received an opportunity to install a basic and certified household wiring solution (a "ready-board") in their homes at no additional cost. Each ready-board—valued at roughly $34 per unit—featured a single light bulb socket, two power outlets, and two miniature circuit breakers.[17] Finally, each connected household received a prepaid electricity meter at no additional charge from Kenya Power.

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[15] We provide an example of this letter in Appendix Figure C2.

[16] In Kenya, one does not need a bank account in order to deposit funds into a specified bank account.

[17] The ready-board was designed and produced for the project by Power Technics, an electronic supplies manufacturer in Nairobi. A diagram of the Power Technics ready-board is presented in Appendix Figure C3.

We registered a pre-analysis plan, which is available at http://www.socialscience-registry.org/trials/350, on the AEA RCT Registry in July 2014 while most treatment offers were still pending and before analysis of any grid connection take-up data (Casey, Glennerster, and Miguel 2012).

After verifying payments, we provided REA with a list of households that would be connected. This initiated a lengthy process to complete the design, contracting, construction, and metering of grid connections: the first household was metered in September 2014, the average connection time was seven months, and the final household was metered over a year later, in October 2015. Additional details are discussed in Section 3.6.2 below.

3.4.3. Data

The analysis combines survey, experimental, and administrative data, collected and compiled between August 2013 and October 2015. The datasets include:

1. *Community characteristics data* (n=150) covering all 150 transformer communities in our sample, including estimates of community population (i.e., within 600 meters of a central transformer), baseline electrification rates, year of community electrification (i.e., transformer installation), distance to REA warehouse, and average land gradient.[18]
2. *Household survey data* (n=2,504) from the baseline survey, consisting of information on respondent and household characteristics, living standards, time use, recent energy consumption, and stated demand (contingent valuation) for an electricity connection.
3. *Experimental demand data* (n=2,289) consisting of take-up decisions for the 1,139 treatment households (collected between May and August 2014) and 1,150 control households (collected between January and March 2015) in our sample.
4. *Administrative cost data* (n=77) supplied by REA including both the budgeted and invoiced costs for each project. For each community in which the project delivered an electricity connection (n=62), we received data on the number of poles and service lines, length of LV lines, and design, labor and transportation costs. Using these data, we calculate the average total cost per household for each community. In addition, REA provided us with cost estimates for higher levels of coverage (i.e., at 60, 80, and 100 percent of the community connected) for a subset of the high subsidy arm communities (n=15).[19] Combining the actual sample and designed communities data (n=77) enables us to trace out the cost curve at all coverage levels.

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[18] Following Dinkelman (2011), gradient data is from the 90-meter Shuttle Radar Topography Mission (SRTM) Global Digital Elevation Model (www.landcover.org). Gradient is measured in degrees from 0 (flat) to 90 (vertical).

[19] REA followed the same costing methodology (e.g., the same personnel visited the field sites to design the LV network and estimate the costs) applied to the communities in which we delivered an electricity connection, to ensure comparability between budgeted estimates for “sample” and “designed” communities, as discussed below.

3.4.4. Baseline characteristics

Table 3.1 summarizes differences between unconnected and connected households at baseline. Connected households are characterized by higher living standards across almost all proxies for income.[20] In particular, these households have higher quality walls (made of brick, cement, or stone, rather than the typical mud walls), have higher monthly basic energy expenditures, and own more land and assets including livestock, household goods (e.g., furniture), and electrical appliances.

The vast majority of unconnected households in our sample (92.4 percent) rely on kerosene as their primary source of lighting, while only 6 and 3 percent of unconnected households own solar lanterns and solar home systems, respectively. These figures point to an opportunity to increase rural energy access through distributed solar systems. Based on current technologies, however, grid connections and distributed solar are vastly different in terms of potential applications. Grid connections allow households to use a far wider range of appliances, and in particular, those that require more power. In Appendix Figure C6, we show that at baseline, many unconnected households owned mobile phones and radios, the types of lower-wattage appliances that could be powered using standard solar home systems. In contrast, connected households were the primary owners of higher-wattage appliances, such as televisions and irons, which are also some of the most desired appliances but which home solar systems typically cannot support (Lee, Miguel, and Wolfram 2016a).

In Appendix Table C2, we report baseline statistics for the control group. On average, 63 percent of respondents are female, just 14 percent have attended secondary school, 66 percent are married, and, in terms of occupation, 77 percent are primarily farmers. Households have 5.3 members on average, of which 3.0 are ages 18 and under. These are overwhelmingly poor households, as evidenced by the fact that only 15 percent have high-quality walls. Households spend \$5.55 per month on (non-charcoal) energy sources, primarily kerosene.[21]

We test for balance across treatment arms by regressing a set of household and community characteristics on indicators for the three subsidy levels, and also conduct *F*-tests that all treatment coefficients are equal to zero. For the 20 household-level and two community-level variables analyzed, *F*-statistics are significant at the 5 percent level for only two variables—a binary variable indicating whether the respondent was able to correctly identify the presidents of

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[20] These patterns are consistent with the stated reasons for why households remain unconnected to electricity. In Appendix Figure C4, we show that, at baseline, 95.5 percent of households cited the high connection price as the primary barrier to connectivity. The second and third most cited reasons—which were the high cost of internal wiring (10.2 percent) and the high monthly cost (3.6 percent)—are also related to costs. Note that no households said they were unconnected because they were waiting for a lower connection price, or a government-subsidized rural electrification program. In fact, prior to our intervention, there were concerns that the price would increase. In Appendix Figure C5, we present a timeline of project milestones and connection price-related news reports over the period of the study. Furthermore, during our intervention, 397 households provided a reason for why they had declined a subsidized offer and not one cited the possibility of a lower future price. Taken together, these factors alleviate concerns that households were anticipating a subsidized government mass electrification program.

[21] In June 2014, the standard electricity tariff for small households was roughly 2.8 cents per kWh. Taking into consideration fixed charges and other adjustments, \$5.55 per month translates into roughly 30 kWh of electricity consumption, which is enough to power basic lighting, television, and fan appliances, each day of the month.

Tanzania, Uganda, and the United States (a measure of political awareness) and monthly (non-charcoal) energy spending, indicating that the randomization created largely comparable groups.

3.5 Results

3.5.1. Estimating the demand for electricity connections

In Figure 3.4, we plot the experimental results on the demand for grid connections. We find that take-up of a free grid connection offer is nearly universal, but demand falls sharply with price, and is close to zero among the low subsidy treatment group, as well as in the control group, which did not receive any subsidies. In Panel A, we present the experimental results and also compare them to two distinct "priors" on demand. The first curve (long-dashed line, black squares) plots our research team's predictions for take-up. These predictions were recorded in our 2014 pre-analysis plan and reflect our "best guess" of the demand curve; they were generated in part due to our need to make realistic budget predictions (since project grants financed the subsidies that households received). The second curve (long-dashed line, grey squares) plots the Ministry of Energy and Petroleum's internal predictions for take-up in rural Kenya. The government demand curve—which we learned of in early-2015 via a government report—was developed independently of our project and served as the justification for the planned LMCP price of \$171 (15,000 KES). A key finding is that, even at generous subsidy levels, actual take-up is significantly lower than predicted by the government or by our team.[22] In Panel B, we show that households with high-quality walls had substantially higher take-up rates in the medium and low subsidy arms, suggesting that demand increases at higher incomes.

In Table 3.2, we report the results of estimating the following regression equation:

$$y_{ic} = \alpha + \beta_1 T_c^L + \beta_2 T_c^M + \beta_3 T_c^H + X'_c\gamma + X'_{ic}\lambda + \epsilon_{ic} \tag{3.1}$$

where y_{ic} is an indicator variable reflecting the take-up decision for household i in transformer community c. The binary variables T_c^L, T_c^M, and T_c^H indicate whether community c was randomly assigned into the low, medium, or high subsidy arm, respectively, and the coefficients β_1, β_2, and β_3 capture the subsidy impacts on take-up.[23] Following Bruhn and McKenzie (2009), we include a vector of community-level characteristics, X_c, containing variables used for stratification during randomization (see Section 3.4.2). In addition, we include a vector of baseline household-level characteristics, X_{ic}, containing standard covariates (specified in our pre-analysis plan) that may also predict take-up, including household size, the number of chickens owned, respondent age, high-quality walls, and whether the respondent attended secondary school, is not a farmer, uses a bank account, engages in business or self-employment, and is a senior citizen. Standard errors are clustered by community, the unit of randomization.

[22] The government report projected take-up in rural areas nationally, rather than in our study region alone, and this is one possible source of the discrepancy, i.e., take-up might be higher (or lower) in other Kenyan regions.

[23] We focus on this non-parametric specification after rejecting the null hypothesis that the treatment coefficients are linear in the subsidy amount (F-statistic = 23.03), a choice we specified in our pre-analysis plan.

The results of estimating equation 3.1 are reported in Table 3.2, column 1. All three subsidy levels lead to significant increases in take-up: the 100 percent subsidy increases the likelihood of take-up by roughly 95 percentage points, and the effects of the partial 57 and 29 percent subsidies are much smaller, at 23 and 6 percentage points, respectively. Columns 2 to 4 include interactions between the treatment indicators and correlates of household economic status, including whether the household has high-quality walls, and the respondent attended secondary school and is not a farmer. Take-up in treatment communities is differentially higher in the low and medium subsidy arms for households with more educated and wealthier respondents.[24]

Based on the findings in Bernard and Torero (2015), one might expect take-up to be higher in areas where electricity is more prevalent if, as they argue, exposure to households with an electricity connection leads individuals to better understand its benefits and value it more. Yet when we include an interaction with the baseline community electrification rate in column 5, or an interaction with the proportion of neighboring households within 200 meters connected to electricity at baseline (column 6), we find no meaningful interaction effects.[25]

3.5.2. Estimating the economies of scale in electricity grid extension

An immediate consequence of the downward-sloping demand curve estimated above is that the randomized price offers generate exogenous variation in the proportion of households in a community that are connected as part of the same construction project. This novel design feature allows us to experimentally assess the economies of scale in electricity grid extension.

In Table 3.3, we report the results of estimating the impact of the number of connections, M_c, and a quadratic term, M_c^2, on the average total cost per connection ("ATC"), Γ_c. Specifically, we estimate the regression equation:

$$\Gamma_c = \pi_0 + \pi_1 M_c + \pi_2 M_c^2 + V_c' \mu + \eta_c \quad (3.2)$$

In the pre-analysis plan, we hypothesized that the ATC would fall with more connections (i.e. $\pi_1 < 0$), but at a diminishing rate (i.e. $\pi_2 > 0$), and we test this for two samples. The first sample (columns 1 to 3) consists of the 62 treatment communities in which we observed non-zero demand. The second sample (columns 4 to 7) also includes the additional 15 sites that were designed and budgeted for us by REA at even higher coverage levels (up to 100 percent). In columns 2, 3, 6, and 7, we also include a vector of community-level characteristics, V_c, which

[24] In Appendix Table C3, we compare the characteristics of households choosing to take up electricity across treatment arms. Households that paid more for an electricity connection (i.e., the low subsidy arm households) are wealthier on average than those who paid nothing (high subsidy), i.e., they are better educated, more likely to have bank accounts, live in larger households with high-quality walls, spend more on energy, and have more assets. In Appendix Tables C4A-C4B, we report all regressions specified in our pre-analysis plan, for completeness.

[25] Of course, this does not rule out the possibility of a differential effect at higher levels of electrification, since baseline household electrification rates are generally low in our sample of communities (the interquartile range is 1.8 to 7.8 percent). Also, since community-level characteristics, such as income, are likely positively correlated across households, the lack of statistically significant coefficients may reflect the joint impacts of negative take-up spillovers and positively correlated take-up decisions; future research could usefully explore these issues.

contains the community-level variables in X_c described above, as well as the round-trip distance between community c and the regional REA warehouse in Kisumu (a determinant of project transport costs), and the average land gradient for each 600-meter radius transformer community. Column 3 reports the results of an instrumental variables specification in which the experimental subsidy terms, T_c^M and T_c^H serve as instruments for the number of connections (M_c and M_c^2).[26]

The mean cost per connection in the data is $1,813.[27] The coefficients on M_c and M_c^2 are both statistically significant and large with the hypothesized signs, and are stable across the OLS and IV specifications. Within the domain of the first sample (which ranges from 1 to 16 connections per community), increasing project scale by a single household decreases the ATC by roughly $500, and costs reach a minimum at approximately 11 households. Within the second sample including the designed communities (which ranges from 1 to 85 connections), the estimated π_1 drops to roughly $84 and costs reach a minimum at approximately 55 households.

In column 5, we estimate the ATC as a quadratic function of community coverage, Q_c, which we define as the proportion of initially unconnected households in the community that become connected. We carry out this transformation (focusing on Q_c instead of M_c) because estimating the ATC in terms of community coverage will allow for a direct comparison of the demand curve to the cost curves in Section 3.5.3 below. In Figure 3.5, Panel A we plot the fitted curve from this regression on a scatterplot of ATC and community coverage. The quadratic function does not appear to provide a particularly good fit to the data visually: it predicts considerably lower costs at intermediate coverage levels while overstating them at nearly universal coverage, in large part because the functional form specified in the pre-analysis plan failed to include a fixed cost at the community level. We therefore estimate an alternative functional form for ATC featuring a fixed community cost and linear marginal costs:

$$\Gamma_c = \frac{b_0}{Q_c} + b_1 + b_2 Q_c \tag{3.3}$$

The nonlinear estimation of equation 3.3 yields coefficient estimates (and standard errors) of b_0= 2287.8 (s.e. 322.8) for the fixed cost, b_1= 1244.3 (s.e. 159.0), and b_2= -6.1 (s.e. 3.4). We plot the predicted values from this nonlinear estimation in Figure 3.5, Panel B, and then take the derivative of the total cost function (which is obtained by first multiplying equation 3.3 by Q_c) to estimate the linear marginal cost function:

$$MC_c = b_1 + 2b_2 Q_c \tag{3.4}$$

While this choice of functional form may appear somewhat arbitrary, we believe that imposing linear marginal costs is both economically intuitive (e.g., as coverage increases, the marginal cost of connecting an additional household decreases) and also closely matches the

[26] In our pre-analysis plan, we specified an IV regression that included three instrumented variables, M_c, M_c^2, and M_c^3. We dropped the third term because we were unable to acquire cost estimates for the control communities, which limited our sample to the treatment communities, and effectively limited our set of instruments to T_c^M and T_c^H.

[27] While this may seem high, recall that it is closely in line with Kenya Power's estimate of $1,435 per rural connection, as well as an internal estimate of $1,602 provided by the Ministry of Energy and Petroleum.

observed data. Regardless of the exact functional form, though, average costs decline in the number of households connected, as in the textbook natural monopoly case.[28] While there are strong initial economies of scale, we also document that the incremental cost savings appear to decline at higher levels of community coverage, and the estimates imply an average cost of approximately \$658 per connection at levels near universal coverage ($Q_c = 100$).

In communities with larger populations, the higher density of households may potentially translate into a larger impact of scale on ATC. In Table 3.3, column 7, we include interactions between scale and community population. While there are no statistically significant effects in the limited range of densities observed in our sample, it seems plausible that per household connection costs could be higher in other parts of rural Kenya with far lower rates of residential density (as shown in Appendix Table C1). There is also no evidence that higher average land gradient is associated with higher ATC.[29]

3.5.3. Social welfare calculations

In Figure 3.6, we compare the experimental demand curve with the average and marginal cost curves (Panel A), and then estimate total cost and consumer surplus at full coverage (Panel B) and at partial coverage using the estimated demand at the planned government LMCP connection price (Panel C). We first focus on the revealed preference demand estimates, and discuss issues of credit constraints and informational asymmetries below in Section 3.6.2.

The main observation is that the estimated demand curve for an electricity connection does not intersect the estimated marginal cost curve. To illustrate, at 100 percent coverage, we estimate the total cost of connecting a community to be \$55,713 based on the mean community density of 84.7 households. In contrast, consumer surplus at this coverage level is estimated based on the demand curve to be far less, at only \$12,421, or less than one quarter the costs. The consumer surplus is substantially smaller than total connection costs at all quantity levels, in fact, suggesting that rural household electrification may reduce social welfare.

Specifically, our calculations suggest that a mass electrification program would result in a welfare loss of \$43,292 per community.[30] In order to justify such a program, discounted future social welfare gains of \$511 would be required for each household in the community, above and beyond any economic or other benefits already considered by households in their own private

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[28] In Appendix Figure C8, we compare alternative functional forms, and the same conclusions hold across all cases.

[29] Based on Dinkelman (2011), we expect land gradient to be positively correlated with ATC. In our setting, the correlation is negative. In Appendix Table C5, we expand the reported results for columns 4 and 6 in Table 3.3, and report the results of a specification including interactions between scale and average land gradient. While the results are counterintuitive, note that there is little variation in average land gradient in our sample, which ranges from 0.79 to 7.76 degrees. Land gradient may be an important predictor of the costs associated with extending high-voltage lines to new areas in KwaZulu-Natal, South Africa, as in the Dinkelman (2011) case. Our data suggest that it is less important in predicting the costs of grid extensions across smaller areas. In Appendix Figure C7, we compare ATC curves for low and high gradient communities and again find no visual evidence of a meaningful difference.

[30] To calculate consumer surplus, we estimate the area under the unobserved [0, 1.3] domain by projecting the slope of the demand curve in the range [1.3, 7.1] through the intercept. The 1.3 percent figure is the proportion of the control group that chose to connect to the grid during the study period. In Appendix Figure C9, we estimate the welfare loss under alternative demand curve assumptions. In Panel C, the most conservative case, demand is a step function and intersects the vertical axis at \$3,000. The welfare loss is still \$32,517 per community in this case.

take-up decisions. These welfare gains could take a number of possible forms, including spillovers in consumption or broader economic production.

Credit constraints, or imperfect household information about the long-run benefits of electrification, may also contribute to lower demand, issues we turn to in the next section, while negative pollution externalities could raise the social costs of grid connections.

In an alternative scenario (Panel C), we estimate the demand for and costs of a program structured like the LMCP, which plans to offer households a connection price of $171. In this case, only 23.7 percent of households would accept the price based on our experimental estimates, and thus unless the government is willing to provide additional subsidies or possibly financing, the resulting electrification level would be low. At 23.7 percent coverage, there is an analogous welfare loss of $22,100 per community, or $1,099 per connected household.

3.6 Institutional and implementation challenges

The results in the previous section—suggesting that rural electrification may reduce social welfare—are perhaps surprising. Previous analyses have found substantial benefits from electrification (Dinkelman 2011, Lipscomb, Mobarak, and Barham 2013), though they have not compared benefits to costs. In the Philippines, Chakravorty, Emerick, and Ravago (2016) find that the physical cost of grid expansion is recovered after just a single year of realized expenditure gains. A World Bank report argues that household willingness to pay for electricity—which is calculated indirectly based on kerosene lighting expenditures—is likely to be well above the average supply cost in South Asia (World Bank 2008). The majority of these studies, however, use non-experimental variation or indirect measures of costs and benefits, and it is possible that they do not account for unobservables correlated with both electrification propensity and improved economic outcomes. In Table 3.1, for example, we document a strong baseline correlation between household connectivity and living standards, and this pattern is consistent with the possibility of meaningful omitted variable bias in non-experimental studies.

In this section, we consider factors that could drive down costs or drive up demand in our setting. Specifically, we present evidence on the role of excess construction costs from leakage, and reduced demand due to bureaucratic red tape, low grid reliability, credit constraints, and possibly unaccounted for spillovers in driving the social welfare results in the previous section.

3.6.1. Excess costs from leakage

In Table 3.4, we report the breakdown of budgeted versus invoiced electrification costs per community. The budgeted (ex-ante) costs for each project are based on LV network drawings prepared by a team of REA engineers.[31] The invoiced (ex-post) costs are based on actual final invoices submitted by local contractors, detailing the contractor components of the labor, transport, and materials that were required to complete each project. In total, it cost $585,999 to build 101.6 kilometers of LV lines to connect 478 households through the project.

[31] An example of an LV network drawing is provided in Appendix Figure C10.

We separate costs into three categories: (1) *Local network costs*, which consist of low- and high-voltage cables, wooden poles and the various components required to attach cables to poles, (2) *Labor and transport costs*, which include the cost of network design, installation, and transportation, and (3) *Service lines*, which are the drop-down cables connecting the homes.[32] Overall, budgeted and invoiced costs per connection were nearly identical, amounting to $1,201 and $1,226, respectively. In other words, contractors submitted invoices that were only 1.7 percent higher than the budgeted amount on average. The similarity between planned and actual costs provides further confidence that the connection costs for the designed communities at higher coverage levels are likely to be reasonably accurate.

These cost figures reflect the reality of grid extension in rural Kenya, but it is possible that they are higher than would ideally be the case due to leakage and other inefficiencies. Of course, leakage is common in the public sector in low income countries: Reinikka and Svenson (2004), for example, find that Ugandan schools received only 13 percent of a central government spending program. In our context, it is possible that leakage occurred during the contracting work, in the form of over-reporting labor and transport, which may be hard to verify, and sub-standard construction quality (e.g., using fewer materials than required). There is evidence of reallocations across the sub-categories in Table 3.4, despite the similarities between ex ante and ex post totals. Invoiced labor and transport costs, for example, were 12.7 percent higher in fact than expected in the plans, while invoiced local network costs were 6.5 percent lower.

We sent teams of enumerators to each treatment community to count the number of electricity poles that were actually installed, and then compare the actual number of poles to the poles included in the project designs in order to gain additional insight on leakage. We find strong evidence of leakage in the form of missing electrical poles. In Figure 3.7, we plot the discrepancies between costs and poles by contractor, where each circle represents one of the 14 contractors participating in the project, and the size of each circle is proportional to the number of household connections supplied by that contractor. While there is minimal variation between overall ex-ante and ex-post total costs, as depicted on the horizontal axis, most contractors' projects showed large differences in the number of observed versus budgeted poles, as depicted on the vertical axis, with nearly all using fewer poles than budgeted. The number of observed poles was 21.3 percent less than the number of budgeted poles, a substantial discrepancy.

In addition to being associated with wastage of public resources, if the planned number of poles reflects accepted engineering standards (i.e., poles are roughly 50 meters apart, etc.), using fewer poles might lead to substandard service quality and even safety risks. For instance, local households may face greater injury risk due to sagging power lines between poles that are spaced too far apart, and the poles could be at greater risk of falling over. It is possible, however, that REA's designs included extra poles, perhaps anticipating that contractors would not use them all.

Labor and transport costs may also reflect leakage. Labor is typically invoiced based on the number of declared poles, and we showed above that those were inflated. Similarly, transport is invoiced based on the declared mileage of vehicles carrying construction materials. In Appendix Table C6, we analyze three highly detailed contractor invoices (for nine communities) that were

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[32] In Table 3.4, we exclude the costs of metering (incurred by Kenya Power) and ready-boards. Including them would not alter the main conclusions since they are the same for all connected households and a small share of total costs.

made available to us. Based on this partial data, we find evidence of over-reported labor costs associated with the electricity poles, at 11.0 percent higher costs than expected, and massively over-reported transport costs: based on a comparison between the reported mileage and the travel routes between the REA warehouse and project sites suggested by Google Maps, invoiced travel costs were 32.9 percent higher than expected.

Taken together, these findings suggest that electric grid construction costs may be substantially inflated due to mismanagement and corruption in Kenya, pointing to the possibility that improved monitoring and enforcement of contractors could reduce costs and possibly improve project quality and safety.[33] On the other hand, note that even with a 20 to 30 percent reduction in construction costs, mass rural household electrification would still lead to a reduction in overall social welfare based on the demand and cost estimates in Figure 3.6.

3.6.2. Factors contributing to lower demand for electricity connections

We next discuss several factors that potentially contribute to lower levels of observed household demand for electricity connections, including bureaucratic red tape, low grid reliability, credit constraints, and unaccounted for positive spillovers.

Long delays in the delivery of electricity services are common in rural Kenya, and low levels of demand may be attributable, in part, to the lengthy and bureaucratic process of obtaining a connection. In our sample, it took a staggering 212 days on average to complete each community project. The World Bank similarly estimates that in practice it takes roughly 110 days to connect new business customers to the electricity grid in Kenya (World Bank 2016).

Figure 3.8 summarizes the time required to complete each major phase associated with obtaining a rural household grid connection in Kenya. The timeline is presented in two panels; Panel A reflects the experience of households, and Panel B reflects supplier performance.[34] From the household's perspective, we identified three phases in the connection process: Payment (A1), Wiring (which also includes submitting a metering application to Kenya Power) (A2), and Waiting (A3). Unexpected delays occurred during the wiring phase, which on average took 24 days, due to complications created by requirements for households to register for Kenya Revenue Authority certificates, spelling mistakes on wiring certificates, and communication breakdowns between REA and Kenya Power; see Appendix Note C3 for details. On average, households waited 188 days, after submitting all of their paperwork, before they began receiving electricity.

From the supplier's perspective, we identified four phases: Design (B1), Contracting (B2), Construction (B3), and Metering (B4). REA completed the design and contracting work, independent contractors (hired by REA) completed the physical construction, and Kenya Power educated households on issues relating to safety, and installed and activated the prepaid meters. The longest delays occurred during the design phase, which took an average of 57 days, and the metering phase, which took 68 days on average. The design phase was adversely affected by

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[33] To the extent costs are high because contractors are over-billing the government, leakage may simply result in a transfer across Kenyan citizens and not a social welfare loss. The social welfare implications would depend on the relative weight the social planner places on contractors, taxpayers, and rural households.

[34] In Appendix Table C7, we document the full list of reasons for the delays encountered during each phase.

competing priorities at REA.[35] There were severe delays during the metering phase due to unexpected issues at Kenya Power, such as insufficient materials (i.e., reported shortages in prepaid meters), lost meter applications, and competing priorities for Kenya Power staff. Additional problems slowed the process as well. For several months, there was a general shortage of construction materials and metering hardware at REA storehouses. In the more remote communities, heavy rains created impassable roads. Difficulties in obtaining wayleaves (i.e., permission to pass electricity lines through other private properties) required redrawing network designs, additional trips to the storehouse, and further negotiations with contractors. In some cases, households that had initially declined a “ready board” changed their minds; in an unfortunate case lightning struck, damaging a household’s electrical equipment; and so on. While these problems increased completion times, their negative effects were almost certainly offset (at least partially) by the weekly and persistent reminders sent to REA and Kenya Power by our project staff, meaning the situation for other rural Kenyans could be even worse.[36]

This experience highlights some common issues and the bureaucratic red tape that can delay the provision of electricity services in rural Kenya. The bottom line is that low observed demand for electricity connections may be due in part to households’ expectations that they would encounter these sorts of lengthy delays.

Another major concern is the reliability of power. Electricity shortages and other forms of low grid reliability are well documented in less developed countries (Steinbuks and Foster 2010; Allcott, Collard-Wexler, and O’Connell 2016). In rural Kenya, households experience both short-term blackouts, which last for a few minutes up to several hours, and long-term blackouts, which can last for months and typically stem from technical problems with local transformers. During the 14-month period between September 2014 and October 2015 when households were being connected to the grid, we documented the frequency, duration, and primary reason for the long-term blackouts impacting our sample of communities. In total, 29 out of 150 transformers (19 percent) experienced at least one long-term blackout. On average, these blackouts lasted four months, with the longest blackout lasting an entire year. During these periods, households and businesses did not receive any grid electricity. The most common reasons included transformer burnouts, technical failures, theft, and replaced equipment.[37] It seems obvious that the value a household places on a grid connection could be substantially lower when service is this unreliable. As a point of comparison, only 0.2 percent of transformers in California failed over the past five years, with the average blackout lasting a mere five hours.[38] That said, there is no strong statistical evidence that a history of recent blackouts affects demand in the data: column 7 in Table 3.2 includes interactions between the treatment subsidy indicators and an indicator for whether any household in the community reported a recent blackout (i.e., over the past three days) at baseline, but finds no statistically significant effects.

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[35] In June 2014, the government announced a program to provide free laptops for all Primary Standard 1 students nationwide. Since roughly half of Kenya’s primary schools were unelectrified at the time of the announcement, there was political pressure on REA to prioritize connecting the remaining unelectrified primary schools during the 2014-15 fiscal year. As a result, fewer REA designers were available to focus on other projects, including ours.

[36] At various points in the overall connection process, field enumerators reported that the electricity connection work may have been delayed due to expectations that bribes would be paid.

[37] In Appendix Table C8, we provide a full list of all of the communities that experienced long-term blackouts.

[38] Based on personal communications with Pacific Gas and Electric Company (PG&E) in December 2015.

Low demand may also be driven in part by household credit constraints, which are well documented in developing countries (De Mel, McKenzie, and Woodruff 2009; Karlan et al. 2014). In Figure 3.9, we compare the experimental results to two sets of stated willingness to pay results obtained in the baseline survey to shed some light on this issue. Stated willingness to pay might better capture household demand in the absence of credit constraints, although this is certainly debatable, since they might also overstate actual demand due to wishful thinking or social desirability bias (Hausman 2012).

Respondents were first asked whether they would accept a randomly assigned, hypothetical price—ranging from \$0 to \$853—for a grid connection.[39] Households were then asked whether they would accept the hypothetical offer if required to complete the payment in six weeks, a period chosen to be similar to the eight week payment period in the experiment. In Panel A, the first curve (long-dashed line, black squares) plots the results of the initial question. The second curve (long-dashed line, grey squares) plots the results of the follow-up question.

Stated demand is generally high. However, the demand curve falls dramatically when households are faced with a hypothetical time constraint, suggesting that households are unable to pay (or borrow) the required funds on relatively short notice, a strong indication that credit constraints are often binding, although an alternative interpretation is that the hypothetical question without time constraints generates exaggerated demand figures.[40] At a price of \$171, for example, stated demand is initially 57.6 percent but it drops to 27.2 percent with the time constraint. Although the experimental demand curve is substantially lower than the stated demand without time limits, it closely tracks the constrained stated demand: at \$171, actual take-up in the experiment is 23.7 percent. The difference between the two contingent valuation results is consistent with the well-documented evidence on hypothetical bias (Murphy et al. 2005; Hausman 2012). However, the similarity between the constrained stated demand and experimental results suggest that augmenting standard stated preference survey questions to incorporate realistic timeframes and other contextual factors could help to elicit responses that more closely resemble revealed preference behavior.

We also regressed a binary variable indicating whether a household first accepted the hypothetical offer without the time constraint, but then declined the offer with the time constraint. Households with low-quality walls and respondents with no bank accounts are the most likely to switch their stated demand decision when faced with a pressing time constraint, consistent with the likely importance of credit constraints for these groups.[41]

In Section 3.5.3 above, we combined the experimental demand and cost curves and show that rural electrification may reduce social welfare. The stated preference results indicate that this outcome is likely to hold even if credit constraints were eased. For example, if we combine the cost curve with the stated demand for grid connections without time constraints, then all of the

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[39] Each of \$114, \$171, \$227, \$284, and \$398 had a 16.7 percent chance of being drawn. Each of \$0 and \$853 had an 8.3 percent chance of being drawn. Nine households are excluded due to errors in administering the question.

[40] In Appendix Table C9A, we estimate the impact of the hypothetical offers on take-up. In Appendix Table C9B, we include interactions between the hypothetical offer indicators and key household covariates. In Appendix Figure C11, we plot hypothetical demand curves for households with and without bank accounts and high-quality walls.

[41] We report the results of this regression in Appendix Table C9C. As specified in our pre-analysis plan, we include a formal comparison of the stated willingness to pay and experimental curves in Appendix Table C9D.

households in the unobserved [0, 16.7] domain of the stated demand curve (i.e., those willing to pay at least $853) must be willing to pay on average $2,920 in order for consumer surplus to be larger than total construction costs. While we cannot rule out that this is true, it appears unlikely in a rural setting where annual per capita income is below $1,000 for most households.

One way to address credit constraints is to offer financing plans for grid connections. In a second set of baseline stated willingness to pay questions, each household was randomly assigned a hypothetical credit offer consisting of an upfront payment (ranging from $39.80 to $127.93), a monthly payment (ranging from $11.84 to $17.22), and a contract length (either 24 or 36 months); we provide details in Appendix Table C10. Households were first asked whether they would accept the offer (short-dashed line, black circles), and then whether they would accept the offer if required to complete the upfront payment in six weeks (short-dashed line, grey circles). In Figure 3.9, Panel B, we plot take-up against the net present value of the credit offers based on a reasonable though somewhat arbitrary annualized discount rate of 15 percent.[42]

When households are offered financing, stated demand is not only high but also appears likely to be exaggerated, particularly when there are no time constraints to complete the upfront payments. For example, 52.7 percent of households accepted the $915.48 net present value offer, a package that consists of an upfront payment of $127.93 and monthly payments of $26.94 for 36 months (see Appendix Table C10). Eight weeks after accepting such an offer, a borrower will have paid $181, with an additional $915.92 due in the future. Yet stated demand for this option is twice as high as what we actually observe for the $171 time-limited, all-in price offered to medium subsidy arm households in the experiment.

In Panel C, we combine the four stated demand curves with the experimental demand and average total cost curves. Visually, the only demand curves that appear to yield consumer surpluses that are potentially larger than total construction costs are the stated demand curves for grid connections with credit offers, which as we point out above, could be overstated. While not definitive, these patterns do not appear to overturn the basic observations above.

Finally, low demand may indicate that even with subsidies, grid connections are simply too expensive for many of the poor, rural households in our setting. After the experiment, we asked households that were connected in the low and medium subsidy arms to name any sacrifices they had made in order to complete their payments: 29 percent of households stated that they had forgone purchases of basic household consumption goods, and 19 percent stated that they had not paid school fees. It seems likely that many of the households that declined the subsidized offer did so due to binding budget constraints.

3.6.3. Is rural electrification a socially desirable policy?

The leading interpretation of our main empirical findings is that mass rural household electrification does not improve social welfare in Kenya, according to standard criteria. The cost of electrifying households appears to be at least four times higher than what households are willing and able to pay for these connections, and consumer surplus appears lower than total costs even with demand estimates that attempt to address credit constraints. While per household

[42] A range of discount rates and net present values is provided in Appendix Table C10, with largely similar results.

costs fall sharply with coverage levels, reflecting the large economies of scale in the creation of local grid infrastructure, they remain far higher than demand, implying that social welfare falls with each additional subsidized connection.

However, there may be additional benefits that are not captured by household willingness to pay. First, as outlined in Section 3.2.2, there may be spillovers from private grid connections, including any benefits that unconnected households experience from being in close proximity to connected households. If these spillovers are positive and sufficiently large, take-up rates may be lower in communities with relatively high electrification rates at baseline, if households prefer to free ride on their neighbors' power. Yet in Section 3.5.1 above, we find no meaningful evidence of an interaction between the treatment indicators and either the overall baseline community electrification rate, or the proportion of neighboring households (within 200 meters) connected to electricity at baseline. This evidence is at best suggestive, however, since we cannot rule out the possibility that any negative effect of these spillovers on take-up is offset by a competing positive "keeping up with the neighbors" mechanism, as argued in Bernard and Torero (2015), or that greater learning about the private benefits of electricity and/or correlated household characteristics are present in addition to negative spillovers. Future research that directly measures the magnitude of household electrification spillovers, in terms of both usage and impacts on outcomes, would be useful in disentangling these factors.

Second, households may have limited information about the future income or broader welfare benefits of electrification, leading them to under-invest. Furthermore, there may be imperfect within-household altruism with respect to the benefits of electricity. Perhaps children stand to gain the most from indoor lighting in the evening, as it allows them to study and learn more, boosting their future earnings potential, but their parents do not fully understand these gains or incorporate them into their decision-making. Grid connections are long-lived, but their long-term benefits may not be fully reflected in willingness to pay if households are liquidity constrained, poorly informed, or face internal agency problems.

However, several other factors that we have not addressed may push up costs, making rural electrification less attractive. For example, access to modern energy could generate a number of negative environmental externalities. The impact on social welfare will therefore depend on the extent to which higher energy consumption results in greater CO_2 emissions and other forms of pollution. Moreover, we have considered neither the costs nor economic impact of the initial investment to extend the high-voltage lines and install transformers in each community. Each transformer in our sample was set up to provide electricity to a critical public facility, such as a market, secondary school, or health clinic. Each installation required a large investment—the median cost of each deployed transformer is $21,820 (Lee et al. 2016)—and the welfare gains from powering such facilities, while potentially quite large, have not been precisely measured. Our analysis treats these costs as sunk and focuses solely on the economics of electrifying "under grid" households, conditional on existing infrastructure. Given the growing support for large-scale policies to boost energy access, such as Kenya's planned LMCP, this is the policy-relevant question in our setting, but the broader costs of transformer installations would need to be considered in many other African and South Asian contexts.

3.7 Conclusion

Over the past century, rural electrification has served as a key benchmark for economic development and social progress. The United States began its mass rural electrification program in the late-1930s, though it required two decades to reach 90 percent of households (Kitchens and Fishback 2015), China did so in the 1950's, and South Africa launched its initiative in the 1990s, eventually reaching 49 percent.[43] Today, access to affordable and reliable energy has emerged as a major political issue across many countries in Sub-Saharan Africa and South Asia, as they aim to repeat the successes of earlier mass electrification programs.

However, the extent to which increases in energy access should be driven by investments in large-scale infrastructure, such as grid connections, or small-scale decentralized solutions, such as solar lanterns and solar home systems, remains contested. Does Africa's energy future even lie with the grid? Although our findings suggest that household electrification may reduce social welfare, they do not necessarily imply that distributed solar systems are any more attractive than the grid, or that the patterns we identify are universal across time and space. In fact, the evidence—on inflated construction costs from leakage, and the pervasiveness of bureaucratic red tape, low grid reliability, and household credit constraints, all of which would suppress demand—suggests that the social welfare consequences of rural electrification are closely tied to organizational performance as well as economic and political institutions. Settings with better performance by the electricity utility—with fewer losses due to leakage and service that is more responsive to customers—may see shifts in both the cost curve and the demand side, and in such a setting mass rural electrification may indeed be the socially optimal policy. Another possibility is that mass electrification is indeed transformative and reshapes social, political, and economic interactions, perhaps in the long-run, but individual rural households do not internalize these benefits and they are thus not reflected in private demand estimates.

Decisions to invest in large-scale energy infrastructure programs are associated with major opportunity costs and long-run consequences for future economic development and climate change, especially in Sub-Saharan Africa, where access to electricity lags the rest of the world. Our findings indicate that connecting rural households is not necessarily an economically productive and high return activity in the world's poorest countries. The social returns to investments in transportation, education, health or other sectors—indeed possibly including the electrification of industrial sites or urban areas—need to be compared to investments in rural electricity grid expansion to determine appropriate public policy choices. Given the high stakes around these policy decisions, and the limited evidence base, there is a need for further research in a number of areas, including estimating the economic and broader social impacts of electric grid connections (as well as any community and regional spillovers), identifying the patterns and drivers of subsequent consumption demand, including for energy-efficient appliances, and determining routes to improved grid reliability and electric utility organizational performance.

[43] In Appendix Table C11, we summarize historical rural electrification initiatives across several countries.

Table 3.1—Differences between electricity grid unconnected vs. grid connected households at baseline

	Unconnected (1)	Connected (2)	p-value of diff. (3)
Panel A: Household head (respondent) characteristics			
Female (%)	62.9	58.6	0.22
Age (years)	52.3	55.8	< 0.01
Completed secondary schooling (%)	13.3	45.1	< 0.01
Married (%)	66.0	76.7	< 0.01
Not a farmer (%)	22.5	39.5	< 0.01
Basic political awareness (%)	11.4	36.7	< 0.01
Has bank account (%)	18.3	60.9	< 0.01
Panel B: Household characteristics			
Number of members	5.2	5.3	0.76
Youth members (age ≤ 18)	3.0	2.6	0.01
High-quality walls (%)	16.0	80.0	< 0.01
Land (acres)	1.9	3.7	< 0.01
Distance to transformer (m)	356.5	350.9	0.58
Monthly (non-charcoal) energy (USD)	5.5	15.4	< 0.01
Panel C: Household assets			
Bednets	2.3	3.4	< 0.01
Sofa pieces	6.0	12.5	< 0.01
Chickens	7.0	14.3	< 0.01
Radios	0.35	0.62	< 0.01
Televisions	0.15	0.81	< 0.01
Sample size	2,289	215	

Notes: Columns 1 and 2 report sample means for households that were unconnected and connected at the time of the baseline survey. Column 3 reports p-value of the difference between the means. Basic political awareness indicator captures whether the household head was able to correctly identify the presidents of Tanzania, Uganda, and the United States. In the 2013 census of all unconnected households, just 5% of rural households were connected to the grid. In our sample of respondents, we oversampled the number of connected households.

Table 3.2—Impact of grid connection subsidy on take-up of electricity connections

		Interacted variable					
		High-quality walls	Attended secondary school	Not a farmer	Baseline electrification rate	Baseline neighbors connected	Report of blackout in past 3 days
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
T1: Low subsidy—29% discount	5.94***	3.57**	4.55***	5.36***	5.56**	4.80**	6.11**
	(1.50)	(1.46)	(1.38)	(1.59)	(2.20)	(1.90)	(2.61)
T2: Medium subsidy—57% discount	22.88***	21.30***	19.79***	20.10***	21.36***	21.38***	18.66***
	(4.02)	(4.41)	(3.80)	(4.59)	(6.18)	(3.51)	(5.11)
T3: High subsidy—100% discount	94.97***	95.61***	95.18***	94.88***	97.51***	96.11***	95.11***
	(1.27)	(1.17)	(1.32)	(1.38)	(1.75)	(1.31)	(2.43)
Interacted variable		0.26	-1.00	-0.75	0.14	0.05	-0.94
		(1.35)	(1.45)	(0.91)	(0.11)	(0.05)	(1.31)
T1 × interacted variable		12.26**	10.22	2.37	0.05	0.19	-0.18
		(6.15)	(7.00)	(3.61)	(0.18)	(0.19)	(3.13)
T2 × interacted variable		8.85	19.54***	13.46*	0.29	0.31	7.58
		(7.77)	(4.62)	(7.71)	(1.21)	(0.23)	(7.80)
T3 × interacted variable		-5.50	-4.28	0.31	-0.49*	-0.21	-0.22
		(3.91)	(4.92)	(2.40)	(0.30)	(0.14)	(2.78)
Take-up in control group	1.30	1.30	1.30	1.30	1.30	1.30	1.30
Observations	2176	2176	2176	2176	2176	2176	2176
R-squared	0.69	0.69	0.70	0.69	0.69	0.69	0.69

Notes: The dependent variable is an indicator variable (multiplied by 100) for household take-up. The mean of the dependent variable is 21.6. Robust standard errors clustered at the community level in parentheses. All specfications include the household and community covariates specified in the pre-analysis plan. Column 6 includes interactions with the proportion of neighbors (i.e., within 200 meters) connected to electricity at baseline. Column 7 includes interactions with an indicator for whether any household in the community reported a recent blackout (i.e., in the past three days) at baseline. Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$. The number of observations in the above regressions is somewhat smaller than the total number of households in our sample (2,289) due to missing data.

Table 3.3—Impact of scale on average total cost (ATC) per household connection

	Sample—OLS & IV						
	OLS		IV	Sample & Designed—OLS			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Number of connections (M)	-472.43***	-510.07***	-492.53**	-87.77***		-81.11***	-96.68***
	(88.60)	(88.01)	(198.98)	(15.11)		(16.45)	(17.99)
M^2	20.40***	23.17***	22.05*	0.83***		0.76***	1.05***
	(5.28)	(5.27)	(11.66)	(0.18)		(0.20)	(0.24)
Community coverage (Q)					-84.34***		
					(12.55)		
Q^2					0.75***		
					(0.13)		
Population							-0.46
							(0.97)
Population × M							0.02
							(0.08)
Population × M^2 / 100							-0.10
							(0.09)
Community controls	No	Yes	Yes	No	No	Yes	Yes
Mean of dep. variable (USD)	1813	1813	1813	1633	1633	1633	1633
S.D. of dep. variable	1113	1113	1113	1065	1065	1065	1065
Observations	62	62	62	77	77	77	77
R^2	0.63	0.71	–	0.43	0.46	0.48	0.52

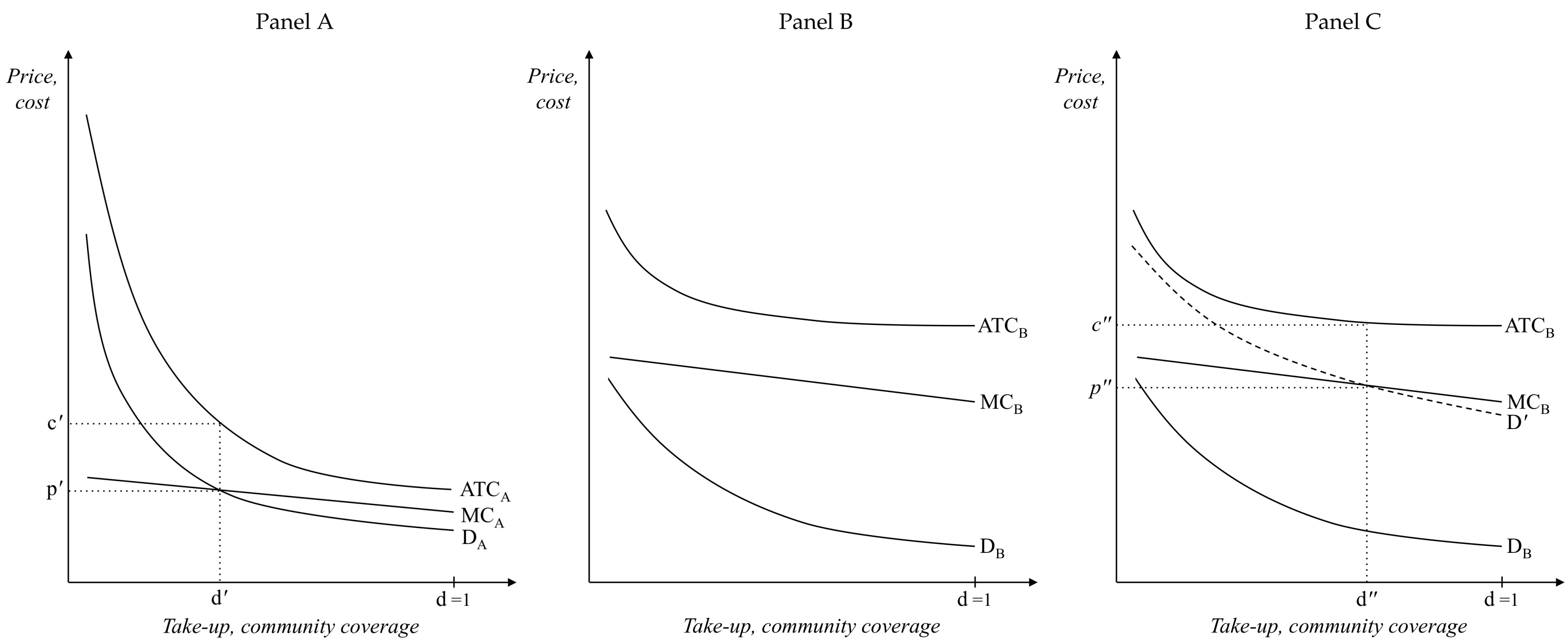
Notes: The dependent variable is the budgeted average total cost (ATC) per connection in USD. Since there was no takeup in 13 communities, the sample size is 62. In column 3, polynomials for the number of grouped connections, M and M^2, are instrumented with T^M and T^H, binary variables indicating whether the community was randomly assigned into the medium and high subsidy treatment arms, respectively. Robust standard errors are clustered at the community level. Community coverage (Q) is defined as the proportion of unconnected households that are ultimately connected (multiplied by 100). Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

Table 3.4—Costs of infrastructure construction associated with electricity connection projects

	Budgeted		Invoiced			Difference	
	Total	Per HH	Total	Per HH	Allocation	Amount	%
Panel A: Project costs (reported)							
Local network	383,207	798	358,235	749	61.1%	-24,972	- 6.5%
Labor and transport	177,457	370	200,080	419	34.1%	22,623	12.7%
Service lines	15,812	33	27,684	58	4.7%	11,873	75.1%
Total cost	576,476	1,201	585,999	1,226	100.0%	9,523	1.7%
Panel B: Project materials (reported and observed)			Observed				
Electricity poles	1,449	3.0	1,141	2.4	–	-308	-21.3%

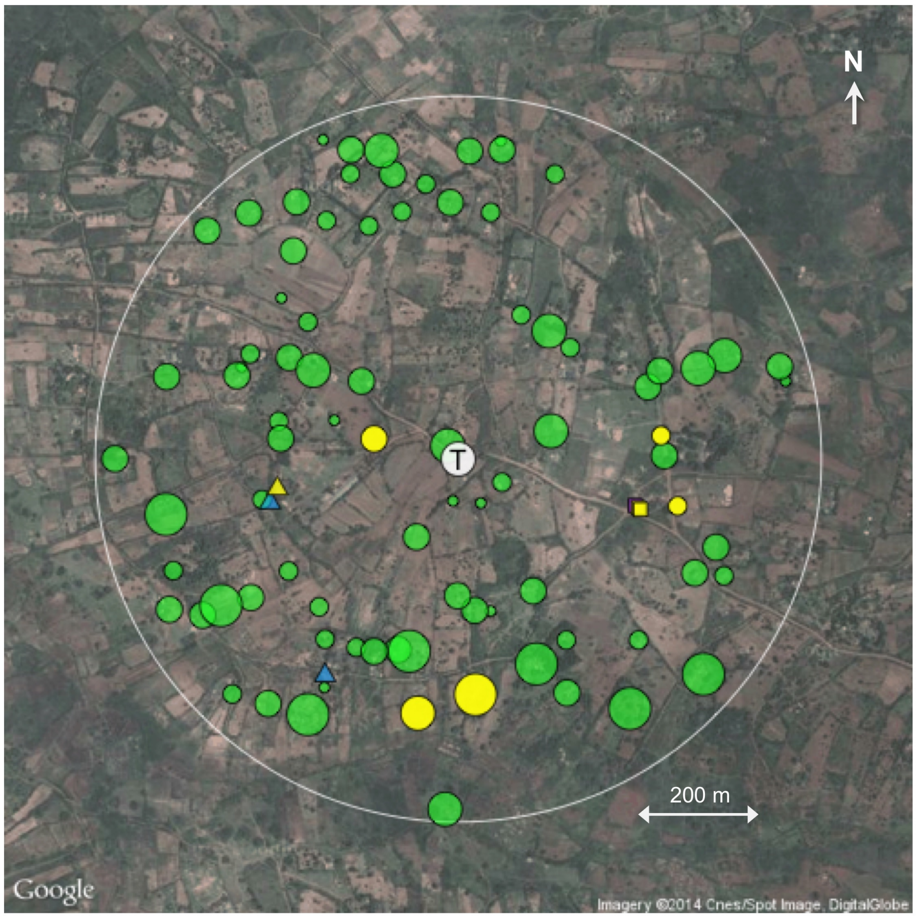
Notes: In Panel A, project costs are reported in USD and consist of administrative budgeted estimates and final invoiced amounts. "Local network" consists of high- and low-voltage electricity poles and cables. "Labor and transport" also includes design work and small contingency items. "Service lines" are typically single "drop-down" cables that connect households to an electricity line. Kenya Power metering costs and houshold wiring costs are not included in this summary. In total, the project involved roughly 101.6 km of new low-voltage lines. In Panel B, we compare the budgeted number of electricity poles to the actual number of poles that were observed to have been installed.

Figure 3.1—The electric utility as a natural monopoly



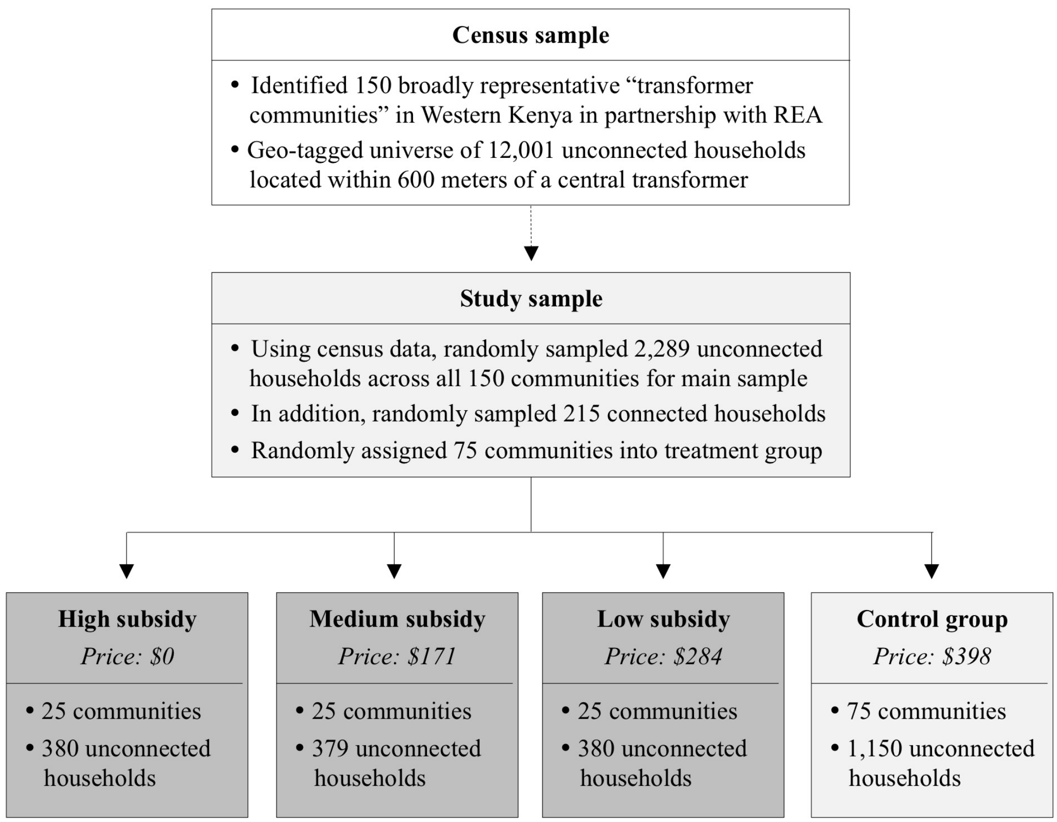
Notes: In Panel A, the electric utility is a natural monopoly facing high fixed costs, decreasing marginal costs (MC_A), and decreasing average total costs (ATC_A). In this case, MC_A intersects demand at d′ and a government-subsidized mass electrification program can increase social welfare. Panel B illustrates an alternative case in which D_B does not intersect MC_B. In this case, a mass electrification program would not increase welfare unless there are, for example, positive externalities from private electricity connections. Panel C illustrates this scenario in which social demand (D′) intersects MC_B at d″.

Figure 3.2—Example of a “transformer community” of typical density



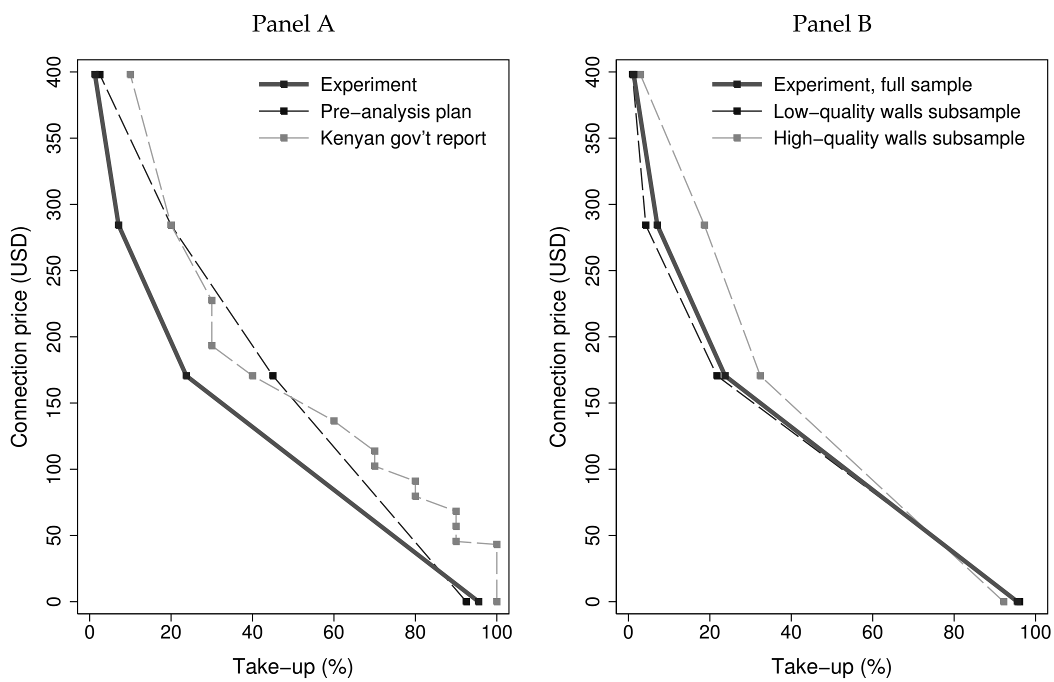
Notes: The white circle labeled T in the center identifies the location of the REA transformer. The larger white outline demarcates the 600-meter radius boundary. Green circles represent unconnected households; purple squares represent unconnected businesses; and blue triangles represent unconnected public facilities. Yellow circles, squares, and triangles indicate households, businesses, and public facilities with visible electricity connections, respectively. Household markers are scaled by household size, with the largest indicating households with more than ten members, and the smallest indicating single-member households. In each community, roughly 15 households were randomly sampled and enrolled into the study. The average density of a transformer community is 84.7 households per community and the average minimum distance between buildings (i.e., households, businesses, or public facilities) is 52.8 meters. In the illustrated community, there are 85 households.

Figure 3.3—Experimental design



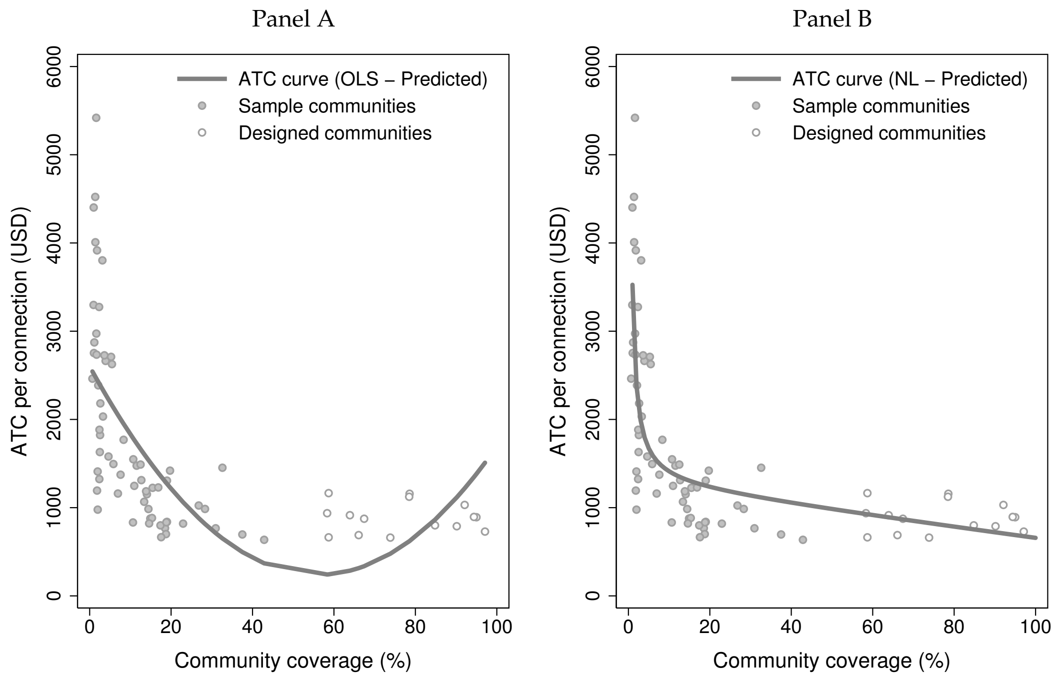
Notes: The 150 transformer communities in our sample covered 62.2% of the universe of REA projects in Busia and Siaya counties in August 2013. See Appendix for details on the community selection procedure. Each transformer community is defined as the group of all households located within 600 meters of a central electricity distribution transformer. All households within 600 meters of a transformer are eligible to apply for an electricity connection. In each of the 150 communities, roughly 15 unconnected households were randomly sampled (using a computer random number generator) and enrolled into our study. Census data on the universe of unconnected households were used as a sampling frame. Baseline surveys were also administered to a random sample of 215 households already connected at baseline. Communities were randomly assigned into three treatment arms and a control group. Treatment offers were distributed in two waves, between May and August 2014, and were valid for eight weeks.

Figure 3.4—Experimental evidence on the demand for rural electrification



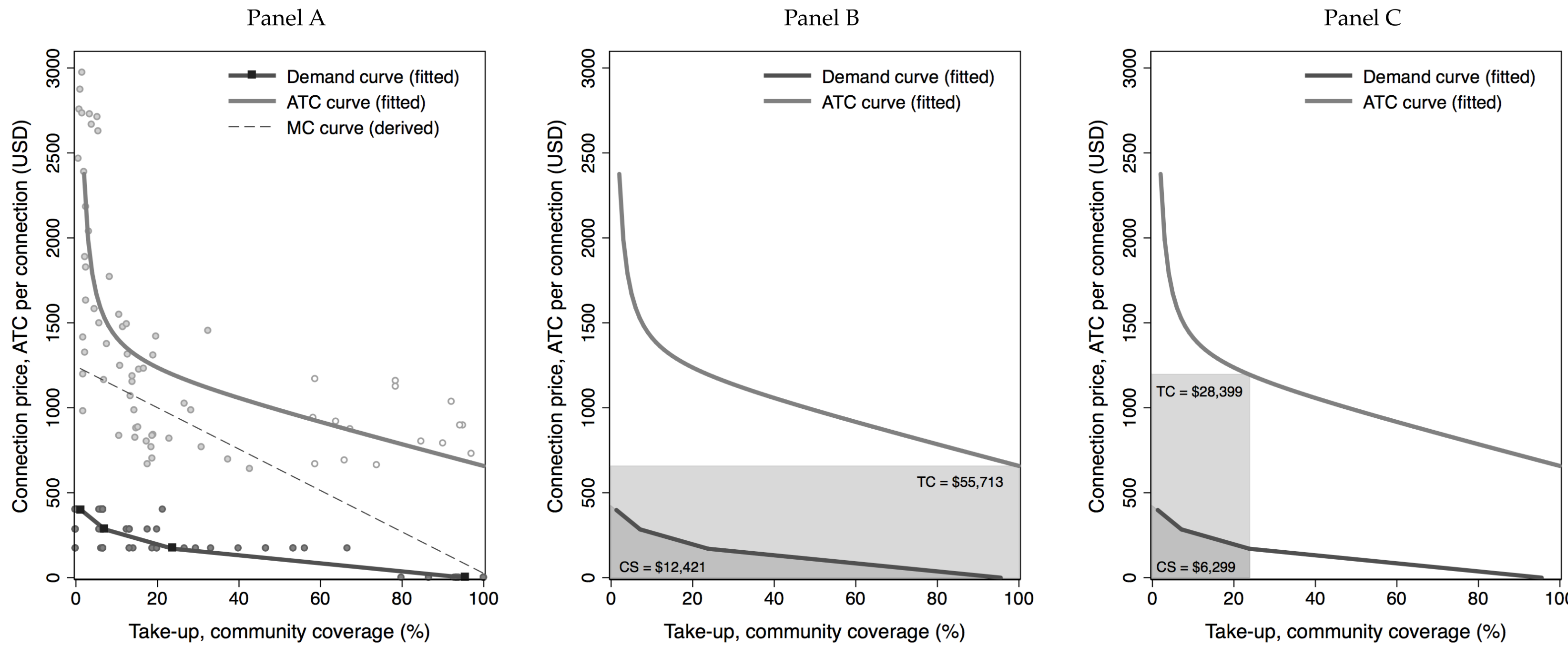
Notes: Panel A compares the experimental results with two sets of initial assumptions based on (i) our pre-analysis plan (available at https://www.socialscienceregistry.org/trials/350), and (ii) an internal government report shared with our team in early-2015. Panel B plots the results separately for households with low- and high-quality walls.

Figure 3.5—Experimental evidence on the costs of rural electrification



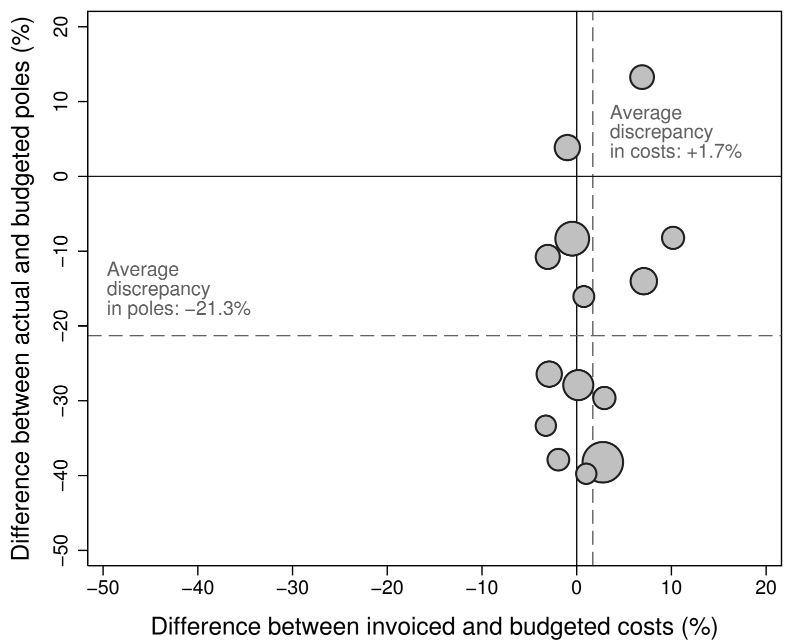
Notes: The above figures plot budgeted estimates of the average total cost (ATC) per connection at various levels of community coverage (i.e., electrification) for both sample and designed communities. Panel A displays the fitted curve from the regression reported in Table 3.3, column 5. Panel B displays predicted vaues from the nonlinear estimation of $ATC = b_0/Q + b_1 + b_2Q$.

Figure 3.6—Experimental estimates of the welfare implications of rural electrification



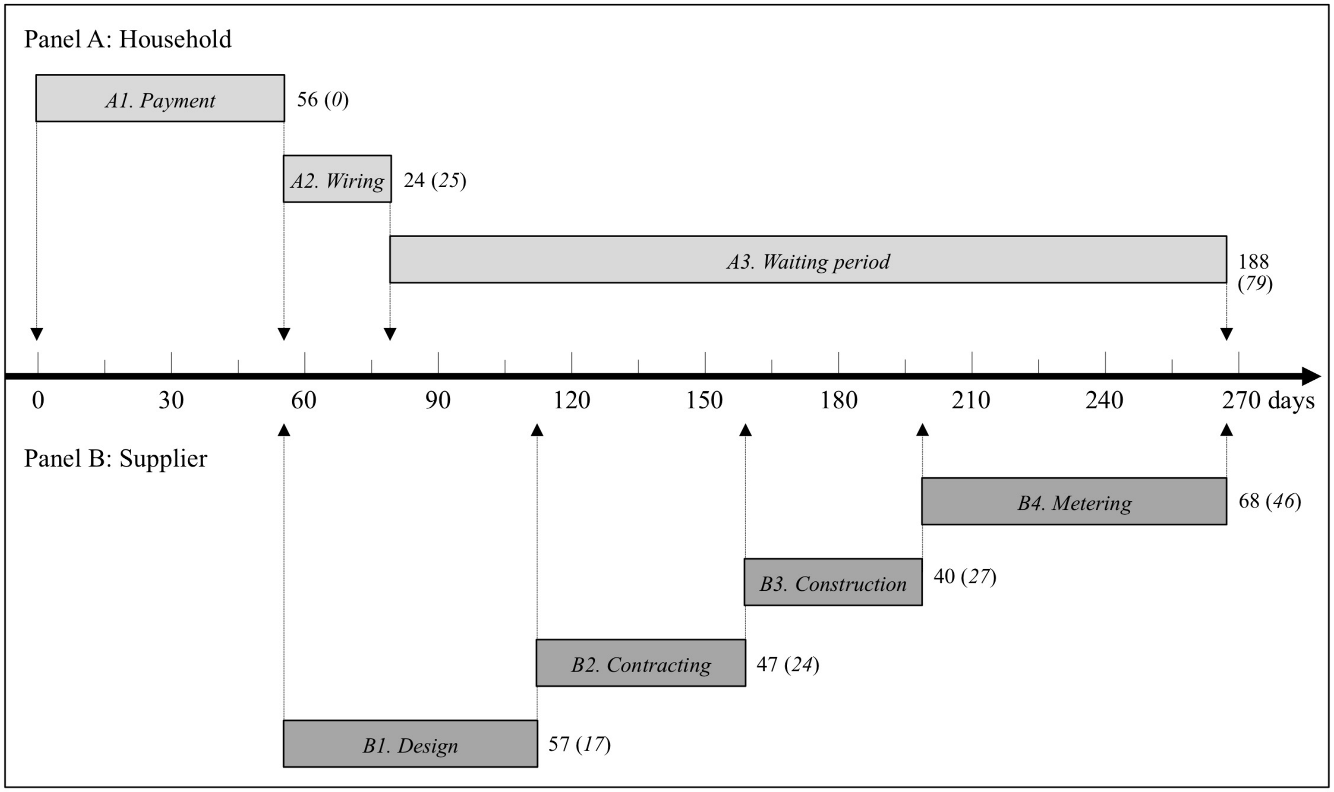
Notes: Panel A combines the experimental demand curve from Figure 3.4 with the experimental average total cost (ATC) curve from Figure 3.5, Panel B. The marginal cost (MC) curve is generated by taking the derivative of the estimated total cost function. Panel B estimates the total cost of fully saturating a community at the cheapest ATC to be $55,713, based on average community density of 84.7 households. Similarly, we estimate the area under the demand curve to be $12,421. The area under the unobserved [0, 1.3] domain is estimated by projecting the [1.3, 7.1] demand curve through the intercept. Results are robust to alternative assumptions regarding demand in the unobserved [0, 1.3] domain (see Appendix Figure C8). Calculations suggest that a mass electrification program would result in a welfare loss of $43,292 per community. In order to justify such a program, discounted average future welfare gains of $511 in social and economic impacts would be required per household. Panel C presents the estimated demand for and costs of a program structured like the planned *Last Mile Connectivity Project*, which offers households a fixed price of $171. In this case, only 23.7% of households would accept the price, and unless the government is willing to provide additional subsidies, the resulting electrification level would be low and there would be a welfare loss of $22,100 per community. Discounted average future welfare gains of $1,099 would be required per household.

Figure 3.7—Discrepancies in project costs and electrical poles, by contractor



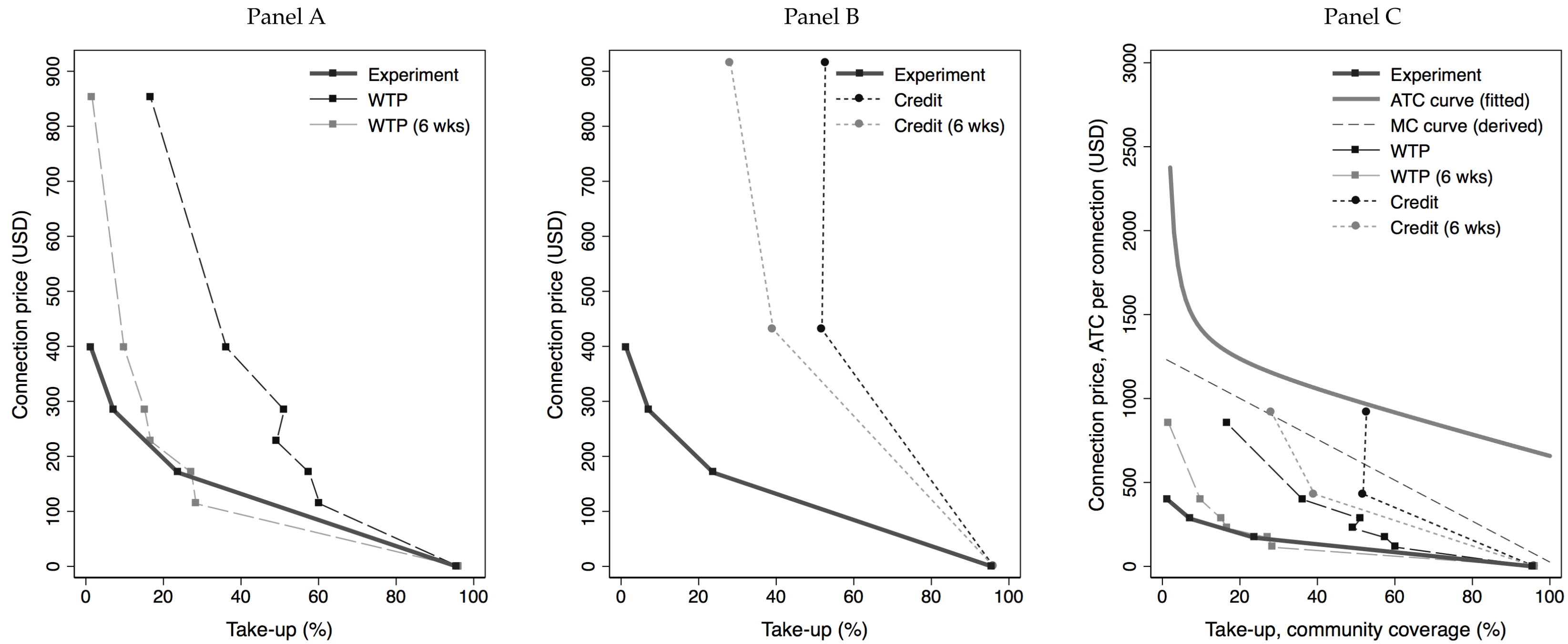
Notes: Each circle represents one of the 14 contractors that participated in the overall project. The size of each circle is proportional to the number of household connections supplied by the contractor (mean=34). The horizontal axis represents the percentage difference between the total invoiced and budgeted cost for each contractor. The vertical axis represents the percentage difference between the actual and designed poles (i.e. materials) for each contractor. The average discrepancies in poles and costs are weighted by the number of connections per contractor and correspond to the values in Table 3.4.

Figure 3.8—Timeline of the rural electrification process



Notes: Panel A summarizes the rural electrification process from the standpoint of the household, divided into three key phases. Panel B summarizes the process from the standpoint of the supplier, divided into four key phases. The numbers to the right of each bar report the average number of days required to complete each phase (standard deviations in parantheses). Households were first given 56 days (8 weeks) to complete their payments. Afterwards, it took on average 212 days (7 months) for households to be metered and electricity to flow to the household. Appendix Table C7 lists specific issues that created delays during each phase of the process.

Figure 3.9—Stated willingness to pay for an electricity connection, with and without time constraints and credit offers



Notes: Panel A combines the experimental demand results (solid black line) with responses to a set of contingent valuation questions included in the baseline survey. Households were first asked whether they would accept a hypothetical offer (i.e., at a randomly assigned price) to connect to the grid (long-dashed line, black squares). Households were then asked whether they would accept the same hypothetical price offer if required to complete the payment in six weeks (long-dashed line, grey squares). Panel B combines the experimental demand results with responses to an alternative set of contingent valuation questions. Each household was randomly assigned a hypothetical credit offer consisting of an upfront payment (ranging from $39.80 to $79.60), a monthly payment (ranging from $11.84 to $17.22), and a contract length (either 24 or 36 months). Applying a discount rate of 15%, we plot the net present value of the credit offers and the take-up results, with and without time constraints. Additional details on the credit offers are provided in Appendix Table C10. Panel C combines the stated and revealed demand curves with the experimental average total cost (ATC) curve from Figure 3.5, Panel B.

Chapter 4

Secondary School Electrification and School Completion

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April 2013[1]

4.1 Introduction

Policymakers in developing countries often state that providing rural schools with electricity leads to large gains in educational outcomes. By introducing electric lighting to classrooms, for example, it is easier for students to read indoors. It is also possible to power complementary appliances that may have educational benefits, such as computers and fans (IEG WB 2008). Furthermore, by investing in school quality, the perceived payoffs to schooling may become larger, improving completion rates. Teacher morale and retention may also increase, because most teachers prefer to work at schools where electricity is available. While all of these mechanisms seem possible, there is little rigorous evidence documenting the impacts of school electrification on student attendance, test scores, school completion, and other outcomes.

In this paper, I examine the impact of rural secondary school electrification on an outcome that is particularly important in Kenya: the number of students writing the Kenya Certificate of Secondary Education examination ("KCSE"). Writing the KCSE, a nationwide standardized exam that is administered at the end of secondary school, is a proxy for school completion because it is not only a major marker of educational achievement but is also required for entrance into public and private universities.

My empirical strategy takes advantage of the rapid rollout of school electrification that took place following the establishment of Kenya's Rural Electrification Authority ("REA") in 2006. Between 2003 and 2012, the proportion of electrified secondary schools in Kenya increased from under 10 percent to almost 100 percent. Although the rollout was not random, I argue that the sequencing of connections is not endogenous to the number of KCSE examinees. The timing of connections can therefore be used as a source of identification in an estimation strategy incorporating school and year fixed effects.

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[1] The material in this chapter was originally prepared as a second year econometrics paper titled, "The Effect of Electrification on the Number of KCSE Examinees in Kenyan Secondary Schools".

I find that I cannot reject the null hypothesis of no effect. However, there is some evidence that electrifying boarding schools increases the number of KCSE examinees by 16.3 percent. The effect on day schools, in contrast, is much smaller and is not statistically significant. This finding is consistent with the idea that school electrification has a larger impact on student outcomes at schools where students are more likely to use electric lighting at night. Given the limitations of the data, however, I cannot determine whether the number of examinees increases along the extensive margin rather than the intensive margin.

Despite these limitations, this paper adds to existing evidence on the impacts of investments in education and rural electrification in developing countries. Earlier work focuses on the impacts of demand-side education programs, such as free primary education.[2] In contrast, this paper examines the impacts of a supply-side investment. In addition, there is some evidence that providing households with access to electricity results in positive impacts on educational outcomes, such as studying hours and enrollment.[3] In comparison, much less is known about the relationship between school electrification and student outcomes.[4] Recent experimental evidence on the impacts of distributing solar lanterns to students on test scores has been mixed.[5] I am unaware of any other studies that analyze the impacts of Kenya's secondary school electrification initiative.

The remainder of this paper is organized as follows. Section 2 provides background information. Sections 3 and 4 describe the data and empirical strategy. Section 5 presents the main results and Section 6 concludes.

4.2 Background

4.2.1 History of rural electrification in Kenya

Rural electrification became a public priority in 1973, when the Kenyan Government first established the Rural Electrification Programme, a policy to subsidize the cost of electricity supply in rural areas. Under this initial setup, rural electrification was the joint responsibility of the Ministry of Energy and its implementing agency, Kenya Power, the country's monopoly transmission, distribution and retail company. However, over the next few decades, the pace of

[2] Deininger (2003), for example, finds evidence that eliminating primary school fees in Uganda led to a dramatic increase in attendance, although possibly at the expense of school quality. Lucas and Mbiti (2012a), find similar effects from Kenya's Free Primary Education program, but also find evidence of a widening gender gap in education.

[3] In Bangladesh, for example, Khandker, Barnes, and Samad (2012) find studying time to increase by 12 to 14 minutes per day. In India, Khandker et al. (2014) find studying time to increase by 1.4 to 1.6 hours per day. In El Salvador, Barron and Torero (2014) estimate a 78 percent increase in time spent studying and at school.

[4] In a literature review, Glewwe, Hanushek, Humpage and Ravina (2011) conclude that the impact of electricity (or more generally, better school facilities) on student test scores may not be very strong, based on a handful of studies that identify both positive and negative (and mainly insignificant) effects.

[5] Hassan and Lucchino (2016), for instance, find evidence that distributing solar lanterns to 7th grade pupils in Kenya increases math grades by 0.88 standard deviations, though substantial spillovers to control students complicate the interpretation of their results. In contrast, Furukawa (2014) finds that distributing solar lanterns in Uganda reduced test scores, possibly due to a flickering, low quality of light, but increased study time by roughly 30 minutes per day.

rural electrification remained stagnant. The cost of grid expansion was prohibitively high and there was a general perception that demand for energy in rural areas was too low to be financially viable. As a result, only 8.6 percent of rural public facilities had been electrified by 2003, and in 2004, the national electrification rate was estimated to be 9.1 percent, well below the average rate of 23.5 percent across Sub-Saharan Africa (IEA 2004).[6]

In November 2006, the Kenyan Parliament passed the Energy Act 2006, vastly restructuring the country's electricity sector. A key change brought about by the policy was the creation of REA. This new agency was tasked with the mandate of managing the newly created Rural Electrification Programme Fund, developing a Rural Electrification Programme Master Plan, and overseeing grid extensions to interconnected areas, with the overall aim of accelerating the pace of electrification. After becoming operational in 2007, REA immediately announced its strategy to prioritize the electrification of all rural public facilities, defined as trading centers, public secondary schools and health clinics. These newly electrified public facilities would serve as community connection points, bringing previously off-grid homes and businesses within reach of the national grid.

Between 2006 and 2012, Kenya experienced a dramatic rise in rural electrification, and in particular, the number of secondary schools connected to the grid. In 2003, a mere 285 public secondary schools across the country had access to electricity (REA 2010). In 2012, the Kenyan newspaper *The Star* predicted that 100 percent of public secondary schools in Kenya would be electrified by the end of the year.[7]

The rollout of secondary school connections was not random. It involved a complex interaction between regional electrification targets, local political objectives, and infrastructure cost considerations. Public facilities were connected in partnership with the local Constituency Development Funds ("CDF").[8] Under this setup, each CDF provided REA with a list of unelectrified schools, dispensaries, and market centers, selected based on local needs and cost assessments. REA then estimated the connection cost for each facility based on technical considerations. The CDFs then selected the sequence of connections, with funding based on a matching scheme (i.e. costs shared equally between the CDF and REA). Facilities that remained unconnected were rolled over onto lists in following years.

4.2.2 Secondary school education in Kenya

Education in Kenya follows an 8-4-4 system with eight years of primary, four years of secondary, and four years of university education. At the end of Grade 8, students write the Kenya Certificate of Primary Education ("KCPE"), a nationwide exam that is required for entry into secondary school. At the time of registration for the KCPE, students submit a list of preferred secondary school choices. Secondary school admissions are then based on a

[6] Electrification rate for rural public facilities is based on: Ondari, Justus. "Kenya: Electrification to Power Growth in Rural Areas." *Daily Nation* on the Web 25 Oct. 2010. Retrieved 9 Dec. 2012. http://allafrica.com/stories/2010-10260163.html.

[7] Waruinge, Maureen. "Public Schools Electricity Projects." *The Star* on the Web 5 Nov. 2012. Retrieved 9 Dec. 2012. http://www.the-star.co.ke/news/article-94270/public-schools-electricity-projects.

[8] CDFs in Kenya are community-driven development organizations established in 2003 to transfer decision-making authority from the central government to the constituencies, the basic units of political representation.

combination of KCPE scores, student preferences, and predetermined district quotas. Several factors contribute to these individual preferences. For low-income families, for example, Ohba (2011) finds that enrollment decisions depend largely on the direct costs, opportunity costs and perceived economic returns of secondary education.[9]

Kenyan secondary schools are categorized as either government-funded, harambee, or private schools. Both government-funded and harambee schools are considered to be public schools. Unlike government-funded schools, harambee schools do not receive full funding from the government, and are often sponsored by religious institutions. Public schools consist of both day and boarding schools. This paper focuses solely on public schools and private schools are excluded from the data. The secondary school system consists of four years of education, beginning with Form 1 and ending with Form 4. Given the competitive admissions process, a relatively low number of students transfer into a given school after Form 1. At the end of Form 4, secondary school students write the KCSE, which is held between October and November of each year. The KCSE represents an important educational milestone and is a major determinant of a student's future career. It marks the completion of secondary education and is required for entry into public and private universities. Students that do not pass the KCSE are unlikely to attend university, which drastically lowers their expected future earnings stream.

4.3 Data

I construct a panel data of school-level student performance on the KCSE and electricity connection dates for public secondary schools in Western Kenya over the period 2006 to 2011. The data combines a variety of data sources, including electricity connection dates provided by Kenya Power, annual student test score distributions published by the Kenya National Examination Council ("KNEC"), a survey of secondary school characteristics published by the Kenya Ministry of Education ("MoE"), and geospatial data published by the World Resources Institute ("WRI").

4.3.1 Data sources

The region covered includes Kenya's Western and Nyanza provinces, and a small number of bordering districts in Rift Valley Province. The connection dates for 1,071 secondary schools are obtained from Kenya Power and includes accounts serviced by the company's 51 Western Region offices.[10] Since Kenya Power does not record a special distinction for secondary school accounts, I do not have a comprehensive list of connected schools. Instead, I have the subset of schools that, at the time of registration, included some variation (or abbreviation) of the words

[9] For high performing students, there is an additional game theoretic aspect in which student perceptions of the likelihood of being admitted into a particular school play an important role in preference rankings (Lucas and Mbiti 2012b).

[10] In Western Province, these offices do not fully cover Tongaren and Lugari districts. In Rift Valley Province, these offices fully cover Bomet, Bureti and Kericho districts, and only partially cover Keiyo, Nandi South, Trans Mara and Uasin Gishu districts. In many cases, there are several connection dates associated with each school, as it is common for the various buildings on the school grounds to register for separate meters. In these cases, I use the earliest associated connection date for each school.

"secondary school" or "high school" in their registered account names.[11] Since there is no systematic reason why certain schools would exclude these words in their account names, I assume that the data is a representative sample of secondary schools in Western Kenya. Figure 4.1 displays the rollout of new connections on a quarterly basis as well as the cumulative number of connections in Western Kenya from mid-1995 to mid-2012. The number of connected secondary schools rises slowly, before increasing rapidly in the years following 2006, after the creation of REA.

The KNEC records contain the student distribution of KCSE scores by gender for each school that officially reported scores between 2006 and 2011. Annual records are merged to create an unbalanced panel of test scores. Secondary schools are matched based on their unique KNEC codes, which are assigned based on province and district. In some cases, the KNEC code for the same school varies from year to year. As a result, I merge the six years of test scores using a fuzzy matching algorithm based on school names, codes and districts. This leaves open the possibility for matching errors. The issue of measurement error is revisited in the results section. The Kenya Power and KNEC data are then merged with the 2007 survey of secondary schools administered by the MoE. The MoE survey contains cross-sectional data on school attributes, such as whether a school is public or private, boarding or day, single sex or co-educational, as well as the acreage, number of students, teachers and non-teaching staff, teacher affiliations and geographic coordinates for each school. Finally, WRI geospatial data is used to calculate distances between secondary schools, roads, and market centers, which are important drivers of economic activity.

The resulting panel consists of 1,304 secondary schools of which 696 and 608 schools are electrified and unconnected, respectively, as of mid-2012. Note that a portion of the unconnected group of schools is likely to have access to some form of electricity (e.g. grid connection or solar electricity). This additional source of measurement error is revisited in the results section.

4.3.2 Summary statistics

Over the past decade, there has been an increase in the number of students writing the KCSE exam. This trend has been driven the construction of new schools and national policies to improve access to education. For example, in 2003, the Kenyan government introduced the Free Primary Education ("FPE") program, abolishing school fees in government primary schools. Similarly, in 2008, the Kenyan government launched the Free Secondary Education ("FSE") program, announcing that it would subsidize the cost of tuition for all secondary school students. Figure 4.2, Panel B illustrates the rising trend in the average number of KCSE examinees per school by gender in Nyanza and Western between 2006 and 2010. Figure 4.2, Panel C compares the upward trend in the average number of examinees per school between schools that are eventually connected and schools that remain unconnected. The focus of this paper is to explore whether the slight divergence between these two curves over time can be explained by the rollout of electricity connections.

[11] Primary schools, special needs schools and private schools were filtered out of the data. Any private schools that remain in the dataset are dropped when merging the electricity connections database with the MoE survey, described below. In discussions with the head of the Western Region business segment in early-2013, I was told that the data contains roughly "70 percent of all connected secondary schools."

Since the rollout is used as a source of identification, it is important to understand the differences between connected and unconnected schools. Table 4.1 compares the characteristics of public schools receiving connections (between 2007 and 2012) to schools that remain unconnected during this period. Connected schools are characterized by a higher proportion of boarding schools (33.1 percent versus 24.3 percent), a higher number of students (228.8 versus 193.3), and a higher number of teachers (13.3 versus 12.0) and non-teaching staff (8.3 versus 6.9). However, these differences disappear when limiting the data to include only boarding schools. In Table 4.2, there are no statistical differences between connected and unconnected boarding schools, with the exception of acreage per student and student to teacher ratios. Connected boarding schools have higher acreage per student (48.9 versus 36.1) and higher student to teacher ratios (17.9 versus 16.0). In Table 4.3, there are significant differences between boarding and day schools. Boarding schools have a higher number of students (307.2 versus 103.9) and higher student to teacher ratios (17.3 versus 15.5).

Table 4.4 compares school performance, as reflected by the number of KCSE examinees, as well as the standardized KCSE score, between various sets of connection cohorts.[12] In the first panel, for example, I compare schools connected in 2007 with schools connected in 2008, focusing on both a base year, 2006, and each cohort's year of connection. In columns 2 through 5, I look for differences in the distribution of scores (mean and percentile ranks) in the base year. Similarly, in columns 6 through 9, I compare each cohort's connection year. In columns 10 and 11, I compare the level of examinees in the base and connection years. Table 4.4 shows that there are key differences in student performance levels. The 2009 and 2011 cohorts, for example, performed relatively poorly in comparison to the 2008 cohort. Furthermore, when comparing the number of examinees (columns 10 and 11), cohorts that are further apart differ in size, while cohorts in adjoining years are roughly equal in size.

From these comparisons, it is possible to make some general observations on the rollout: First, larger schools were prioritized for electrification and these schools tended to be boarding schools. It is possible that these schools enjoyed greater local support due to their size. Alternatively, larger schools may be located in areas that are cheaper to connect, due to their proximity to existing infrastructure, which tends to be situated in market centers and geographically favorable areas. Second, if the student to teacher ratio is a measure of the quality of the learning environment, it is not clear that the rollout targeted higher quality schools. Connected schools tended to have higher student to teacher ratios. Third, there are key differences in student performance between schools connected in different years. Fourth, there are no key differences between connected and unconnected boarding schools.[13]

These observations raise important concerns with respect to the endogeneity of the rollout. However, it may still be possible to use the rollout for identification if it can be shown that the sequencing itself was not endogenous to the outcome of interest. In column 12 of Table 4.4, I look for differences between connection cohorts in the pre-trend (2006-07) examinee growth. In this case, I find no statistically significant differences. This latter result is encouraging, and in the following section, I test the sequencing of the rollout more formally.

[12] I calculate the mean standardized KCSE score by first standardizing the distribution of letter grades for each school, based on the national distribution, and then calculating the arithmetic mean.
[13] This will be useful to keep in mind when interpreting the regressions that include only the boarding schools.

4.4 Empirical approach

In an ideal experiment, secondary schools would be randomly assigned electricity connections and data would be collected on a host of time-varying covariates, including unexpected changes in school infrastructure, and the availability of student scholarships, for example. Unfortunately, school electrification in Western Kenya was not random, and data on yearly attendance records, as well as individual student characteristics, are unavailable. Instead, I observe the rollout of electricity connections and the distribution of KCSE test scores for each school over a period of six years. The data provides information on both the performance of examinees, as well as the number of examinees at a given school in each examination year. I do not observe initial enrollment and subsequent dropout rates, which should have large effects on the number of examinees. If electrification affects initial enrollment, there should be a positive relationship between electrification in the year of a particular cohort's registration (i.e. the KCPE year) and the number of examinees four years later (i.e. the year that particular cohort completes secondary school). In order for this relationship to hold, I assume that electrification does not have a differential effect on the dropout rates of students who are exposed to electricity at their schools for different amounts of time.

4.4.1 Instrumental variables

The endogenous placement of electricity has been addressed using instruments ranging from geographic factors (e.g., Dinkelman 2011; Lipscomb, Mobarak and Bahram 2013) to the proportion of households in a community who already have electricity (e.g., Khandker et al. 2014). I explore whether this approach can be followed in this setting. Since I have just a single cross-section of school survey data (from 2007), I create two periods of data: (1) a baseline period covering 2006 and 2007, and (2) a follow-up period, covering 2010 and 2011. In each period, I classify all of the schools into those that were connected before 2006, those that were connected between 2006 and 2007, and those that remained unconnected. Figure 4.3 plots the spatial distribution of connected and unconnected secondary schools in 2007.

Following Dinkelman (2011), I instrument the likelihood of electrification during the baseline period using the average land gradient around each school, Z_i. The first-stage equation for $T_{id,t=0}$, the electricity connection status of school i in district d, during the baseline period, can be written as follows:

$$T_{id,t=0} = \alpha_1 + \beta_1 Z_i + X_{id,t=0}\lambda_1 + \gamma_{d,1} + \epsilon_{id,1} \tag{4.1}$$

where $X_{id,t=0}$ is a vector of school covariates from the cross-sectional school survey, including total enrollment, the number of teachers, acreage, as well as locational factors, such as the distance to the nearest town and road (i.e., capturing the proximity to local market centers) and the distance to an already connected secondary school, and $\gamma_{d,1}$ captures district fixed effects.[14]

In the second-stage, I utilize the predicted values from the first-stage to estimate the

[14] Ideally, I would condition on the distance to the existing grid infrastructure. Since this data is not available, I use the distance to an already connected secondary school as a proxy.

impacts of electrification on the number of KCSE examinees in the follow-up period, in the following equation:

$$y_{id,t=1} = \alpha_2 + \beta_2 \hat{T}_{id,t=0} + X_{id,t=0}\lambda_2 + \gamma_{d,2} + \epsilon_{id,2} \quad (4.2)$$

where $y_{id,t=1}$ is the number of KCSE examinees during the follow-up period and $\gamma_{d,2}$ captures district fixed effects. The exclusion restriction holds if, conditional on school characteristics, distance to economic centers, distance to the national grid, and district fixed effects, land gradient does not affect the number of KCSE examinees through any channel other than its effect on the net cost of grid extension, which affects the likelihood of electrification.

4.4.2 Fixed effects

I also estimate the effects of electrification by incorporating school fixed effects in a panel regression. The key identification assumption is that school-specific time series variation in the connection date is a valid source of variation for identifying causal effects. Since the rollout of secondary school connections was not random, it is necessary to test the sequencing of the rollout to ensure that it was not endogenous to outcomes. Following de Janvry, McIntosh, and Sadoulet (2010), I first perform a simple exogeneity test on the rollout of connections, before describing the fixed effects strategy.

The dependent variable, $\Delta y_{id,p}$, is the change in the number of KCSE examinees at school *i* in district *d* over the pre-period *p*. This variable is regressed on N_i, the numerical order of connection for school *i*, and district fixed effects in the following specification:

$$\Delta y_{id,p} = \gamma_d + \beta N_i + \eta_{id} \quad (4.3)$$

For each pre-period, the sample is limited to include only those schools connected in subsequent years. For example, if the pre-period is 2006-07, the sample includes schools connected in 2008 and on. If pre-period trends are uncorrelated with the sequencing of the subsequent rollout, the coefficient β will be statistically insignificant. Table 4.5 reports the results of estimating equation 4.3 across ten periods ranging from 2006-07 to 2006-10. The results do not indicate a statistically significant coefficient on N_i.[15]

Assuming that the identification assumption for the fixed effects regression holds, I estimate the following regression:

$$y_{it} = \sum_p \beta_p \mathbb{I}(\text{Year of exposure} = \text{p})_{\text{it}} + \omega_i + \gamma_t + \epsilon_{it} \quad (4.4)$$

where ω_i and γ_t represent school and year fixed effects. School fixed effects capture time-invariant characteristics that are unique to each school. These differences would include school

[15] Ideally, the pre-period trend would cover the years leading up to 2006, which represents both the start of the panel data, as well as the year in which REA was established. Unfortunately, data on school performance prior to 2006 is unavailable.

reputation, the quality of teachers and facilities, and perhaps even local attitudes towards educational achievement. Similarly, year fixed effects capture differences between years that are universal across schools. These differences would capture time trends and the effects of national policies such as the FPE and FSE programs.

I am interested in the coefficients on the $\mathbb{I}(\mathrm{p})_{\mathrm{it}}$ variables, which are indicators for the length of time the KCSE-writing cohort at school i in year t first received an electricity connection at their school. I include six of these dummy variables, controlling for electrification during Form 4 (i.e., the year of the KCSE examination), Form 3, Form 2, Form 1, the KCPE year (i.e., the final year of primary school and the year in which students applied for secondary school admission), and earlier. In this specification, the baseline state is "never connected." If electrification has a positive effect on the number of KCSE examinees, I would expect to find positive and significant coefficients on the $\mathbb{I}(\mathrm{p})_{\mathrm{it}}$ variables, and in particular for the *p* = *KCPE* and *p* = *Earlier* indicators, since these correspond to the years in which primary school students are deciding where to apply.

Finally, it is possible that electrification may have a larger effect at boarding schools, compared to day schools. Boarding school students are able to use electricity to light up their dormitories, and in some cases, watch television and listen to the radio with their classmates on weekends. I estimate equation 4.4 separately for boarding schools and day schools, as well as the following regression that incorporates interactions:

$$y_{it} = \sum_p \beta_{1p} \mathbb{I}(\mathrm{p})_{\mathrm{it}} + \sum_p \beta_{2p} \mathbb{I}(\mathrm{p})_{\mathrm{it}} \times B_i + \omega_i + \gamma_t + \epsilon_{it} \qquad (4.5)$$

where B_i is a dummy variable indicating whether school *i* is a boarding school and the baseline is the never connected state for both boarding and day schools. B_i is omitted from the specification because its effect is captured in ω_i. If school electrification has a differential effect on boarding schools, I would expect to find positive β_{2p} coefficients.

4.5 Results

4.5.1 Instrumental variables: Weak first-stage results

Table 4.6 reports the first-stage results. The dependent variable is a binary variable indicating whether the school was connected in 2006 or 2007. If gradient is a suitable instrument for electrification, then the coefficients on gradient should be negative and significant, conditional on the covariates and district fixed effects. Even without fixed effects, the coefficient is insignificant and close to zero across all columns. The weak first-stage results contrasts with the results in Dinkelman (2011), where the *F*-statistics in the first-stage regressions range from 4.20 to 8.34. Perhaps in Kenya, the quality of the terrain has less of an effect on the likelihood that public facilities are electrified. Western Kenya is relatively flat compared to KwaZulu-Natal, South Africa. Due to this weak first-stage, I focus on the results of the fixed effects strategy.

4.5.2 Fixed effects: Effects of electrification on KCSE outcomes

Fixed effects results are reported in Table 4.7 where the dependent variable is the log number of examinees. Standard errors are clustered at the district level to address serial correlation between neighboring schools in the same districts and the data is limited to exclude schools connected prior to the year 2000.[16] Pooled OLS estimates are reported in the first column. The coefficients on the $\mathbb{I}(p)_{it}$ indicator variables are large and statistically significant, which is expected, given that the number of connected schools and the number of examinees both rise over time (see Figure 4.2, Panel A).

Year and school fixed effects are introduced in columns 2 through 5. The results of the main specification, equation 4.4, are presented in column 2. While I find that I cannot reject the null hypothesis of no effect, the coefficients are not precisely estimated zeros. For example, the coefficients on the *Form 1* and *KCPE* indicators are relatively large (7.2 percent and 8.7 percent, respectively) with *t*-statistics (1.45 and 1.47, respectively) that are close to significant. The coefficients on school electrification, which are plotted in Figure 4.4, Panel A, are positive and higher for cohorts that were supplied with electricity at earlier dates.

In column 3, I report the results of estimating equation 4.5. I cannot reject the null hypothesis of no differential effect for boarding schools. However, if boarding schools differ substantially from day schools, in terms of how students utilize electricity, it may be preferable to estimate separate regressions for day schools and boarding schools. I report the results of these regressions in columns 4 and 5. While I cannot reject the null hypothesis of no effect at day schools, there is evidence of a large effect at boarding schools. The coefficients on the *Form 1* and *KCPE* indicators are large (11.4 percent and 16.3 percent, respectively) and statistically significant. I plot these coefficients in Figure 4.4, Panel B. At boarding schools, there is a noticeable improvement in the number of examinees for cohorts that benefited from four full years of electrification. I cannot determine whether this increase is driven by higher enrollment rates or lower dropout rates.

4.5.3 Issues of concern

The results suggest that boarding school electrification during the year of registration, or the first year of secondary school, leads to a greater number of students who eventually complete secondary school. At 16.4 percent and 11.4 percent, respectively, the magnitudes of the effects for boarding schools are large. However, there are two reasons why these effect sizes may be overestimated. First, the coefficients may be biased upwards because of omitted variables that are positively correlated with both the timing of electrification and the outcome variables. For example, school electrification, which represents an important community investment, may coincide with the sudden introduction of other programs with educational benefits. These programs may include, for example, tuition scholarships or bursaries funded by the local CDFs or non-profit organizations. Alternatively, the timing of connections may be correlated with the electrification of neighboring homes and businesses, and there may be spillover effects that bias

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[16] Given the low level of electrification in Kenya during the 1990s, it is likely that public secondary schools connected during this time were fundamentally different from the schools connected in more recent years. These schools are therefore excluded from the data. While the choice of the year is somewhat arbitrary, changing the cutoff to 2002, for example, does not significantly alter the results.

the coefficients upwards. Second, if school electrification causes students to transfer from unelectrified schools to electrified schools, then the stable unit treatment value assumption may not hold. In this case, the number of KCSE examinees graduating from unconnected schools would be negatively impacted by the placement of electricity connections at neighboring schools, further biasing the coefficients upwards. A final issue concerns measurement error. Sources of measurement error include the imperfect matching algorithm employed, and the possibility that some of the unconnected schools are using other sources of electricity such as solar lanterns.

4.6 Conclusion

This paper provides suggestive evidence that the electrification of secondary schools in Western Kenya led to an increase in the number of KCSE examinees at boarding schools. The impacts of school electrification may depend on the time frame of the analysis, and the availability of complementary inputs, such as computers and fans, as well as the reliability of the electricity supply, all of which are unobserved on this study. The findings in Lee, Miguel, and Wolfram (2016b) suggest that rural household electrification may reduce welfare, in part due to the high costs. A question that follows is whether the gains from extending the grid to rural public facilities, including secondary schools, are large enough to offset the overall costs of both public facility and household electrification. This paper does not provide a definitive answer to this question but highlights the need for further research in this area.

Table 4.1—Characteristics of public secondary schools in Western Kenya by sample group

	Unconnected	Connected	p-value of diff.
Number of schools	548	502	
% sponsored by religious institutions	77.0	75.5	0.566
% sponsored by government	17.9	19.3	0.550
% boarding schools	24.3	33.1	0.002
Total enrolment	193.3	228.8	0.000
School acreage	6.9	6.8	0.858
Acreage per student	44.9	53.2	0.096
Number of teachers	12.0	13.3	0.008
% female teachers	24.4	25.5	0.252
% Teachers Service Commission	68.2	70.0	0.200
% PTA Board of Governors	31.6	29.5	0.124
Number of non-teaching staff	6.9	8.3	0.000
Teacher to non-teaching staff ratio	2.2	2.0	0.115
Student to teacher ratio	14.9	16.2	0.004

Notes: Connected includes the 548 schools with KPLC-verified electricity connection dates between January 2007 and mid-August 2012. Unconnected' includes remaining 502 schools. Based on the 2007 MoE survey.

Table 4.2—Characteristics of public boarding secondary schools in Western Kenya by sample group

	Unconnected	Connected	p-value of diff.
Number of schools	133	166	
% sponsored by religious institutions	83.5	78.3	0.265
% sponsored by government	12.0	18.1	0.151
Total enrolment	287.1	299.9	0.597
School acreage	12.1	9.5	0.114
Acreage per student	36.1	48.9	0.015
Number of teachers	17.0	16.2	0.476
% female teachers	30.2	29.2	0.598
% Teachers Service Commission	77.1	75.3	0.345
% PTA Board of Governors	22.6	24.7	0.260
Number of non-teaching staff	11.5	11.9	0.717
Teacher to non-teaching staff ratio	1.7	1.5	0.114
Student to teacher ratio	16.0	17.9	0.020

Notes: Connected includes the 133 boarding schools with KPLC-verified electricity connection dates between January 2007 and mid-August 2012. Unconnected′ includes remaining 166 schools. Based on the 2007 MoE survey.

Table 4.3—Comparison of day and boarding schools in Western Kenya

	Day	Boarding	*p*-value of diff.
Number of schools	817	369	
% sponsored by religious institutions	74.05	79.13	0.059
% sponsored by government	20.32	15.72	0.061
Total enrolment	183.05	307.22	0.000
School acreage	5.36	10.87	0.000
Acreage per student	52.20	43.96	0.096
Number of teachers	11.32	17.20	0.000
% female teachers	23.71	29.62	0.000
% Teachers Service Commission	66.91	76.42	0.000
% PTA Board of Governors	32.58	23.40	0.000
Number of non-teaching staff	6.08	12.17	0.000
Teacher to non-teaching staff ratio	2.27	1.54	0.000
Student to teacher ratio	15.52	17.29	0.004
% electrified during sample period	49.20	63.96	0.000

Notes: Excludes schools connected prior to the year 2000.

Table 4.4—Comparison of school performance between various sets of connection cohorts

		Standardized KCSE score								KCSE examinees		
		Base year: 2006 (t)				Connection year (s)						
	n	Mean	25^{th}	50^{th}	75^{th}	Mean	25^{th}	50^{th}	75^{th}	Year t	Year s	06-07 (%)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
2007 vs. 2008 connections												
2007 cohort	41	-0.06	-0.62	-0.08	0.45	-0.09	-0.64	-0.15	0.34	60	65	11.02
2008 cohort	65	-0.07	-0.67	-0.11	0.41	-0.05	-0.63	-0.10	0.40	51	65	15.72
p-value of diff.		0.829	0.670	0.733	0.711	0.720	0.945	0.664	0.655	0.197	0.946	0.420
2008 vs. 2009 connections												
2008 cohort	65	-0.07	-0.67	-0.11	0.41	-0.05	-0.63	-0.10	0.40	51	65	15.72
2009 cohort	105	-0.21	-0.78	-0.25	0.23	-0.23	-0.85	-0.27	0.20	46	61	11.18
p-value of diff.		0.029	0.119	0.037	0.039	0.004	0.002	0.011	0.015	0.267	0.528	0.383
2009 vs. 2010 connections												
2009 cohort	105	-0.21	-0.78	-0.25	0.23	-0.23	-0.85	-0.27	0.20	46	61	11.18
2010 cohort	95	-0.21	-0.80	-0.24	0.19	-0.15	-0.77	-0.20	0.31	39	61	18.04
p-value of diff.		0.958	0.793	0.906	0.551	0.176	0.249	0.263	0.134	0.086	0.999	0.156
2010 vs. 2011 connections												
2010 cohort	95	-0.21	-0.80	-0.24	0.19	-0.15	-0.77	-0.20	0.31	39	61	18.04
2011 cohort	88	-0.37	-0.92	-0.39	0.04	-0.38	-0.86	-0.54	0.04	36	53	10.07
p-value of diff.		0.010	0.089	0.019	0.100	0.002	0.224	0.000	0.002	0.376	0.128	0.116
2007 vs. 2009 connections												
2007 cohort	41	-0.06	-0.62	-0.08	0.45	-0.09	-0.64	-0.15	0.34	60	65	11.02
2009 cohort	105	-0.21	-0.78	-0.25	0.23	-0.23	-0.85	-0.27	0.20	46	61	11.18
p-value of diff.		0.031	0.065	0.028	0.023	0.040	0.010	0.101	0.130	0.009	0.508	0.979

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		Standardized KCSE score								KCSE examinees		
		Base year: 2006 (t)				Connection year (s)						
	n	Mean	25^{th}	50^{th}	75^{th}	Mean	25^{th}	50^{th}	75^{th}	Year t	Year s	06-07 (%)
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
2008 vs. 2010 connections												
2008 cohort	65	-0.07	-0.67	-0.11	0.41	-0.05	-0.63	-0.10	0.40	51	65	15.72
2010 cohort	95	-0.21	-0.80	-0.24	0.19	-0.15	-0.77	-0.20	0.31	39	61	18.04
p-value of diff.		0.057	0.108	0.063	0.025	0.209	0.121	0.198	0.394	0.014	0.579	0.647
2009 vs. 2011 connections												
2009 cohort	105	-0.21	-0.78	-0.25	0.23	-0.23	-0.85	-0.27	0.20	46	61	11.18
2011 cohort	88	-0.37	-0.92	-0.39	0.04	-0.38	-0.86	-0.54	0.04	36	53	10.07
p-value of diff.		0.005	0.028	0.017	0.014	0.011	0.794	0.000	0.031	0.011	0.080	0.828
2007 vs. 2010 connections												
2007 cohort	41	-0.06	-0.62	-0.08	0.45	-0.09	-0.64	-0.15	0.34	60	65	11.02
2010 cohort	95	-0.21	-0.80	-0.24	0.19	-0.15	-0.77	-0.20	0.31	39	61	18.04
p-value of diff.		0.064	0.071	0.049	0.021	0.477	0.218	0.529	0.802	0.000	0.566	0.243
2008 vs. 2011 connections												
2008 cohort	65	-0.07	-0.67	-0.11	0.41	-0.05	-0.63	-0.10	0.40	51	65	15.72
2011 cohort	88	-0.37	-0.92	-0.39	0.04	-0.38	-0.86	-0.54	0.04	36	53	10.07
p-value of diff.		0.000	0.001	0.000	0.000	0.000	0.003	0.000	0.000	0.002	0.037	0.291

Notes: Connection cohort sample size in column 1. Columns 3, 4, 5, 7, 8, and 9 report the means of the normalized KCSE mean scores relating to each particular percentile across each connection cohort. Columns 10 and 11 report the mean number of examinees across each connection cohort in 2006, the base year (t), and the connection year (s). Column 12 reports the 2006-07 year-over-year percentage change in the number of examinees (y) across each connection cohort.

Table 4.5—Testing the exogeneity of the secondary school electric connection rollout in Western Kenya

	Dependent variable: Δ outcome of interest over the pre-period							
	Log KCSE examinees				Standardized KCSE score			
	β	p-value	n	R^2	β	p-value	n	R^2
Pre-period	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A								
2006-07	0.000	0.736	379	0.045	0.000	0.612	379	0.220
Panel B								
2007-08	-0.002	0.116	336	0.071	0.002	0.257	336	0.151
2006-08	-0.002	0.204	317	0.090	0.002	0.200	317	0.088
Panel C								
2008-09	-0.002	0.426	231	0.104	0.002	0.162	231	0.142
2007-09	-0.006	0.076	231	0.117	0.004	0.096	231	0.229
2006-09	-0.007	0.046	218	0.110	0.004	0.210	218	0.086
Panel D								
2009-10	0.004	0.328	129	0.192	0.000	0.922	129	0.212
2008-10	0.001	0.796	129	0.244	0.003	0.487	129	0.352
2007-10	-0.005	0.410	129	0.173	0.005	0.244	129	0.326
2006-10	0.004	0.695	119	0.159	0.001	0.864	119	0.171

Notes: Standard errors clustered at the district level. All regressions include district fixed effects. Panel A: Dependent variable, y_i, is the change in the outcome of interest (log examinees or normalized KCSE mean score) between 2006-07. Sample includes only those schools that received electricity connections in 2008 and on. β estimates the relationship between T_i, the position of school i in the subsequent rollout, and y_i, the pre-period performance of the school i, conditional on district fixed effects. Panel B: Dependent variable covers the periods 2007-08 and 2006-08. Sample includes only those schools that received electricity connections in 2009 and on. Panel C: Dependent variable covers the periods 2008-09, 2007-09, and 2006-09. Sample includes only those schools that received electricity connections in 2010 and on. Panel D: Dependent variable covers the periods 2009-10, 2008-10, 2007-10, and 2006-10. Sample includes only those schools that received electricity connections in 2011 and on.

Table 4.6—Electrification in 2006-07: First-stage OLS estimates

	Electrification in 2006-07 = [1 or 0]				
	(1)	(2)	(3)	(4)	(5)
Gradient	-0.001	-0.001	0.002	0.000	0.003
	(0.004)	(0.004)	(0.004)	(0.004)	(0.005)
Nearest road (km)		-0.004**	-0.004	-0.004**	-0.004
		(0.002)	(0.003)	(0.002)	(0.003)
Nearest town (km)		0.002	-0.002	0.001	-0.003
		(0.002)	(0.003)	(0.002)	(0.003)
Nearest connected school (km)		-0.004	-0.002	-0.003	0.000
		(0.006)	(0.008)	(0.005)	(0.007)
Population density in 1999		0.000	0.000	0.000	0.000
		(0.000)	(0.000)	(0.000)	(0.000)
School enrolment				-0.000	-0.000
				(0.000)	(0.000)
Number of teachers				0.006	0.007
				(0.006)	(0.007)
Non-teaching staff				0.006	0.005
				(0.005)	(0.006)
School acreage				0.002	0.000
				(0.003)	(0.003)
Boarding school				0.017	0.030
				(0.056)	(0.062)
Government-sponsored				-0.000	0.000
				(0.000)	(0.001)
District fixed effects	No	No	Yes	No	Yes
Mean of outcome variable	0.15	0.15	0.15	0.15	0.15
Schools	473	473	473	446	446
R-squared	0.00	0.02	0.07	0.06	0.11
F-statistic on gradient	0.04	0.02	0.20	0.00	0.42

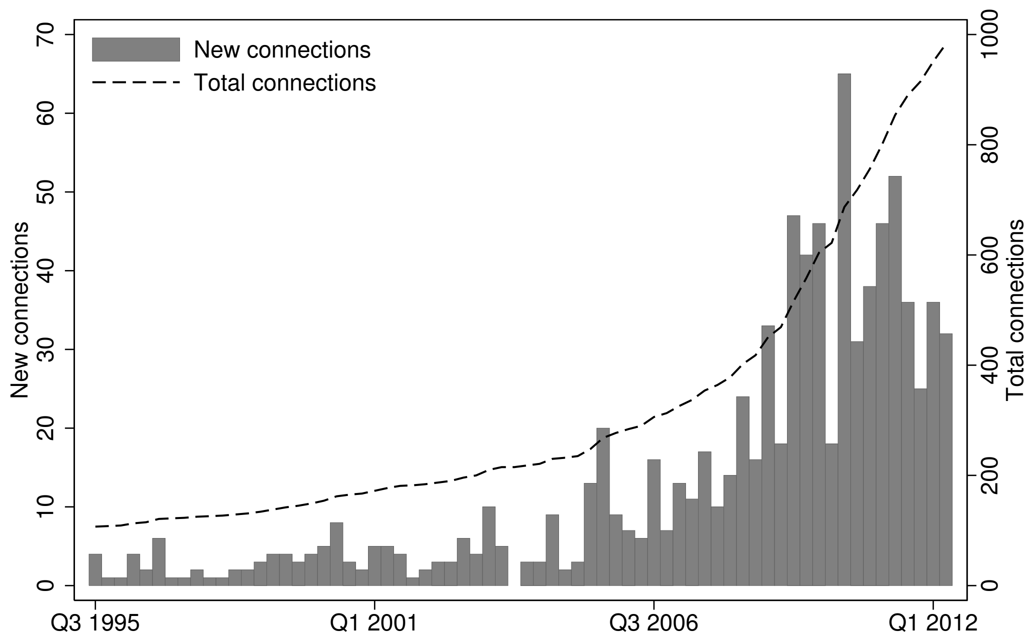
Notes: Dependent variable is a binary variable indicating whether the school was connected in 2006 or 2007. Significance levels indicated by $^{*}p < .10$, $^{**}p < .05$, $^{***}p < .01$. Standard errors in parantheses are clustered at the district level.

Table 4.7—Fixed effects regressions with log examinees as dependent variable

		School and Year FE			
	OLS	All	All	Day	Board
	(1)	(2)	(3)	(4)	(5)
Connected during Form 4	0.232***	0.025	0.040**	0.034	0.010
	(0.021)	(0.023)	(0.019)	(0.023)	(0.036)
Connected during Form 3	0.314***	0.023	0.021	0.014	0.043
	(0.031)	(0.033)	(0.029)	(0.034)	(0.042)
Connected during Form 2	0.388***	0.028	0.028	0.017	0.051
	(0.039)	(0.043)	(0.046)	(0.052)	(0.054)
Connected during Form 1	0.509***	0.072	0.063	0.049	0.114*
	(0.052)	(0.049)	(0.047)	(0.057)	(0.061)
Connected during KCPE year	0.556***	0.087	0.052	0.036	0.163**
	(0.051)	(0.059)	(0.054)	(0.065)	(0.070)
Connected earlier	0.122**	0.096	0.090	0.069	0.152
	(0.050)	(0.075)	(0.067)	(0.086)	(0.092)
Form 4 × Boarding			-0.043		
			(0.034)		
Form 3 × Boarding			0.002		
			(0.033)		
Form 2 × Boarding			-0.002		
			(0.051)		
Form 1 × Boarding			0.017		
			(0.045)		
KCPE year × Boarding			0.072		
			(0.058)		
Earlier × Boarding			0.012		
			(0.079)		
School and year FE	No	Yes	Yes	Yes	Yes
Mean of dependent variable	3.846	3.846	3.846	3.711	4.144
Observations	6,933	6,933	6,933	4,775	2,158
Years in panel		6	6	6	6
Schools		1,186	1,186	817	369
R-squared	0.04	0.29	0.29	0.28	0.32

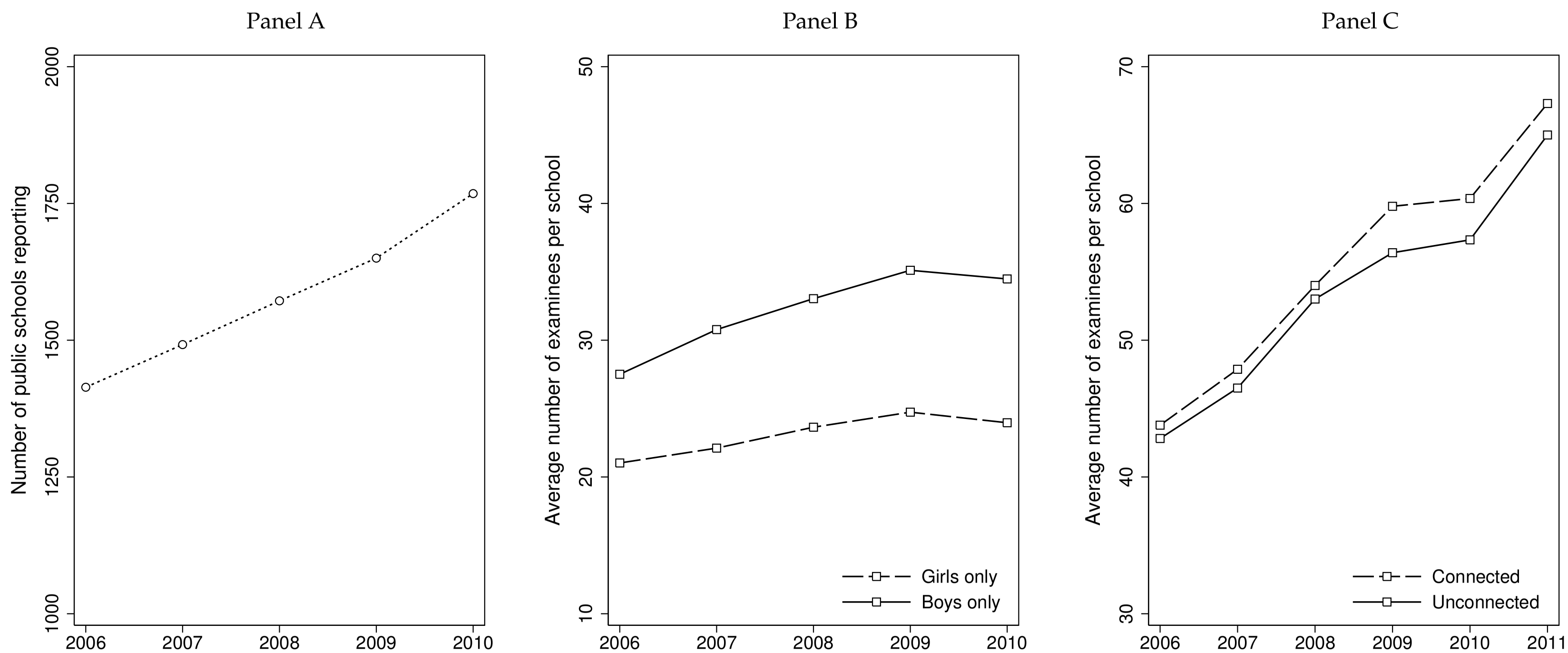
Notes: Dependent variable is $y_{i,t}$, the log number of examinees for school i in year t. Significance levels indicated by $^{*}p < .10$, $^{**}p < .05$, $^{***}p < .01$. Standard errors in parantheses are clustered at the district level. Each regressor is a dummy variable indicating the year in which the school of the test taking cohort first received electricity. Schools connected prior to the year 2000 are excluded from the data set.

Figure 4.1—Quarterly secondary school connections in Western Kenya sample



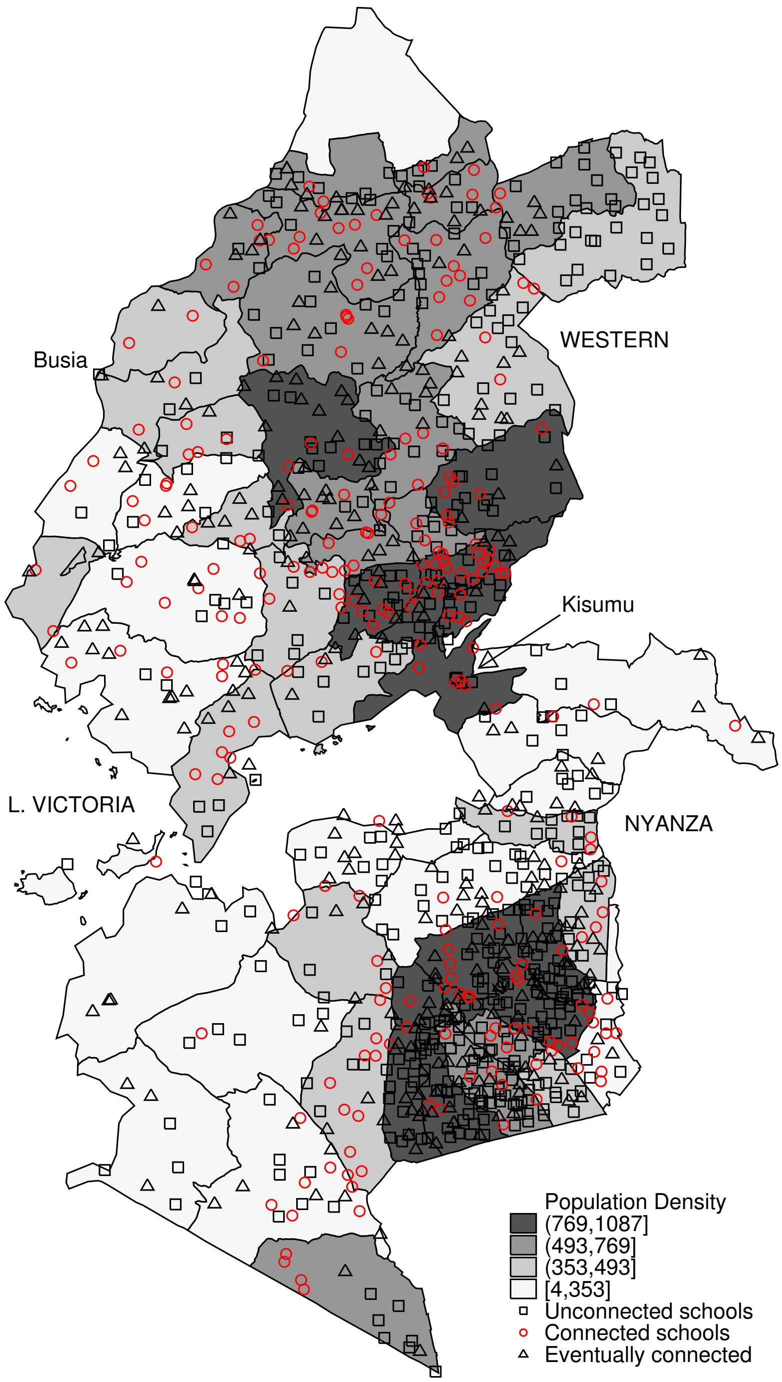
Notes: Data obtained directly from KPLC. Includes a sample of secondary school electricity accounts located across Nyanza and Western provinces, and neighboring districts in Rift Valley province.

Figure 4.2—Number of public schools reporting scores, and the average number of examinees per school, by gender and by sample group



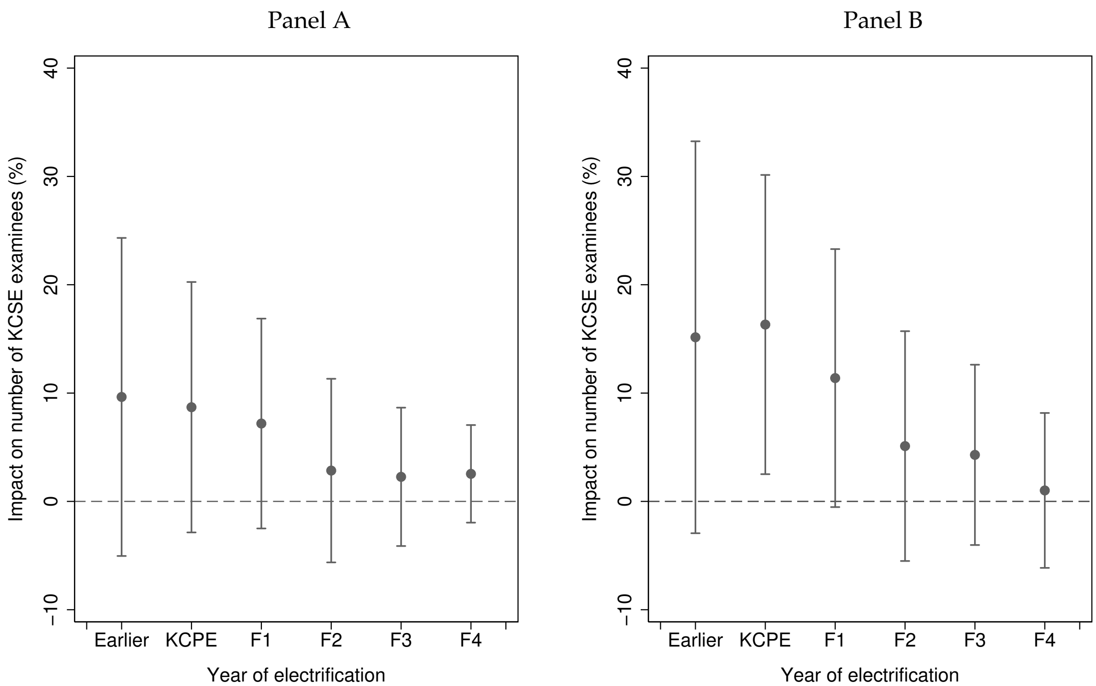
Notes: Based on data from the Kenya Open Data Initiative. In Panel C, Connected includes 550 schools with Kenya Power-verified electricity connection dates ranging from January 2007 to mid-2012. Unconnected includes the remaining 756 schools that were deemed to be either unconnected as of mid-2012, or connected but missing from the Kenya Power database.

Figure 4.3—Distribution of connected and unconnected secondary schools in Western Kenya in 2007



Notes: Connected includes 550 schools in the unbalanced panel with Kenya Power-verified electricity connection dates ranging from January 2007 to mid-2012. Unconnected includes the remaining 756 schools that were deemed to be either unconnected as of mid-2012, or connected but missing from the Kenya Power database.

Figure 4.4—Coefficients on year of electrification indicators, all schools vs. boarding schools



Notes: Coefficients and 95 percent confidence intervals for the $\mathbb{I}(p)_{i,t}$ indicators. In Panel A, we plot the results of a regression on the full sample (1,186 schools) (see Table 4.7, column 2). In Panel B, we plot the results of a regression on a limited sample of 369 boarding schools (see Table 4.7, column 5). The coefficient on electrification during the KCPE year (i.e. the year of registration) is significant at the 5 percent level.

Bibliography

Abdullah, Sabah, and P. Wilner Jeanty. 2011. "Willingness to Pay for Renewable Energy: Evidence from a Contingent Valuation Survey in Kenya." *Renewable and Sustainable Energy Reviews* 15(6): 2974-2983.

Allcott, Hunt, Allan Collard-Wexler, and Stephen D. O'Connell. 2016. "How Do Electricity Shortages Affect Industry? Evidence from India." *American Economic Review* 106(3): 587-624.

Alstone, Peter, Dimitry Gershenson, and Daniel M. Kammen. 2015. "Decentralized Energy Systems for Clean Electricity Access." *Nature Climate Change* 5: 305-314.

Aker, Jenny C. 2010. "Information from Markets Near and Far: Mobile Phones and Agricultural Markets in Niger." *American Economic Journal: Applied Economics* 2: 46-59.

Barron, Manuel, and Maximo Torero. 2014. "Short Term Effects of Household Electrification: Experimental Evidence from Northern El Salvador." Unpublished manuscript.

———. 2016. "Household Electrification and Indoor Air Pollution." Unpublished manuscript.

Baumol, William J. 1977. "On the Proper Cost Tests for Natural Monopoly in a Multiproduct Industry." *American Economic Review* 67(5): 809-822.

Bernard, Tanguy, and Maximo Torero. 2015. "Social Interaction Effects and Connection to Electricity: Experimental Evidence from Rural Ethiopia." *Economic Development and Cultural Exchange* 63(3): 459-484.

Bruhn, Miriam, and David McKenzie. 2009. "In Pursuit of Balance: Randomization in Practice in Development Field Experiments." *American Economic Journal: Applied Economics* 1(4): 200-232.

Burlig, Fiona and Louis Preonas. 2016. "Out of the Darkness and Into the Light? Development Effects of Electrification in India." Unpublished manuscript.

Caine, Mark, Jason Lloyd, Max Luke, Lisa Margonelli, Todd Moss, Ted Nordhaus, Roger Pielke Jr., Mikael Roman, Joyashree Roy, Daniel Sarewitz, Michael Shellenberger, Kartikeya Singh, and Alex Trembath. 2014. "Our High-Energy Planet: A Climate Pragmatism Project." *The Breakthrough Institute*. http://thebreakthrough.org/images/pdfs/Our-High-Energy-Planet.pdf.

Carlton, Dennis W., and Jeffrey M. Perloff. 2005. *Modern Industrial Organization*. Boston: Pearson/Addison Wesley.

Casey, Katherine, Rachel Glennerster, and Edward Miguel. 2012. "Reshaping Institutions: Evidence on Aid Impacts Using a Preanalysis Plan." *Quarterly Journal of Economics* 127(4): 1755-1812.

Chakravorty, Ujjayant, Kyle Emerick, and Majah-Leah Ravago. 2016. "Lighting Up the Last Mile: The Benefits and Costs of Extending Electricity to the Rural Poor." Unpublished manuscript.

Christensen, Laurits R., and William H. Greene. 1976. "Economies of Scale in U.S. Electric Power Generation." *Journal of Political Economy* 84(4): 655-676.

Craine, Stewart, Evan Mills, and Justin Guay. 2014. "Clean Energy Services for All: Financing Universal Electrification." *The Sierra Club*.

de Janvry, Alain, Craig McIntosh, and Elisabeth Sadoulet. 2010. "The Supply- and Demand-Side Impacts of Credit Market Information." *Journal of Development Economics* 93: 173-188.

de Mel, Suresh, David McKenzie, and Christopher Woodruff. 2009. "Are Women More Credit Constrained? Experimental Evidence on Gender and Microenterprise Returns." *American Economic Journal: Applied Economics* 1(3): 1-32.

Deichmann, Uwe, Craig Meisner, Siobhan Murray, and David Wheeler. 2010. "The Economics of Renewable Energy Expansion in Rural Sub-Saharan Africa." *Energy Policy* 39(1): 215-227.

Deininger, Klaus. 2003. "Does Cost of Schooling Affect Enrollment by the Poor? Universal Primary Education in Uganda." *Economics of Education Review* 22(3): 291-305.

Devoto, Florencia, Esther Duflo, Pascaline Dupas, William Parente, and Vincent Pons. 2012. "Happiness on Tap: Piped Water Adoption in Urban Morocco." *American Economic Journal: Economic Policy* 4(4): 68-99.

Dinkelman, Taryn. 2011. "The Effects of Rural Electrification on Employment: New Evidence from South Africa." *American Economic Review* 101(7): 3078-3108.

Donaldson, Dave. 2013. "Railroads of the Raj: Estimating the Impact of Transportation Infrastructure." *American Economic Review*, forthcoming.

Duflo, Esther, Michael Kremer, and Jonathan Robinson. 2011. "Nudging Farmers to Use Fertilizer: Theory and Experimental Evidence from Kenya." *American Economic Review* 101(6): 2350-2390.

ESMAP (Energy Sector Management Assistance Program). 2015. "Beyond Connections: Energy Access Redefined." http://www.worldbank.org/content/dam/Worldbank/Topics/Energy%20-and%20Extract/Beyond_Connections_Energy_Access_Redefined_Exec_ESMAP_2015.pdf.

Faber, Benjamin. 2014. "Trade Integration, Market Size, and Industrialization: Evidence from China's National Trunk Highway System." *Review of Economic Studies*, forthcoming.

Furukawa, Chishio. 2014. "Do Solar Lamps Help Children Study? Contrary Evidence from a Pilot Study in Uganda." Journal of Development Studies 50(2): 319-341.

Glewwe, Paul W., Eric A. Hanushek, Sarah D. Humpage, Renato Ravina. 2014. "School Resources and Educational Outcomes in Developing Countries: A Review of the Literature from 1990 to 2010." In P. Glewwe, ed., *Education Policy in Developing Countries*. Chicago and London: University of Chicago Press.

Hassan, Fadi, Paulo Lucchino. 2016. "Powering Education." Unpublished manuscript.

Hausman, Jerry. 2012. "Contingent Valuation: From Dubious to Hopeless." *Journal of Economic Perspectives* 26(4): 43-56.

IEA (International Energy Agency). 2004. *World Energy Outlook*. http://www.worldenergy-outlook.org/we-2004/.

———. 2012. *World Energy Outlook*. http://www.worldenergyoutlook.org/weo2012/.

———. 2013. *World Energy Outlook*. http://www.worldenergyoutlook.org/weo2013/.

———. 2014. *Africa Energy Outlook*. http://www.iea.org/publications/freepublications/publication/WEO2014_AfricaEnergyOutlook.pdf

Jack, William, and Tavneet Suri. 2011. "Mobile Money: The Economics of M-PESA." *NBER Working Paper* 16721.

Jacobsen, Arne. 2007. "Connective Power: Solar Electrification and Social Change in Kenya." *World Development* 35(1): 144-162.

Jensen, Robert. 2007. "The Digital Provide: Information (Technology), Market Performance, and Welfare in the South Indian Fisheries Sector." *Quarterly Journal of Economics* 122(3): 879-924.

Joskow, Paul. 2000. "Deregulation and Regulatory Reform in the U.S. Electric Power Sector," in *Deregulation of Network Industries: What's Next?* Sam Peltzman and Clifford Winston, eds. Washington, D.C.: AEI-Brookings Joint Center for Regulatory Studies, 113-54.

Karlan, Dean, Robert Osei, Isaac Osei-Akoto, and Christopher Udry. 2014. "Agricultural Decisions After Relaxing Credit and Risk Constraints." *Quarterly Journal of Economics* 129(2): 597-652.

Khandker, Shahidur, Hussain A. Samad, Rubaba Ali, and Douglas F. Barnes. 2014. "Who Benefits Most from Rural Electrification? Evidence in India." *Energy Journal* 35(2): 75-96.

Khandker, Shahidur R., Douglas F. Barnes, and Hussain A. Samad. 2012. "The Welfare Impacts of Rural Electrification in Bangladesh." Energy Journal 33(1): 187-206.

———. 2013. "Welfare Impacts of Rural Electrification: A Panel Data Analysis from Vietnam." *Economic Development and Cultural Change* 61(3): 659-692.

Kitchens, Carl, and Price Fishback. 2015. "Flip the Switch: The Impact of the Rural Electrification Administration 1935-1940." *Journal of Economic History* 75(4): 1161-1195.

Kline, Patrick, and Enrico Moretti. 2014. "Local Economic Development, Agglomeration Economies, and the Big Push: 100 Years of Evidence from the Tennessee Valley Authority." *Quarterly Journal of Economics* 129(1): 275-331.

Kremer, Michael, and Edward Miguel. 2007. "The Illusion of Sustainability." *Quarterly Journal of Economics* 122(3): 1007-1065.

Kremer, Michael and Jack Willis. 2016. "Guns, Latrines, and Land Reform: Dynamic Pigouvian Taxation." *American Economic Review: Papers & Proceedings* 106(5): 83-88.

Lipscomb, Molly, Mobarak, Ahmed Mushfiq, and Tania Barham. 2013. "Development Effects of Electrification: Evidence from the Topographic Placement of Hydropower Plants in Brazil." *American Economic Journal: Applied Economics* 5(2): 200-231.

Lee, Kenneth, Eric Brewer, Carson Christiano, Francis Meyo, Edward Miguel, Matthew Podolsky, Javier Rosa, and Catherine Wolfram. 2016. "Electrification for "Under Grid" Households in Rural Kenya." *Development Engineering* 1: 26-35.

Lee, Kenneth, Edward Miguel, Catherine Wolfram. 2016a. "Appliance Ownership & Aspirations among Electric Grid and Home Solar Households in Rural Kenya." *American Economic Review: Papers & Proceedings* 106(5): 89-94.

———. 2016b. "Experimental Evidence on the Demand for and Costs of Rural Electrification." Unpublished working paper.

Lucas, Adrienne M., and Isaac M. Mbiti. 2012a. "Access, Sorting, and Achievement: The Short-Run Effects of Free Primary Education in Kenya." *American Economic Journal: Applied Economics* 4(4): 226-253.

———. 2012b. "The Determinants and Consequences of School Choice Errors in Kenya." *American Economic Review: Papers & Proceedings* 102(3): 283-288.

Mankiw, N. Gregory. 2011. *Principles of Economics, 5th Edition*. Cengage Learning.

Murphy, James J., P. Geoffrey Allen, Thomas H. Stevens, Darryl Weatherhead. 2005. "A Meta-Analysis of Hypothetical Bias in Stated Preference Valuation." *Environmental and Resource Economics* 30(3): 313-325.

Ohba, Asayo. 2011. "The Abolition of Secondary School Fees in Kenya: Responses by the Poor." *International Journal of Educational Development* 31: 402-408.

Parshall, Lily, Dana Pillai, Shashank Mohan, Aly Sanoh, Vijay Modi. 2009. "National Electricity Planning in Settings with Low Pre-Existing Grid Coverage: Development of a Spatial Model and Case Study of Kenya." *Energy Policy* 37(6): 2395-2410.

Patil, Sumeet R., Benjamin F. Arnold, Alicia L. Salvatore, Bertha Briceno, Sandipan Ganguly, John M. Colford Jr., and Paul Gertler. 2014. "The Effect of India's Total Sanitation Campaign on Defecation Behaviors and Child Health in Rural Madhya Pradesh: A Cluster Randomized Controlled Trial" *PLoS Medicine* 11(8): e1001709.

Reinikka, Ritva, Jakob Svensson. 2004. "Local Capture: Evidence from a Central Government Transfer Program in Uganda." *Quarterly Journal of Economics* 119(2): 679-705.

Samuelson, Paul A., and William D. Nordhaus. 1998. *Economics*. Boston: Irwin/McGraw-Hill.

Steinbuks, J., and V. Foster. 2010. "When Do Firms Generate? Evidence on In-House Electricity Supply in Africa." *Energy Economics* 32(3): 505-14.

Viscusi, W. Kip, John M. Vernon, and Joseph Emmett Harrington. 2005. *Economics of Regulation and Antitrust*. Cambridge, Mass: MIT Press.

Wolfram, Catherine, Orie Shelef, and Paul Gertler. 2012. "How Will Energy Demand Develop in the Developing World?" *Journal of Economic Perspectives* 26(1): 119-138.

World Bank. 2008. "The Welfare Impact of Rural Electrification: A Reassessment of the Costs and Benefits. An IEG Impact Evaluation." Washington, DC.

———. 2016. "Doing Business 2016: Measuring Regulatory Quality and Efficiency." Washington, DC.

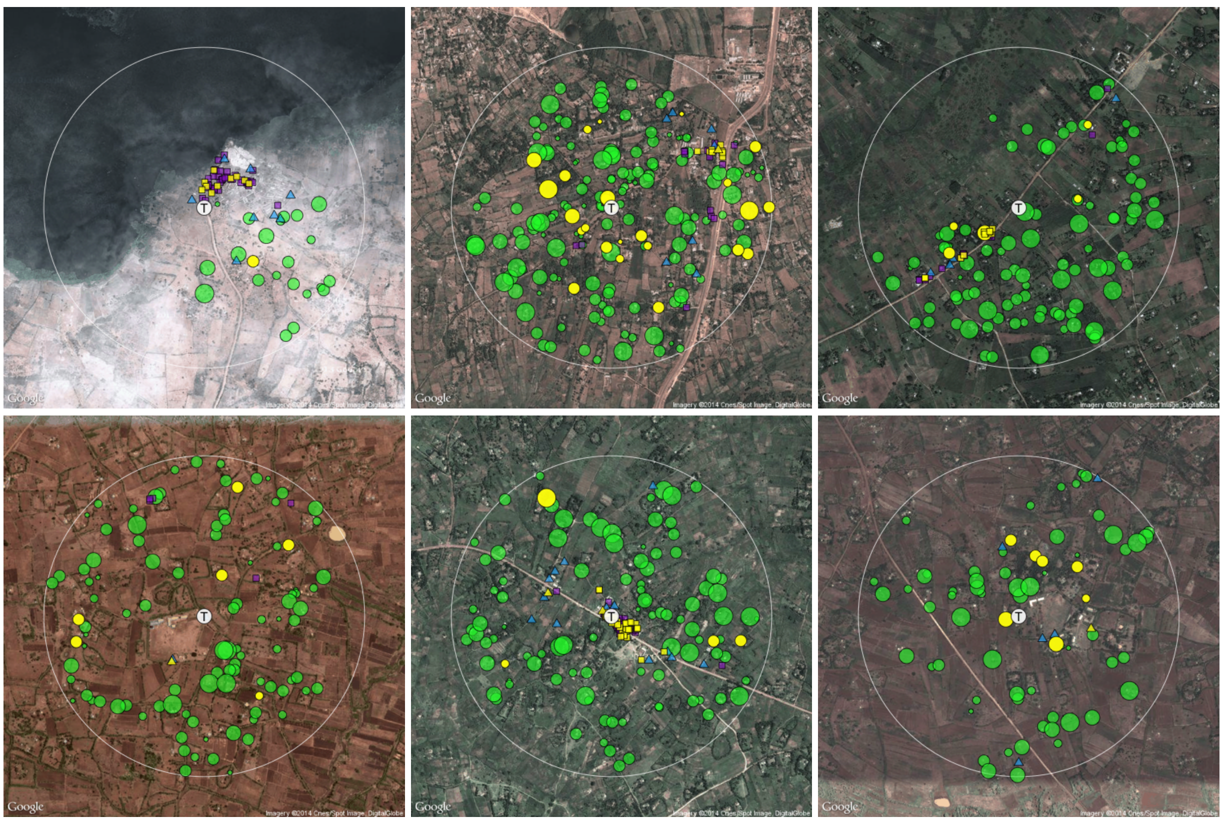
Yatchew, Adonis. 2000. "Scale Economies in Electricity Distribution: A Semiparametric Analysis." *Journal of Applied Econometrics* 15: 187-210.

Zvoleff, Alex, Ayse Selin Kocaman, Woonghee Tim Huh, and Vijay Modi. 2009. "The Impact of Geography on Energy Infrastructure Costs." *Energy Policy 37* (10): 4066-4078.

Appendix A

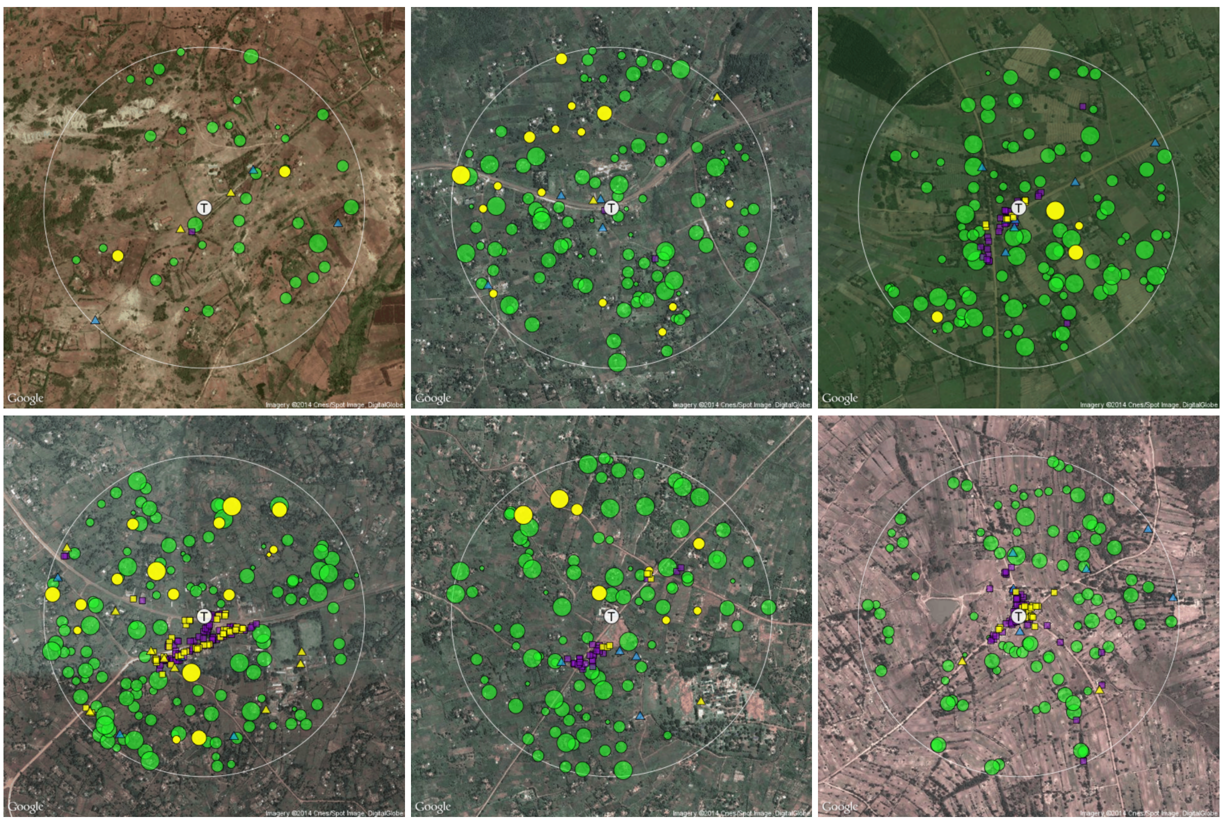
Electrification for "Under Grid" Households Appendix

Appendix Figure A1—Maps of transformer communities 1 to 6.



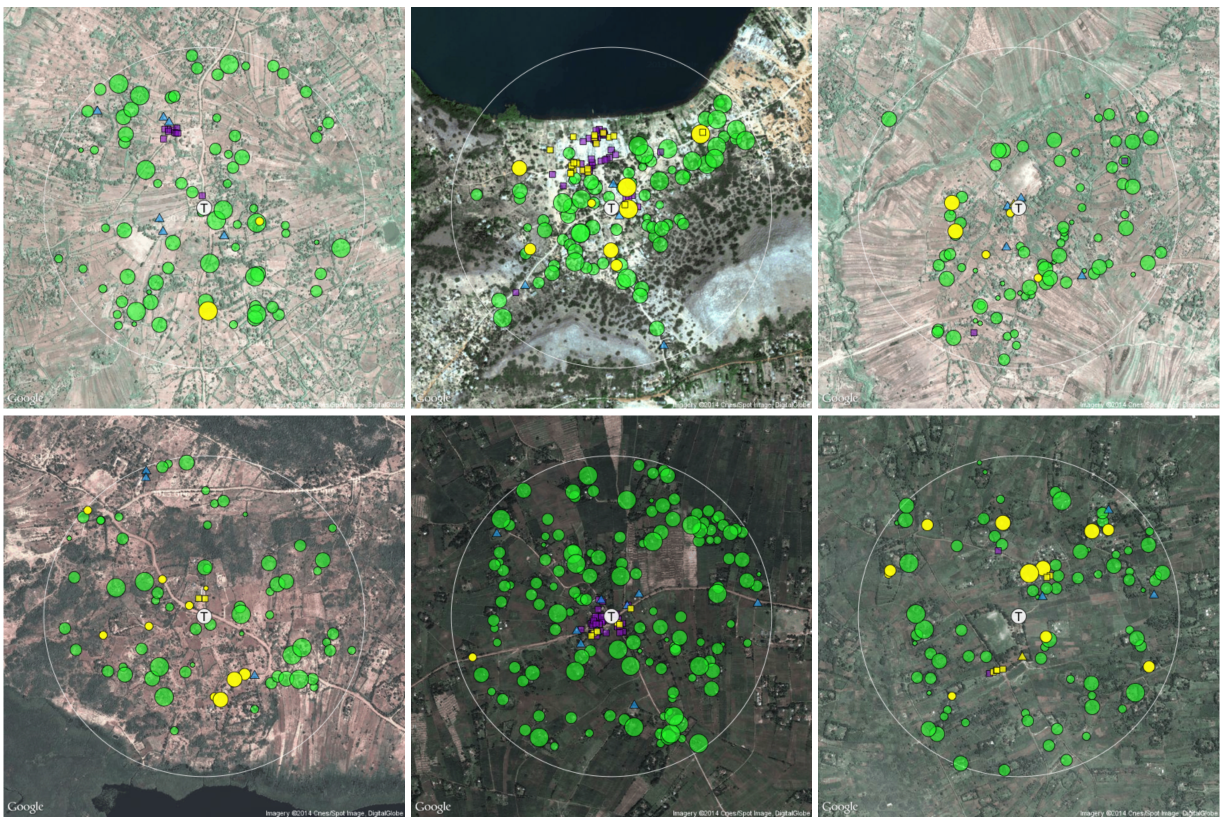
Note: The white circle labeled “T” in the center identifies the location of the REA transformer. The larger white outline demarcates the 600-meter radius boundary. Green circles represent unconnected households; purple squares represent unconnected businesses; and blue triangles represent unconnected public facilities. Yellow circles, squares, and triangles indicate households, businesses, and public facilities with visible electricity connections, respectively. Household markers are scaled by household size, with the largest indicating households with more than ten members, and the smallest indicating single-member households. Residential rental units are categorized as households.

Appendix Figure A2—Maps of transformer communities 7 to 12.



Note: The white circle labeled "T" in the center identifies the location of the REA transformer. The larger white outline demarcates the 600-meter radius boundary. Green circles represent unconnected households; purple squares represent unconnected businesses; and blue triangles represent unconnected public facilities. Yellow circles, squares, and triangles indicate households, businesses, and public facilities with visible electricity connections, respectively. Household markers are scaled by household size, with the largest indicating households with more than ten members, and the smallest indicating single-member households. Residential rental units are categorized as households.

Appendix Figure A3—Maps of transformer communities 13 to 18.



Note: The white circle labeled “T” in the center identifies the location of the REA transformer. The larger white outline demarcates the 600-meter radius boundary. Green circles represent unconnected households; purple squares represent unconnected businesses; and blue triangles represent unconnected public facilities. Yellow circles, squares, and triangles indicate households, businesses, and public facilities with visible electricity connections, respectively. Household markers are scaled by household size, with the largest indicating households with more than ten members, and the smallest indicating single-member households. Residential rental units are categorized as households.

Appendix B

Appliance Ownership and Aspirations Appendix

Table B1—Difference between kerosene and home solar households

	Kerosene (1)	Home solar (2)	p-value of diff. (3)
Panel A: Household head (respondent) characteristics			
Female (%)	63.1	60.1	0.40
Age (years)	52.5	50.6	0.12
Completed secondary schooling (%)	12.1	26.3	< 0.01
Married (%)	64.9	76.8	< 0.01
Not a farmer (%)	22.1	26.3	0.19
Basic political awareness (%)	10.7	18.7	< 0.01
Has bank account (%)	16.0	42.4	< 0.01
Panel B: Household characteristics			
Number of members	5.2	6.0	< 0.01
Youth members (age $\leqq 18$)	3.0	3.3	0.04
High-quality walls (%)	14.3	34.8	< 0.01
Land (acres)	1.9	2.8	< 0.01
Distance to transformer (m)	356.8	353.8	0.77
Monthly (non-charcoal) energy (USD)	5.42	6.53	< 0.01
Monthly kerosene (USD)	3.90	3.41	0.06
Panel C: Household assets			
Bednets	2.2	3.0	< 0.01
Sofa pieces	5.6	10.1	< 0.01
Chickens	6.5	12.1	< 0.01
Radios	0.41	0.55	< 0.01
Televisions	0.16	0.45	< 0.01
Sample size	2,091	198	

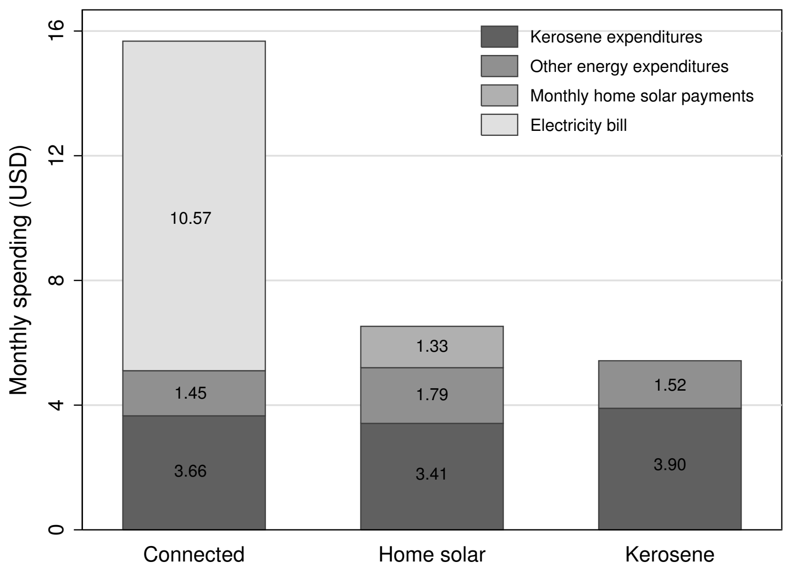
Notes: Columns 1 and 2 report sample means for unconnected households that primarily rely on kerosene and home solar at the time of the survey. Column 3 reports p-value of the difference between the means. Basic political awareness indicator captures whether the household head was able to correctly identify the presidents of Uganda, Tanzania, and the United States. Monthly (non-charcoal) energy expenditures includes kerosene expenditures.

Table B2—Current and future installed capacity in Kenya

(in MW)	2014	%	2031*e*	%
Hydro	827	36.0	1,039	5.3
Diesel	751	32.8	1,955	10.0
Geothermal	593	25.9	5,530	25.6
Gas turbine	60	2.6	2,340	11.9
Wind	26	1.1	2,036	10.4
Nuclear	0	0.0	4,000	20.4
Coal	0	0.0	2,720	13.9
Other	38	1.7	0.0	0.0
Total	2,295	100.0	19,620	100.0
Fossil	*811*	*35.3*	*7,015*	*35.8*
Non-fossil	*1,484*	*64.7*	*12,605*	*64.2*

Notes: Breakdown of 2014 installed capacity is obtained from the website of Kenya's Energy Regulatory Commission. Breakdown of 2031 installed capacity is based on the Government of Kenya's *Vision 2030: Least Cost Power Development Plan*. Fossil fuel energy sources include coal, gas turbines (LNG), and diesel. In the planning documents, an additional 2,000 MW of electricity will be imported through regional interconnections with Uganda, Tanzania, and Ethiopia in 2031. These imports will consist primarily of hydroelectric power sources from Ethiopia and Uganda.

Figure B1—Monthly spending on all energy sources (excluding charcoal)



Notes: Other energy expenditures includes batteries, car battery charging, fuel for generators, and mobile charging. Monthly amounts for kerosene and other energy expenditures are estimated based on household responses to total spending amounts over the last seven days.

Note B1—Additional notes for Figure 2.1

Based on a survey of 2,504 connected and unconnected households in Western Kenya. Households are divided into three categories: (1) *connected* to the grid ($n = 215$), (2) unconnected to the grid but using *home solar* (e.g. solar lanterns or solar home systems) ($n = 198$), and (3) *unconnected* to the grid with no home solar ($n = 2,091$). For each item, the bars indicate the proportion of households in each group declaring that they either own (dark grey) or desire (light grey) the appliance. Electrical appliances are divided into two categories based on required wattages. Low-wattage appliances can be powered using most solar home products. High-wattage appliances require higher power systems or connections to the grid. In addition, "torch" refers to rechargeable lanterns, "music" includes stereo systems and electronic musical instruments, "kitchen" includes blenders, kettles, microwaves, toasters, water coolers, and food processors, and "income" includes large appliances that are typically used for income-generating purposes, including posho mills, welding machines, blowdryers and shavers, water pumps, and battery chargers.

Note B2—Data sources for Figure 2.2

In this note, we summarize the data sources used to construct Figure 2.2.

I. Newly Industrialized Countries (NICs)

All estimates of installed capacity, non-fossil fuel generation and population are obtained from The World Factbook. The list of NICs includes China (CHN), India (IND), Indonesia (IDN), Brazil (BRA), Mexico (MEX), Philippines (PHL), Turkey (TUR), Thailand (THA), South Africa (ZAF), and Malaysia (MYS). Estimates for installed capacity range in date from 2012 to 2014.

II. Sub-Saharan Africa (SSA)

We focus on the top ten electricity producers in Sub-Saharan Africa based on The World Factbook's 2012 rankings. The list of SSAs include Nigeria (NGA), Ethiopia (ETH), Democratic Republic of the Congo (COD), Kenya (KEN), Ghana (GHA), Mozambique (MOZ), Cote dIvoire (CIV), Angola (AGO), Zambia (ZMB), and Zimbabwe (ZWE). For the NICs, we rely solely on The World Factbook estimates. For the SSAs, we examine current and future installed capacities more closely, referring to all types of publicly available sources online. Population estimates are obtained from The World Factbook.

a) Nigeria (NGA)

There are a variety of estimates for recent installed capacity and non-fossil fuel generation. These include USAID Power Africa, which estimates 6,000 MW of current installed capacity and non-fossil fuel generation of 20-30%. We use an alternative, more detailed source, energypedia.info, which provides a list of grid-connected power plants in Nigeria. We exclude the 2015 plant from the list and estimate 2014 installed capacity to be 6,713 MW with 16.19% coming from non-fossil fuel sources. However, it should be noted that in Nigeria, there is a discrepancy between installed capacity and actual capacity due to gas shortages. For future installed capacity, we use the estimates on energypedia.info that cite “The Presidency of the Federal Republic of Nigeria, August 2013, Roadmap for Power Sector Reform, Revision1, p. 24-25.” We could not find the original source.

b) Ethiopia (ETH)
We refer to USAID Power Africa for estimates of 2015 installed capacity and non-fossil fuel generation. These estimates are dated to 2015 and cite the “Ethiopian Ministry of Water, Irrigation and Energy (2015).” We could not find the original source. For future installed capacity, we note that according to USAID Power Africa, “Ethiopia aspires to have a total installed generation capacity of 37,000 MWs and become a major power exporter [by 2037].” There are many sources that state that Ethiopia is targeting 37,000 MW by 2037. However, we could not find the Government of Ethiopia’s “Power System Expansion Master Plan” which we assume provides the breakdown of future installed capacity. In the news, we find that hydropower covers some 80 per cent of total energy the country plans to generate, followed by geothermal sources ((Article #1), and that “according to the EEPCo, Ethiopia has a potential to produce some 45,000 megawatts of electricity from hydro-power alone” (Article #2). This leads us to the assumption that the majority of (if not all) new capacity will come from non-fossil sources. Furthermore, in a presentation by the Ministry of Water and Energy, delivered in 2013, the next 9,000 MW of capacity will come from hydro, wind, and geothermal. In Figure 2, we assume that all new capacity will come from non-fossil fuel sources.

c) Democratic Republic of the Congo (COD)
Estimates for 2012 installed capacity and non-fossil fuel generation are based on The World Factbook. We could not find any government projections for future installed capacity.

d) Kenya (KEN)
Estimates for 2014 installed capacity are obtained from the Energy Regulatory Commission (ERC) website. Estimates for 2031 installed capacity are based on Kenya Vision 2030. In 2031, non-fossil fuel sources will consist of geothermal, nuclear, wind, and hydro. Fossil fuel sources will consist of coal, gas turbines (LNG), and diesel. These figures are also confirmed on the ERC Least Cost Power Development Plan. We exclude the 2,000 MW of imports that are shown in these figures, since we are primarily interested in installed capacity.

e) Ghana (GHA)
Estimates for 2014 installed capacity are obtained from the Ghana Energy Commission. Current non-fossil fuel generation is based on the list of power plants provided on energypedia.info. In the Ministry of Energys Energy Sector Strategy and Development Plan, there is a target of 5,000 MW by 2015 with 10% coming from (non hydro) renewable sources by 2020. According to USAID Power Africa, the 5,000 MW capacity is targeted by 2016, not 2015. There is no breakdown provided for the 5,000 MW of future capacity. In Figure 2, we assume that 10% of the 5,000 MW will come from renewable sources, and

the remainder will come in the same proportion as the existing portfolio. We assume a target year of 2020.

f) Mozambique (MOZ)
Estimates for 2014 installed capacity are obtained from energypedia.info. Estimates of future installed capacity are obtained from news articles citing the Government of Mozambique's (2015-2019) 5-Year Plan (Article #1). We assume that the 3,600 MW of new capacity will consist entirely of hydro sources .

g) Cote dIvoire (CIV)
Estimates for 2012 installed capacity and non-fossil fuel generation are based on The World Factbook. Estimates for 2030 are based on a slide citing CI-ENERGIES 2013. The figure also appears here. We could not locate the original source.

h) Angola (AGO)
Estimates for 2012 installed capacity and non-fossil fuel generation are based on The World Factbook. Future installed capacity based on a Bloomberg article citing 9,000 MW of installed capacity by 2025. We assume that all of this new capacity will be hydro, based on the Energy Information Agency, which states that "Angola has also set an ambitious long-term goal of increasing hydropower capacity to 9,000 megawatts by 2025 by building up to 15 new plants, with the help of foreign investment."

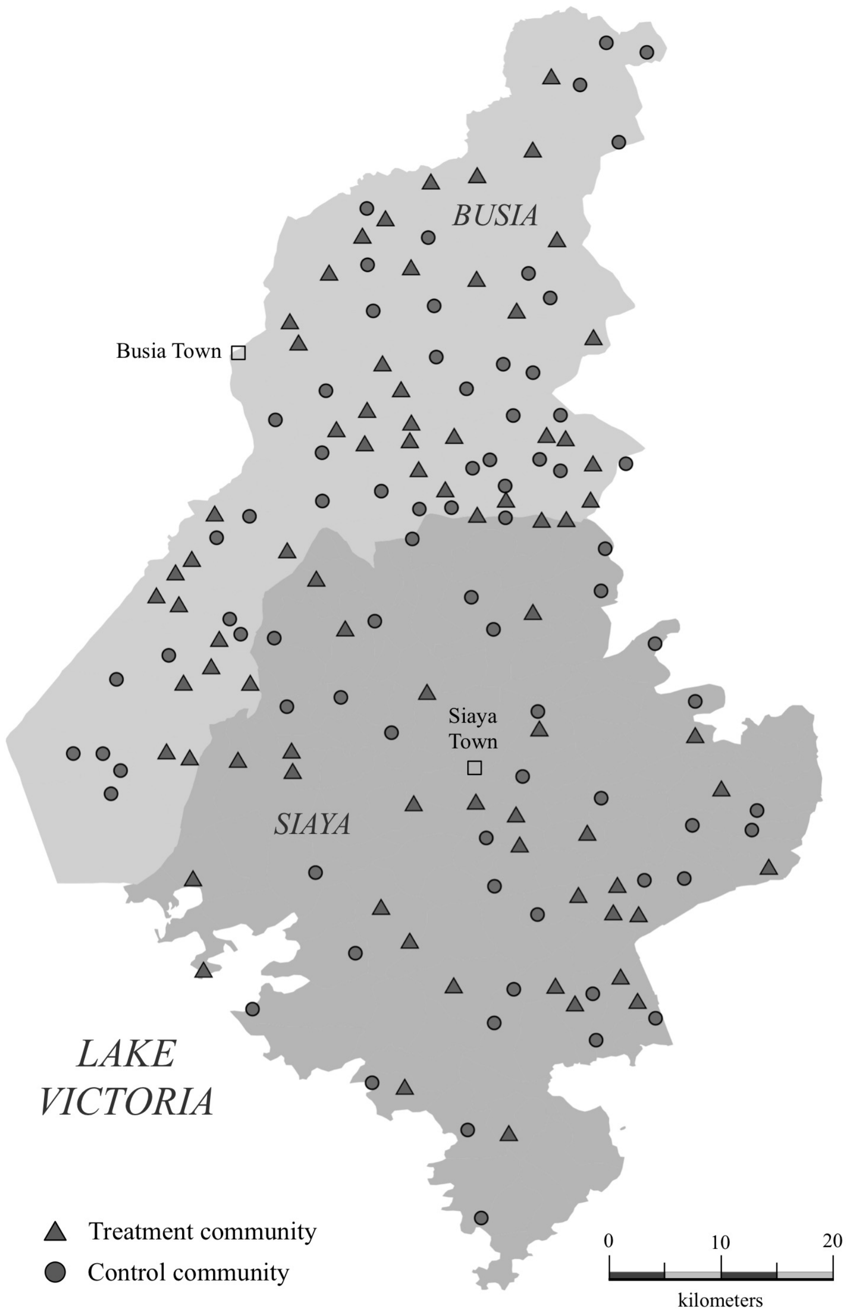
i) Zambia (ZMB)
Estimates for 2014 and 2018 installed capacity and non-fossil fuel generation are obtained from the Zambia Energy Regulation Board. We assume that the target completion year for the Kafue Gorge Lower Hydropower Project is 2018 based on this source.

j) Zimbabwe (ZWE)
Estimates for 2012 installed capacity and non-fossil fuel generation are based on The World Factbook. We could not find any government projections for future installed capacity.

Appendix C

Experimental Evidence Appendix

Figure C1—150 sample communities in Busia and Siaya counties in Kenya



Notes: The final sample of 150 communities includes 85 and 65 transformers in Busia and Siaya counties, respectively.

Figure C2—Example of REA offer letter for a subsidized household electricity connection

Rural Electrification Authority

NYANZA REGION OFFICE
Mamboleo junction, Opposite Lake Basin Development Authority, Kisumu – Kakamega Highway
P.O. Box 2604 – 40100

ipa Innovations for Poverty Action

Tom Mboya Drive,
Milimani Kisumu.
P.O. Box 313

ELECTRICITY SUPPLY TO YOUR PREMISES (ESP)

UNIQUE CUSTOMER LOCATION DETAILS:

Project name: |______________________| Reference number: |______________________|

Transformer: |______________________| Substation number: |______________________|

Customer name: |______________________________________|

Customer address: |______________________________________|

Household coordinates: |______________________| LATITUDE

|______________________| LONGITUDE

Dear Sir/Madam,

Reference is made to the ongoing *Rural Electric Power Project* research project that is being carried out by Innovations for Poverty Action (IPA) in partnership with REA in this community. As part of this research project, we are pleased to advise you that a single-phase service cable can be installed to your premises at the following price:

SINGLE-PHASE SUPPLY CONNECTION: KES [EFFECTIVE PRICE]

If you would like to accept this offer, kindly arrange to pay this amount to the Rural Electrification Authority account at Kenya Commercial Bank, Milimani Branch, Account Number: 1103201557.

NOTICE: When making your payment, please remember to quote your unique ID number: [NUMBER] in the memo line. Please keep a copy of your bank payment slip for official receipting. This receipt is very important and must be shown to IPA in order to complete this process. No payment should be made to any individual. Your payment should only be made to the REA bank account above. This offer is valid for 8 weeks:

DATE OF OFFER: DD-MM-YY **DATE OF EXPIRY:** DD-MM-YY

For further enquiries, please contact the REA Regional Coordinator, Nyanza Region, [NAME] at [MOBILE] or the IPA Project Associate in Busia Town, [NAME] at [MOBILE].

For: RURAL ELECTRIFICATION AUTHORITY

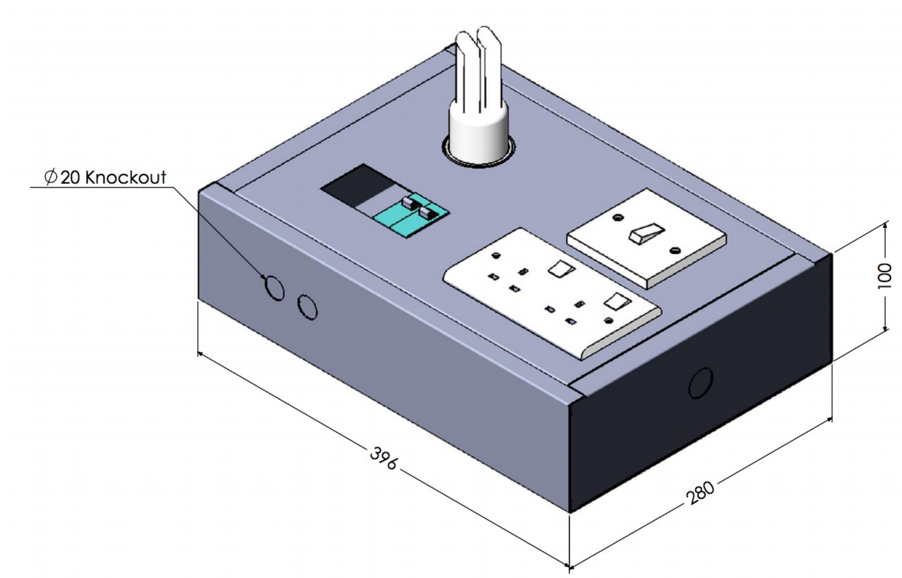
____

[NAME]
REGIONAL CO-ORDINATOR, NYANZA REGION.

Unique ID: [NUMBER]

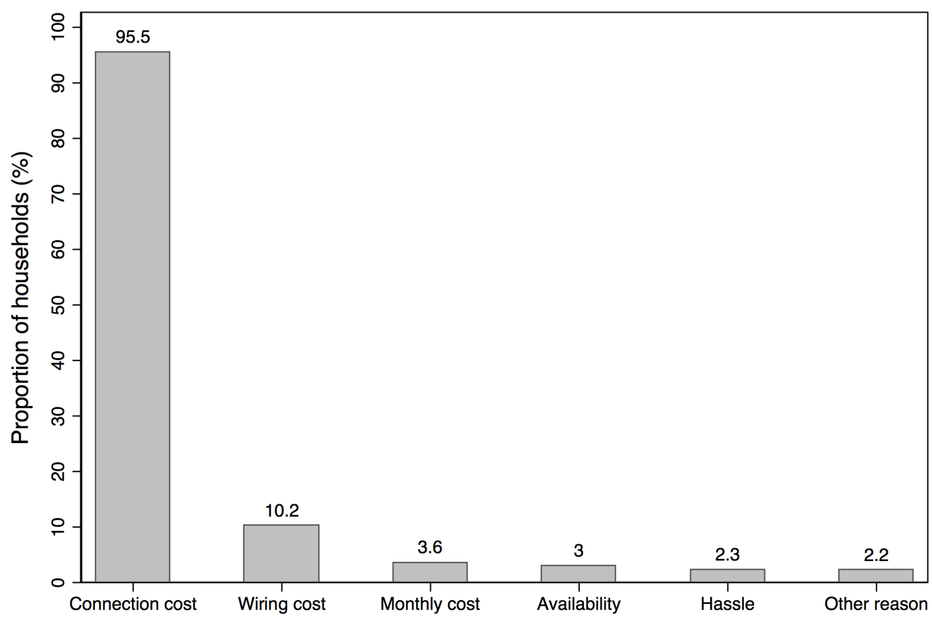
Notes: Each offer letter was signed and guaranteed by REA management. Project field staff members visited each treatment community and explained the details of the offer to a representative from each household in a community meeting.

Figure C3—*Umeme Rahisi* “ready-board” designed by Power Technics



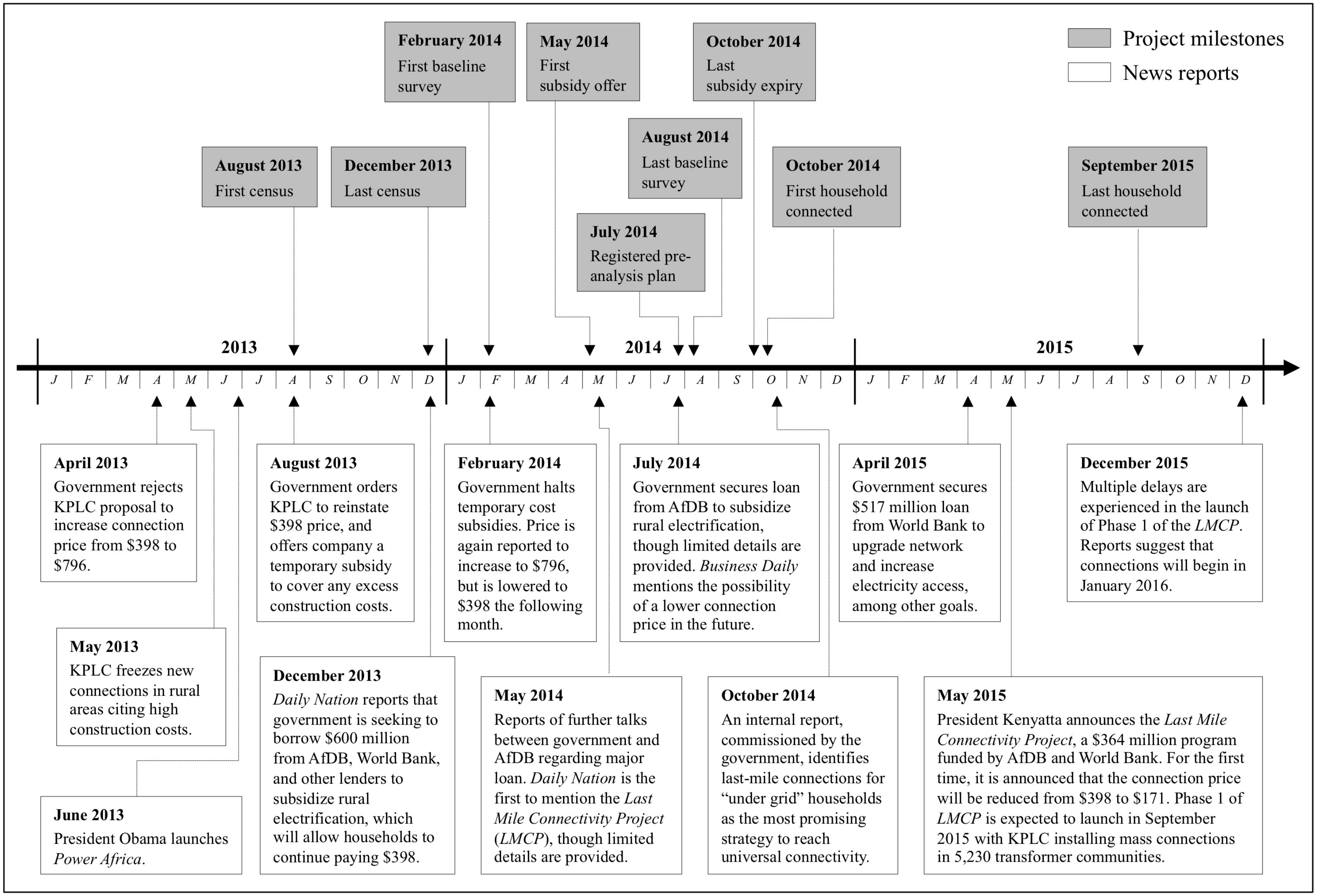
Notes: Treatment households received an opportunity to install a certified household wiring solution in their homes at no additional cost. 88.5 percent of the households connected in the experiment accepted this offer, while 11.5 percent provided their own wiring. Each ready-board, valued at roughly $34 per unit, featured a single light bulb socket, two power outlets, and two miniature circuit breakers. The unit is first mounted onto a wall and the electricity service line is directly connected to the back. The hardware was designed and produced by Power Technics, an electronic supplies manufacturer in Nairobi.

Figure C4—Stated reasons why households remain unconnected to electricity at baseline



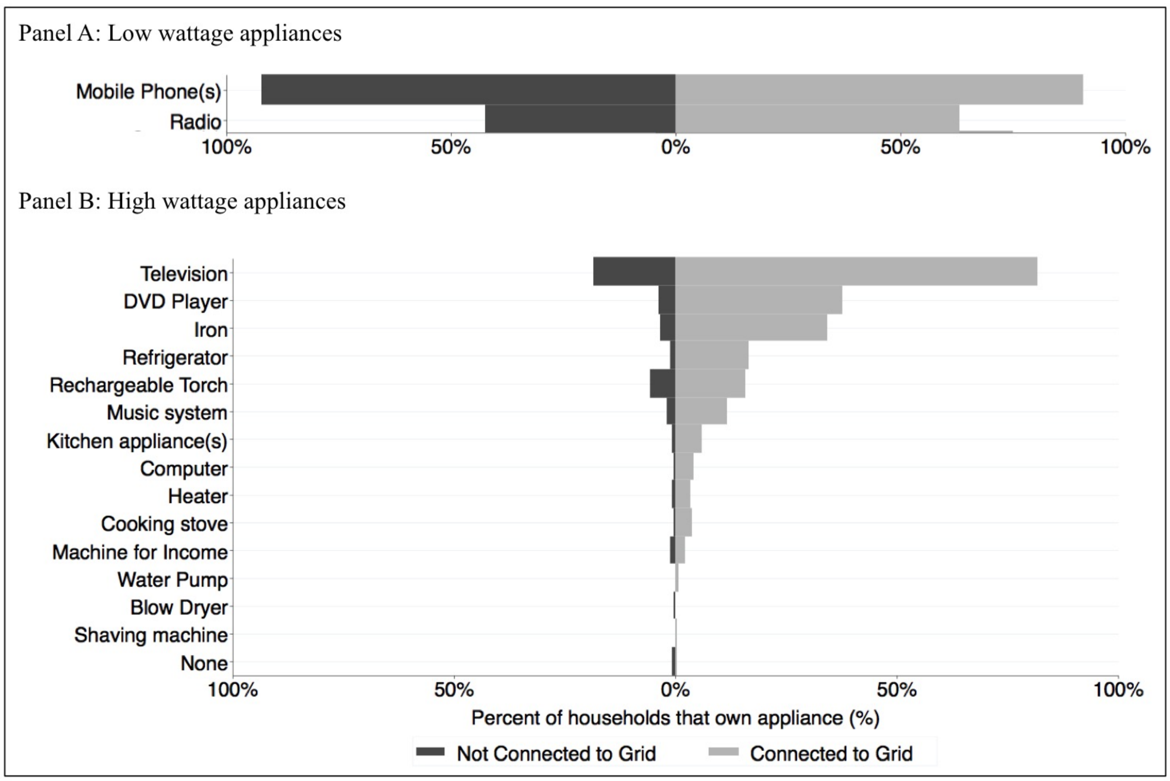
Notes: Based on the responses of 2,289 unconnected households during the baseline survey round.

Figure C5—Timeline of project milestones and connection price-related news reports over the period of study



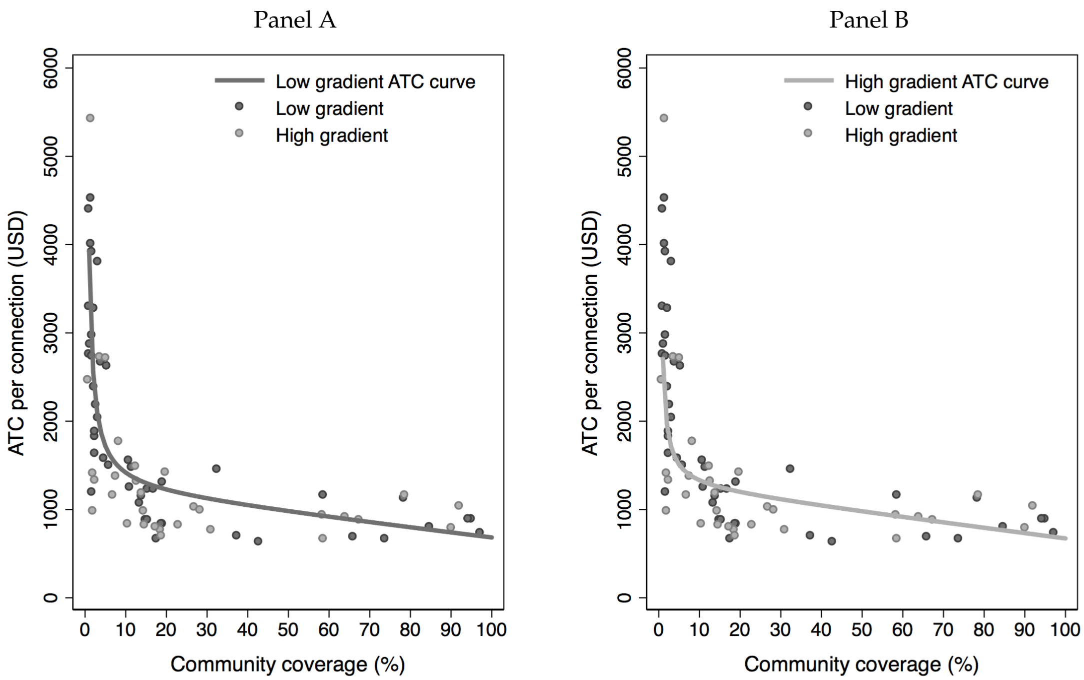
Notes: Sources for news reports include *Daily Nation*, Kenya's leading national newspaper, and *Business Daily*.

Figure C6—Electrical appliances owned by unconnected and connected households at baseline



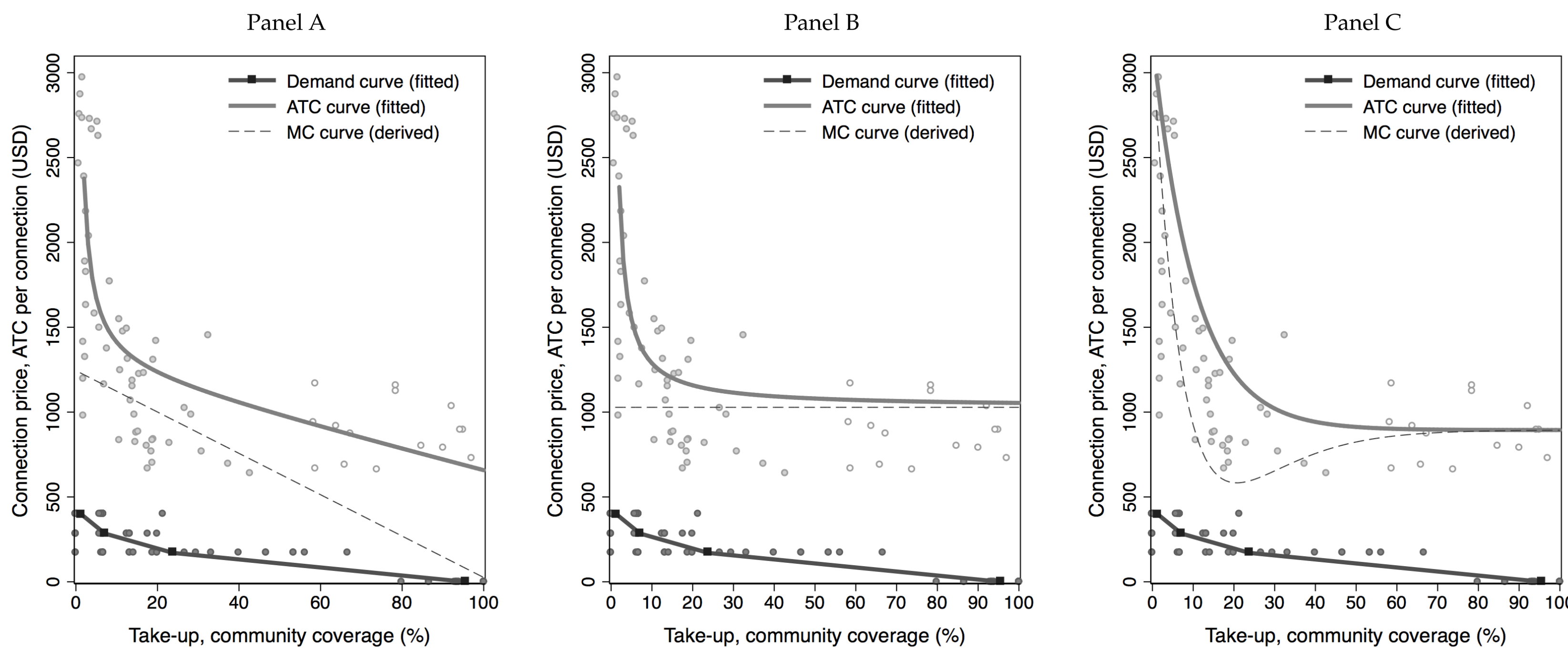
Notes: Based on the responses of 2,289 unconnected households and 215 connected households during the baseline survey round. See Lee, Miguel, and Wolfram (2016a) for a discussion.

Figure C7—Average total cost (ATC) per connection by land gradient



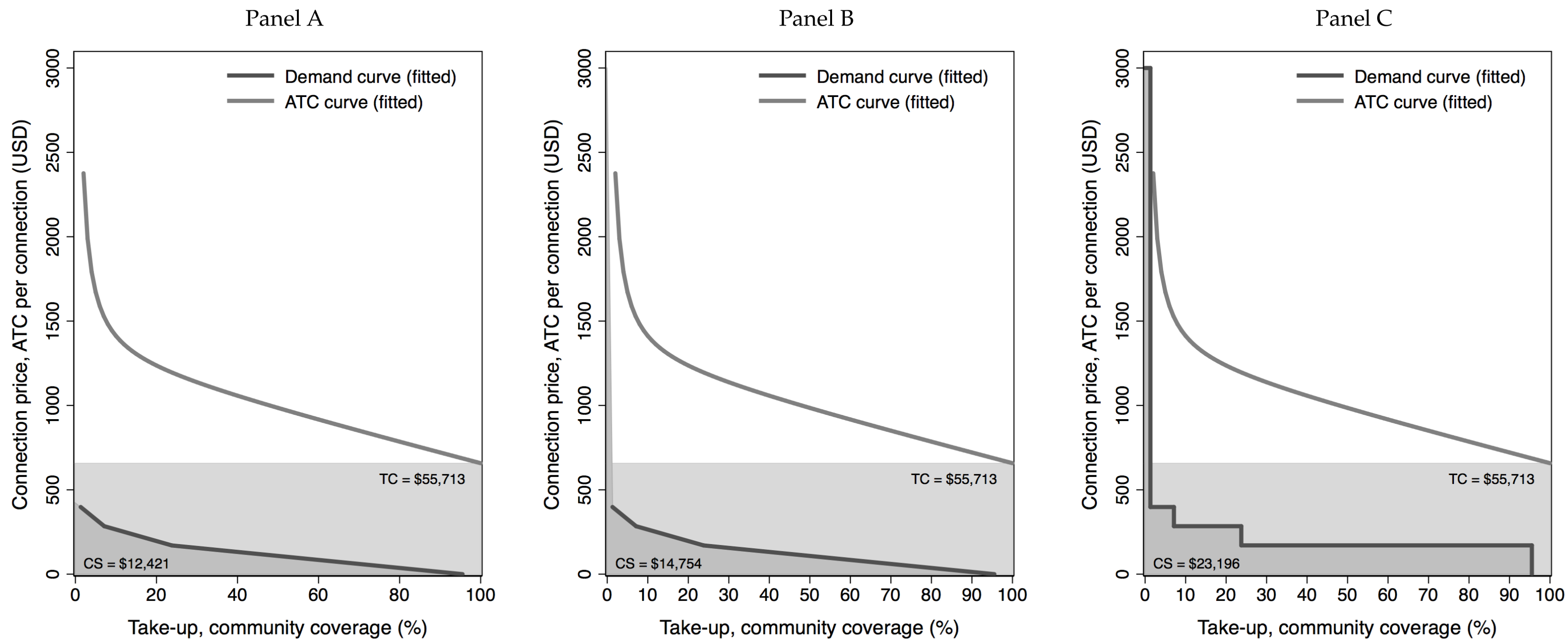
Notes: In the sample of communities, average land gradient ranges from 0.79 to 7.76 degrees with a mean of 2.15 degrees. We divide the sample into communities with "low" average land gradient (i.e., below median) gradient and communities with "high" average land gradient (i.e., above median). In Panels A and B, we plot fitted lines from nonlinear estimations of $ATC = b_0/x + b_1 + b_2x$ for the low and high gradient subsamples, respectively (they lie nearly on top of each other so we present them here in separate panels for clarity).

Figure C8—Experimental estimates of a natural monopoly: Alternative functional forms



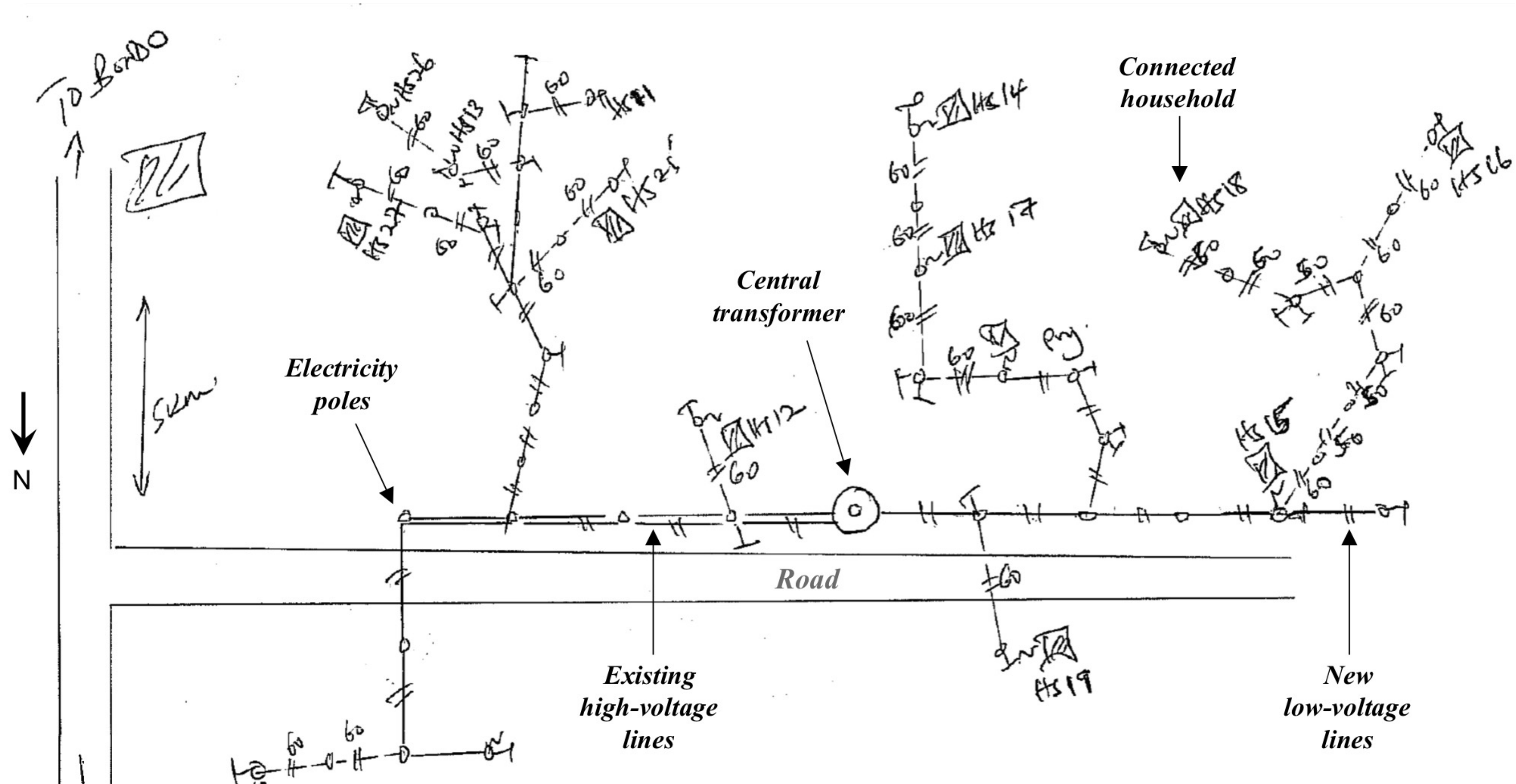
Notes: Panel A reproduces Figure 3.6, Panel A. In Panel B, we estimate an average total cost curve with constant variable costs. In Panel C, we estimate an exponential function to derive a marginal cost curve.

Figure C9—Welfare loss associated with rural electrification under various demand curve assumptions



Notes: Panel A reproduces Figure 3.6, Panel B. In this scenario, the welfare loss associated with a mass electrification program is $43,292 per community. In Panel B, we estimate the area under the unobserved [0, 1.3] domain by assuming that the demand curve intercepts the vertical axis at $3,000, rather than $424 (as in Panel A). In this more conservative case, the welfare loss is $41,611 per community. In order to overturn this result (i.e. costs exceeding the consumer surplus), the intercept would need to be an astronomical $32,300. In Panel C, the most conservative case, we assume that demand is a step function and calculate the welfare loss to be $32,517 per community. The required discounted future welfare gains needed for consumer surplus to exceed total costs across the three scenarios range from $384 (in Panel C) to $511 (in Panel A) per household.

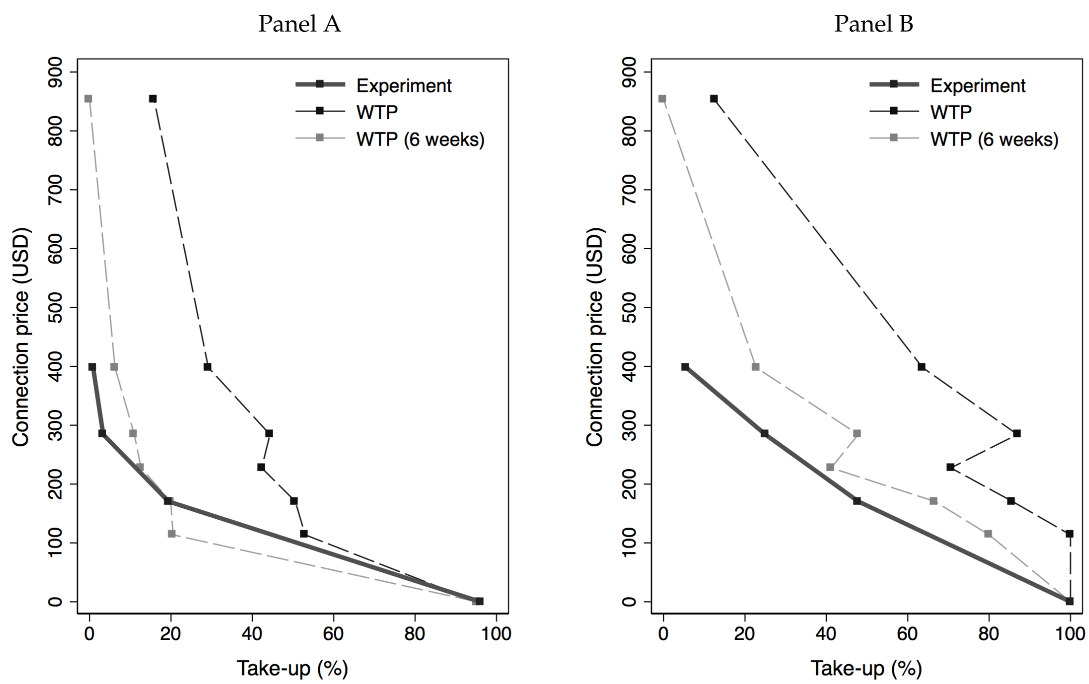
Figure C10—Example of a REA design drawing in a high subsidy treatment community



Treatment Site #1113:					
Location:	Market	Designed poles:	27	Budgeted cost:	$9,104
HHs connected:	15	Actual poles:	27	Invoiced cost:	$8,674

Notes: After receiving payment, REA designers visited each treatment community to design the local low-voltage network. The designs were then used to estimate the required materials and determine a budgeted estimates of the total construction cost. Materials (e.g. poles, electricity line, service cables) represented 65.9 percent of total installation costs. The community in this example is the same as that shown in Figure 3.2.

Figure C11—Stated willingness to pay with and without time constraints, by wall quality and bank accounts



Notes: We plot the experimental results (solid black line) against the responses to a set of contingent valuation questions included in the baseline survey. Households were first asked whether they would accept a hypothetical offer (i.e., randomly assigned price) to connect to the grid (dashed line, black squares). Households were then asked whether they would accept the same hypothetical offer if required to complete the payment in six weeks (dashed line, grey squares). In Panel A, the sample contains all households with low-quality walls and no bank account (n=1,647). In Panel B, the sample contains all households with high-quality walls and a bank account (n=236).

Table C1—Comparison of social and economic indicators for study region and nationwide counties

		Nationwide county percentiles		
	Study region	25th	50th	75th
Total population	793,125	528,054	724,186	958,791
per square kilometer	375.4	39.5	183.2	332.9
% rural	85.7	71.6	79.5	84.4
% at school	44.7	37.0	42.4	45.2
% in school with secondary education	10.3	9.7	11.0	13.4
Total households	176,630	103,114	154,073	202,291
per square kilometer	83.6	7.9	44.3	78.7
% with high quality roof	59.7	49.2	78.5	88.2
% with high quality floor	27.7	20.6	29.7	40.0
% with high quality walls	32.2	20.3	28.0	41.7
% with piped water	6.3	6.9	14.2	30.6
Total public facilities	644	356	521	813
per capita (000s)	0.81	0.59	0.75	0.98
Electrification rates				
Rural (%)	2.3	1.5	3.1	5.3
Urban (%)	21.8	20.2	27.2	43.2
Public facilities (%)	84.1	79.9	88.1	92.6

Notes: The study region column presents weighted-average and average (where applicable) statistics for Busia and Siaya counties. Specifically, total population, total households, and total public facilities represent averages for Busia and Siaya. We exclude Nairobi and Mombasa, two counties that are entirely urban, from the nationwide county percentile columns. Demographic data is obtained from the 2009 Kenya Population and Housing Census (KPHC). Public facility electrification data is obtained from the Rural Electrification Authority (REA). High quality roof indicates roofs made of concrete, tiles, or corrugated iron sheets. High quality floor indicates floors made of cement, tiles, or wood. High quality walls indicates walls made of stone, brick, or cement. Rural and urban electrification rates represent the proportion of households that stated that electricity was their main source of lighting during the 2009 census. Based on the 2009 census data, the mean (county-level) electrification rates in rural and urban areas were 4.6 and 32.6 percent, respectively. Nationally, the rural and urban electrification rates were 5.1 and 50.4 percent, respectively, and 22.7 percent overall. An earlier version of this table is presented in Lee et al. (2016).

Table C2—Baseline summary statistics and randomization balance check

		Regression coefficients on subsidy treatment indicators			
	Control	Low	Medium	High	p-value of F-test
	(1)	(2)	(3)	(4)	(5)
Panel A: Household head (respondent)					
Female=1	0.63	0.021	-0.026	-0.015	0.624
	[0.48]	(0.031)	(0.029)	(0.032)	
Age (years)	52.04	-1.098	1.029	1.701	0.287
	[16.29]	(1.242)	(1.064)	(1.388)	
Completed secondary school=1	0.14	-0.012	0.025	-0.033	0.297
	[0.34]	(0.024)	(0.027)	(0.025)	
Married=1	0.66	-0.005	0.013	-0.024	0.856
	[0.47]	(0.033)	(0.033)	(0.033)	
Not a farmer=1	0.23	0.002	-0.029	-0.004	0.793
	[0.42]	(0.036)	(0.031)	(0.026)	
Basic political awareness=1	0.13	-0.051***	-0.009	-0.026	0.039
	[0.33]	(0.018)	(0.020)	(0.016)	
Has bank account=1	0.19	-0.032	0.003	-0.022	0.452
	[0.39]	(0.022)	(0.028)	(0.025)	
Panel B: Household characteristics					
Number of members	5.30	-0.265*	0.100	-0.294*	0.071
	[2.71]	(0.145)	(0.160)	(0.177)	
Youth members (age $\leqq$ 18)	3.03	-0.101	0.075	-0.214	0.247
	[2.17]	(0.122)	(0.120)	(0.144)	
High-quality walls=1	0.15	0.051**	0.039	-0.014	0.092
	[0.36]	(0.025)	(0.030)	(0.026)	
Land (acres)	1.85	0.299	0.229	0.054	0.414
	[2.14]	(0.201)	(0.214)	(0.149)	
Distance to transformer (m)	348.6	14.85	9.50	22.10**	0.173
	[140.0]	(9.85)	(12.15)	(10.64)	
Monthly (non-charcoal) energy (USD)	5.55	-0.234	0.495*	-0.432	0.026
	[5.20]	(0.266)	(0.267)	(0.283)	

(*Table continued on next page*)

(*Table continued from previous page*)

		Regression coefficients on subsidy treatment indicators			
	Control	Low	Medium	High	p-value of F-test
	(1)	(2)	(3)	(4)	(5)
Panel C: Household assets					
Bednets	2.27	-0.032	0.056	0.000	0.887
	[1.50]	(0.091)	(0.092)	(0.096)	
Bicycles	0.66	-0.027	0.076	0.016	0.353
	[0.74]	(0.042)	(0.052)	(0.052)	
Sofa pieces	5.92	-0.039	0.477	-0.008	0.66
	[5.21]	(0.366)	(0.399)	(0.403)	
Chickens	7.03	0.420	-0.421	-0.218	0.739
	[8.74]	(0.690)	(0.616)	(0.680)	
Cattle	1.74	0.069	0.190	0.232	0.514
	[2.32]	(0.151)	(0.192)	(0.185)	
Radios	0.34	-0.015	0.047	-0.002	0.41
	[0.48]	(0.028)	(0.033)	(0.040)	
Televisions	0.16	0.001	-0.003	-0.054**	0.132
	[0.37]	(0.022)	(0.025)	(0.024)	
Panel D: Community characteristics					
Electrification rate (%)	5.25	1.57	-0.03	-0.08	0.674
	[4.61]	(1.34)	(0.99)	(0.86)	
Community population	534.69	42.10	26.37	9.85	0.793
	[219.02]	(45.01)	(41.70)	(39.13)	

Notes: Column 1 reports mean values for the control group, with standard deviations in brackets. Columns 2 to 4 report the coefficients from separate regressions in which a dependent variable is regressed on the full set of treatment indicators and stratification variables (including county, market status, and whether the transformer was funded and installed early on, between 2008 and 2010). Standard errors are in parantheses. Column 5 reports the p-values of F-tests of whether the treatment coefficients are jointly equal to zero. Robust standard errors clustered at the community level. Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$. Sample sizes range from 2,279 to 2,289 depending on missing values except in the specification with Age as the dependent variable where the sample size is 2,205. The variables selected for the randomization check were not specified in the pre-analysis plan.

Table C3—Characteristics of households taking-up electricity by treatment arm

	High subsidy Price: $0 (1)	Medium subsidy Price: *$171* (2)	Low subsidy Price: *$284* (3)	Control Price: $398 (4)
Panel A: Resp. characteristics				
Female (%)	61.71	58.89	59.26	60.00
Age (years)	53.69	52.82	50.56	51.62
Attended sec. school (%)	9.92	27.78***	33.33***	26.67**
Married (%)	64.19	74.44*	70.37	66.67
Not a farmer (%)	22.31	28.89	29.63	28.57
Basic political awareness (%)	9.64	16.67*	14.81	6.67
Has bank account (%)	17.13	31.11***	40.74***	35.71*
Panel B: Household characteristics				
Number of members	5.02	6.19***	6.22**	5.80
Youth members	2.81	3.52***	3.89**	3.29
High-quality walls (%)	12.95	25.56***	51.85***	33.33**
Land (acres)	1.93	2.20	2.56	2.14
Distance to transformer (m)	369.74	357.41	369.06	360.67
Monthly energy (USD)	5.16	7.62***	8.24***	5.88
Panel C: Household assets				
Bednets	2.29	2.77***	3.44***	2.53
Sofa pieces	5.88	8.96***	9.44***	8.87**
Chickens	6.90	9.07**	10.31*	6.43
Radios	0.34	0.48**	0.48	0.53
Televisions	0.11	0.28***	0.48***	0.40***
Take-up of elec. connections	363	90	27	15

Notes: Columns 1, 2, and 3 report sample means for unconnected households that chose to take-up a subsidized electricity connection. Column 4 reports sample means for control group households that chose to connect on their own. Basic political awareness indicator captures whether the household head was able to correctly identify the heads of state of Tanzania, Uganda, and the United States. The asterisks in columns 2, 3, and 4 indicate statistically significant differences compared to column 1: * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

Table C4A—Impact of connection subsidy on take-up: Interactions with community-level variables

		Interacted variable			
		Busia county	Transformer funded early on	Market center	Baseline population
	(1)	(2)	(3)	(4)	(5)
T1: Low subsidy—29% discount	5.94***	2.65	4.97***	6.34***	2.29
	(1.50)	(1.71)	(1.89)	(1.71)	(3.97)
T2: Medium subsidy—57% discount	22.88***	20.93***	26.81***	23.54***	18.48*
	(4.02)	(5.78)	(6.23)	(4.80)	(10.27)
T3: High subsidy—100% discount	94.97***	95.19***	93.74***	94.92***	100.05***
	(1.27)	(1.69)	(1.73)	(1.64)	(4.49)
Interacted variable		0.20	0.24	0.88	-0.00
		(0.85)	(0.81)	(1.01)	(0.00)
T1 × interacted variable		5.59**	2.06	-1.64	0.01
		(2.65)	(3.06)	(3.32)	(0.01)
T2 × interacted variable		3.48	-8.19	-2.71	0.01
		(8.01)	(7.90)	(8.98)	(0.02)
T3 × interacted variable		-0.42	2.67	0.15	-0.01
		(2.59)	(2.52)	(2.43)	(0.01)
Take-up in control group	1.30	1.30	1.30	1.30	1.30
Observations	2176	2176	2176	2176	2176
R-squared	0.69	0.69	0.69	0.69	0.69

Notes: The dependent variable is an indicator variable (multiplied by 100) for household take-up. The mean of the dependent variable is 21.6. Robust standard errors clustered at the community level in parentheses. All specfications include the household and community covariates specified in the pre-analysis plan. Household covariates include the age of the household head, indicators for whether the household respondent attended secondary school, is a senior citizen, is not primarily a farmer, is employed, and has a bank account, an indicator for whether the household has high-quality walls, and the number of chickens (a measure of assets) owned by the household. Community covariates include indicators for the county, market status, whether the transformer was funded and installed early on (between 2008 and 2010), baseline electrification rate, and community population. Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$. The number of observations in the above regressions is somewhat smaller than the total number of households in our sample (2,289) due to missing data. The coefficients do not change appreciably when the households with missing data are included in the regression with no covariates (as in column 1).

Table C4B—Impact of connection subsidy on take-up: Interactions with household-level variables

	Interacted variable				
	Household size	Age of household head	Senior household head	Number of chickens	Has bank account
	(1)	(2)	(3)	(4)	(5)
T1: Low subsidy—29% discount	0.61	5.49	5.55***	4.68***	4.50***
	(2.67)	(4.96)	(1.71)	(1.42)	(1.38)
T2: Medium subsidy—57% discount	9.81*	26.19***	23.66***	17.21***	20.30***
	(5.71)	(7.06)	(4.17)	(3.78)	(4.10)
T3: High subsidy—100% discount	94.16***	95.22***	95.50***	93.79***	94.91***
	(2.75)	(3.52)	(1.24)	(1.83)	(1.43)
Interacted variable	0.00	0.04	1.19	-0.07*	1.07
	(0.16)	(0.04)	(1.31)	(0.04)	(1.24)
T1 × interacted variable	1.01*	0.01	1.70	0.18	8.43
	(0.53)	(0.09)	(4.25)	(0.12)	(5.87)
T2 × interacted variable	2.41***	-0.06	-3.05	0.84***	13.54*
	(0.88)	(0.11)	(3.56)	(0.27)	(7.25)
T3 × interacted variable	0.13	-0.01	-2.01	0.16	-0.04
	(0.44)	(0.07)	(2.28)	(0.11)	(2.55)
Take-up in control group	1.30	1.30	1.30	1.30	1.30
Observations	2176	2176	2176	2176	2176
R-squared	0.69	0.69	0.69	0.70	0.69

Notes: The dependent variable is an indicator variable (multiplied by 100) for household take-up. The mean of the dependent variable is 21.6. Robust standard errors clustered at the community level in parentheses. All specfications include the household and community covariates specified in the pre-analysis plan. Household covariates include the age of the household head, indicators for whether the household respondent attended secondary school, is a senior citizen, is not primarily a farmer, is employed, and has a bank account, an indicator for whether the household has high-quality walls, and the number of chickens (a measure of assets) owned by the household. Community covariates include indicators for the county, market status, whether the transformer was funded and installed early on (between 2008 and 2010), baseline electrification rate, and community population. Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$. The number of observations in the above regressions is somewhat smaller than the total number of households in our sample (2,289) due to missing data. The coefficients do not change appreciably when the households with missing data are included in the regression with no covariates (as in column 1).

Table C5—Impact of scale on average total cost (ATC) per connection

	Sample & Designed—OLS			
	(1)	(2)	(3)	(4)
Number of connections (M)	-87.77***	-81.11***	-83.42***	-114.05***
	(15.11)	(16.45)	(17.01)	(18.84)
M^2	0.83***	0.76***	0.79***	1.31***
	(0.18)	(0.20)	(0.21)	(0.25)
Land gradient		-173.90***	-599.29***	
		(58.05)	(164.10)	
Land gradient × M			36.68***	
			(13.86)	
Land gradient × M^2			-0.33*	
			(0.17)	
Households				-6.07
				(11.49)
Households × M				0.17
				(0.47)
Households × M^2 / 100				-0.91*
				(0.53)
Busia=1		247.69	461.80	304.85
		(388.75)	(391.79)	(448.41)
Market transformer=1		-148.84	-32.07	-170.02
		(195.41)	(185.58)	(177.70)
Transformer funded early on=1		109.29	128.41	41.56
		(218.63)	(216.06)	(205.59)
Community electrification rate		15.89	15.16	9.18
		(15.41)	(14.09)	(13.90)
Community population		-0.66	-0.90	0.48
		(0.66)	(0.68)	(1.92)
Round-trip distance to REA (km)		1.60	-2.45	-0.08
		(3.61)	(3.66)	(3.80)
Community controls	No	Yes	Yes	Yes
Observations	77	77	77	77
R^2	0.43	0.48	0.54	0.52

Notes: The dependent variable is the budgeted average total cost (ATC) per connection in USD. Robust standard errors are clustered at the community level. Community covariates were specified in the pre-analysis plan. Average land gradient ranges from 0.79 to 7.76 degrees with a mean of 2.15 degrees. Column 4 includes interaction terms with an additional variable—the (demeaned) number of households (i.e., residential compounds) in each community. Asterisks indicate coefficient significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

Table C6—Breakdown of labor and transport costs for nine projects (three contracts)

	Contract #1	Contract #2	Contract #3
Panel A: Labor costs (e.g., digging holes, installation, clearing bush, dropping service lines, etc.)			
Budgeted LV poles	40	107	62
Invoiced LV poles	38	98	76
Actual (counted) LV poles	39	92	60
Difference (Actual - Invoiced)	*+1*	*-6*	*-16*
Avg. labor cost per LV pole	*27.59*	*27.59*	*27.59*
Total LV poles labor	1,048	2,704	1,655
Budgeted stays	–	–	35
Invoiced stays	32	68	43
Avg. labor cost per stay	*19.22*	*19.22*	*19.22*
Total stays labor	615	1,308	827
Budgeted HV poles	–	–	6
Invoiced HV poles	12	5	6
Avg. labor cost per HV pole	*35.59*	*35.59*	*35.59*
Total HV poles labor	427	178	214
Additional labor	832	1,552	2,199
Total labor	2,922	5,742	4,895

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	Contract #1	Contract #2	Contract #3
Panel B: Transport costs (e.g., wood pole and other materials)			
Large lorries	2	4	4
Invoiced round-trip distance (km)	320	300	300
Google round-trip distance (km)	218	256	218
Difference (Actual - Invoiced)	*-102*	*-44*	*-82*
Avg. cost per km	*3.75*	*3.75*	*3.75*
Total large lorry transport	2,402	4,503	4,503
Small lorries	1	3	2
Invoiced round-trip distance (km)	250	250	250
Avg. cost per km	2.98	2.98	2.98
Total small lorry transport	745	2,234	1,490
Total transport	3,146	6,738	5,993
Budgeted labor and transport costs	6,126	12,708	8,956
Invoiced labor and transport costs	7,040	14,477	12,516
Difference (Invoiced - Budgeted)	*14.9%*	*13.9%*	*39.8%*
Projects, households connected	3, 18	3, 38	3, 22
Construction days	36	31	35

Notes: "LV" denotes low-voltage and "HV" denotes high-voltage. Additional labor includes costs of bush clearing, tree cutting, signage, dropping service cables, and other expenses. Each large lorry is capable of transporting 30 poles. Each small lorry is capable of transporting 2.3 km of line materials.

Table C7—Reasons for unexpected delays in household electrification

Phase	Description	Reasons for unexpected delays
A2	Wiring	• In order to begin using electricity, households are required to have a valid meter and a certificate of wiring safety. A large proportion of households were not able to register for a meter because they lacked a PIN (*Personal Identification Number*) certificate from the Kenya Revenue Authority. In our sample, 42 percent of households applying for electricity needed assistance in applying for a PIN certificate.
B1	Design	• Competing priorities at REA due to the 2014/15 nationwide initiative to connect primary schools to the national grid. This resulted in a persistent shortage of REA designers and planners. • Low motivation to perform design duties. In addition, since REA designers were required to physically visit each community, there were numerous challenges in scheduling field visits.
B2	Contracting	• Competing priorities (described above) delayed the bureaucratic paperwork required to prepare contracts. • REA staff members had strong preferences to assign certain projects to specific contractors. This resulted in delays because REA wanted to wait until specific contractors were free to take on new projects.
B3	Construction	• Insufficient materials (e.g., poles, cables) requiring site revisits. • Poor weather (i.e., rainy conditions) made roads impassable and digging holes (for electricity poles) impossible. • Issues in securing wayleaves (i.e., right of ways) to pass through neighboring properties. • Low-quality construction work that needed to be fixed. • Missing materials. • Faulty transformers requiring contractors to revisit sites to complete the final step of the process (e.g., connecting the new low-voltage network to the existing line). • Incorrect households were connected to the network, requiring site revisits. • Contractor issues installing “ready-boards” due to lack of experience.

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Phase	Description	Reasons for unexpected delays
B4	Metering	• Insufficient materials (e.g., prepaid meters, cables) contributed to lengthy delays at Kenya Power. • Lost meter application forms at local Kenya Power offices. • Changes in internal Kenya Power processes requiring applications to be approved in Nairobi as well as local offices in Siaya, Kisumu, and Busia. • Unexpected requests by local Kenya Power representatives for additional documents (e.g., photocopies of payment receipts). • Local Kenya Power representatives unable to perform metering duties due to competing priorities. • Scheduling difficulties due to the necessity for Kenya Power to make multiple trips to remote village sites, which increased the costs (metering costs are not documented in our cost estimates).

Notes: Each phase of the construction process corresponds to the timeline bar in Figure 3.8.

Table C8—Transformer problems in study communities during the 14-month study period (between September 2014 and October 2015)

Row	Site ID	Group	Wave	Treated HHs	Connected	Metered	Blackout	Primary issue
1	1204	Treatment	2	15	Feb-15	May-15	4 months	Burnt out
2	1403	Treatment	1	15	Mar-15	Jul-15	1 month	Commissioning
3	1505	Treatment	2	1	Mar-15	May-15	1 month	Commissioning
4	2101	Treatment	1	0	n/a	n/a	8 months	Burnt out
5	2103	Treatment	1	0	n/a	n/a	4 months	Technical failure
6	2106	Treatment	1	15	Nov-14	Nov-14	8 months	Commissioning
7	2114	Treatment	1	8	Dec-14	Dec-14	12 months	Relocated by Kenya Power
8	2116	Treatment	1	14	Sep-14	May-15	2 months	Technical failure
9	2202	Treatment	1	1	Sep-14	Oct-14	1 month	Technical failure
10	2217	Treatment	1	13	Oct-14	Dec-14	1 month	Technical failure
11	2222	Treatment	1	3	Oct-14	Dec-14	4 months	Leaking oil
12	2303	Treatment	2	7	May-15	Jun-15	4 months	Technical failure
13	2406	Treatment	2	15	Apr-15	Jun-15	1 month	Burnt out
14	2503	Treatment	1	1	Oct-14	Oct-14	6 months	Burnt out
15	2506	Treatment	1	15	Dec-14	Feb-15	9 months	Commissioning

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Row	Site ID	Group	Wave	Treated HHs	Connected	Metered	Blackout	Primary issue
16	1103	Control	n/a	0	n/a	n/a	2 months	Technical failure
17	1109	Control	n/a	0	n/a	n/a	6 months	Burnt out
18	1203	Control	n/a	0	n/a	n/a	1 month	Technical failure
19	1205	Control	n/a	0	n/a	n/a	1 month	Technical failure
20	1405	Control	n/a	0	n/a	n/a	6 months	Burnt out
21	1410	Control	n/a	0	n/a	n/a	2 months	Relocated by Kenya Power
22	2103	Control	n/a	0	n/a	n/a	4 months	Burnt out
23	2115	Control	n/a	0	n/a	n/a	2 months	Technical failure
24	2212	Control	n/a	0	n/a	n/a	5 months	Burnt out
25	2220	Control	n/a	0	n/a	n/a	8 months	Burnt out
26	2304	Control	n/a	0	n/a	n/a	3 months	Stolen
27	2315	Control	n/a	0	n/a	n/a	3 months	Burnt out
28	2504	Control	n/a	0	n/a	n/a	4 months	Technical failure
29	2515	Control	n/a	0	n/a	n/a	4 months	Damaged by weather

Note: "Commissioning" refers to a situation in which the transformer (and related equipment) is installed but electricity is not being delivered.

Table C9A—Impact of randomized offers on take-up

	WTP 1	WTP 2	Experiment
	(1)	(2)	(3)
\$853 offer	-19.74***	-8.21***	
	(3.68)	(2.11)	
\$284 offer / T1: Low subsidy—29% discount	16.26***	6.02**	5.94***
	(3.39)	(2.50)	(1.50)
\$227 offer	14.25***	7.33***	
	(3.56)	(2.74)	
\$171 offer / T2: Medium subsidy—57% discount	24.08***	18.50***	22.88***
	(3.37)	(2.66)	(4.02)
\$114 offer	25.20***	19.71***	
	(3.51)	(2.88)	
Free offer / T3: High subsidy—100% discount	62.04***	87.47***	94.97***
	(2.90)	(2.20)	(1.27)
Number of household members	1.26***	0.43	0.62***
	(0.39)	(0.33)	(0.21)
High-quality walls=1	9.07***	11.63***	3.53
	(2.66)	(2.34)	(2.14)
Number of chickens=1	0.70***	0.40***	0.12**
	(0.12)	(0.11)	(0.06)
Age (years)	-0.39***	-0.18**	0.03
	(0.09)	(0.07)	(0.04)

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	WTP 1	WTP 2	Experiment
	(1)	(2)	(3)
Attended secondary school=1	15.61***	5.41**	3.77**
	(2.69)	(2.36)	(1.71)
Over 65 years old=1	0.90	1.30	0.53
	(3.48)	(3.04)	(1.40)
Not a farmer=1	0.37	0.10	1.86
	(2.40)	(1.94)	(1.63)
Has bank account=1	11.13***	11.03***	2.57
	(2.51)	(2.49)	(1.70)
Employed=1	2.27	1.18	1.06
	(2.17)	(1.88)	(1.27)
Take-up in status quo (i.e., $398) group	36.24	9.81	1.30
Mean of dependent variable	53.73	25.54	21.60
Observations	2,157	2,157	2,176
R^2	0.23	0.35	0.69

Notes: In column 1, the dependent variable is an indicator for whether the household accepted the hypothetical offer (i.e. randomly assigned price) to connect to the grid; in column 2, an indicator for whether the household accepted the hypothetical offer if required to complete the payment in six weeks; in column 3, an indicator for experimental take-up. All dependent variables are multplied by 100. Robust standard errors clustered at the community level in parentheses. All specfications include community covariates. Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

Table C9B—Impact of WTP offer on stated take-up of electricity connections

		Interacted variable		
	Baseline	High-quality walls	Has bank account	Attended secondary schooling
	(1)	(2)	(3)	(4)
\$853 offer	-8.21***	-6.00***	-7.95***	-5.40**
	(2.11)	(2.24)	(1.92)	(2.17)
\$284 offer / T1: Low subsidy—29% discount	6.02**	5.02**	4.86*	6.01**
	(2.50)	(2.42)	(2.57)	(2.40)
\$227 offer	7.33***	6.59**	7.15**	7.73***
	(2.74)	(2.82)	(2.80)	(2.72)
\$171 offer / T2: Medium subsidy—57% discount	18.50***	15.96***	16.59***	17.14***
	(2.66)	(2.69)	(2.85)	(2.69)
\$114 offer	19.71***	18.40***	15.03***	20.02***
	(2.88)	(3.21)	(2.94)	(2.91)
Free offer / T3: High subsidy—100% discount	87.47***	89.64***	89.58***	89.32***
	(2.20)	(2.27)	(2.08)	(2.15)
Interacted variable		7.95	5.63	7.23
		(5.26)	(4.76)	(5.94)
\$853 offer × interacted variable		-8.95	-4.06	-17.96***
		(6.43)	(7.56)	(6.14)
\$284 offer × interacted variable		6.40	5.47	0.02
		(8.51)	(7.28)	(8.82)
\$227 offer × interacted variable		4.62	0.60	-2.70
		(8.51)	(7.39)	(8.54)
\$171 offer × interacted variable		15.71*	9.90	11.38
		(8.29)	(7.79)	(9.88)
\$114 offer × interacted variable		8.50	25.10***	-2.09
		(8.55)	(8.38)	(9.16)
Free offer × interacted variable		-11.53*	-15.06**	-17.21**
		(5.92)	(5.91)	(6.62)
Take-up in status quo (i.e., \$398) group	9.81	9.81	9.81	9.81
Mean of dependent variable	25.54	25.54	25.54	25.54
Observations	2,157	2,157	2,157	2,157
R^2	0.35	0.36	0.36	0.35

Notes: The dependent variable is an indicator (multiplied by 100) for whether the household accepted the hypothetical offer if required to complete the payment in six weeks. All specfications include the household and community covariates specified in the pre-analysis plan. Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

Table C9C—Predictors of financial constraints in WTP questions

	(1)	(2)
\$853 offer	90.32***	91.37***
	(5.24)	(5.53)
\$398 offer / Existing fixed price	72.93***	75.86***
	(4.10)	(4.05)
\$284 offer / T1: Low subsidy—29% discount	70.30***	72.20***
	(3.33)	(3.44)
\$227 offer	65.92***	68.21***
	(3.72)	(3.80)
\$171 offer / T2: Medium subsidy—57% discount	52.73***	55.05***
	(3.30)	(3.39)
\$114 offer	52.89***	54.20***
	(3.35)	(3.40)
Number of household members		-0.05
		(0.53)
High-quality walls=1		-12.51***
		(3.27)
Number of chickens=1		-0.23*
		(0.14)
Age (years)		0.14
		(0.12)
Attended secondary school=1		0.09
		(3.07)
Over 65 years old=1		-3.53
		(5.18)
Not a farmer=1		0.27
		(3.16)
Has bank account=1		-10.74***
		(3.21)
Employed=1		0.37
		(2.91)
Mean of dependent variable	52.36	52.46
Observations	1,184	1,159
R^2	0.25	0.27

Notes: The dependent variable is an indicator (multiplied by 100) for whether the household first accepted the hypothetical offer to connect to the grid, and then declined the hypothetical offer if required to pay in six weeks. Robust standard errors clustered at the community level in parentheses. Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$.

Table C9D—Comparison of stated willingness to pay and experimental curves

	WTP1	WTP2
	(1)	(2)
\$284 offer / T1: Low subsidy—29% discount	5.80***	5.80***
	(1.37)	(1.37)
\$171 offer / T2: Medium subsidy—57% discount	22.44***	22.44***
	(4.01)	(4.01)
Free offer / T3: High subsidy—100% discount	94.22***	94.22***
	(1.17)	(1.17)
WTP indicator	34.94***	8.50***
	(2.73)	(1.71)
\$284 × WTP indicator	9.10**	-0.42
	(3.69)	(2.83)
\$171 × WTP indicator	-1.09	-5.03
	(5.28)	(4.69)
Free offer × WTP indicator	-34.42***	-7.99***
	(3.31)	(2.48)
Mean of dependent variable	34.22	24.46
Observations	3,635	3,635
R^2	0.50	0.57
F-statistic (test for equality between WTP and experimental results)	103.22	10.54

Notes: The dependent variable is an indicator (multiplied by 100) for whether the household accepted the hypothetical (i.e., willingness to pay) or experimental offer. Columns 1 and 2 pool the results of the first hypothetical offer (i.e., without time constraints) with the experimental results, and the second hypothetical offer (i.e., with time constraints) with the experimental results, respectively. WTP indicates whether the observation is generated by the stated willingness to pay portion of the experiment. Robust standard errors clustered at the community level in parentheses. Asterisks indicate coefficient statistical significance level (2-tailed): * $P < 0.10$; ** $P < 0.05$; *** $P < 0.01$. *F*-statistics correspond to the test that $\beta_{\text{WTP}} = \beta_{\text{WTP}} + \beta_{284\times\text{WTP}} = \beta_{\text{WTP}} + \beta_{171\times\text{WTP}} = \beta_{\text{WTP}} + \beta_{\text{Free}\times\text{WTP}} = 0$.

Table C10—Summary of randomly-assigned, hypothetical credit offers

				NPV at discount rate of				Take-up	
Offer	Months	Upfront	Monthly	5%	15%	25%	n	Time unlimited	6 week deadline
1	36	79.60	11.84	475.23	425.67	387.38	406	50.6%	38.3%
2	36	59.70	12.58	480.03	427.38	386.69	379	53.5%	38.9%
3	36	39.80	13.32	484.83	429.09	386.01	369	52.7%	39.6%
4	36	59.70	13.45	509.29	452.98	409.46	353	49.7%	39.1%
5	24	59.70	17.22	452.57	418.07	389.91	419	52.4%	40.2%
6	36	127.93	26.94	1028.26	915.48	828.34	363	52.7%	28.2%
Offer 1 to 5 (average)		59.70	13.68	480.39	430.64	391.89		52.0%	39.3%

Notes: During the baseline survey, each household was randomly assigned a hypothetical credit offer consisting of an upfront payment (ranging from $39.80 to $79.60), a monthly payment (ranging from $11.84 to $17.22), and a contract length (either 24 or 36 months). Respondents were first asked whether they would accept the offer, and then asked whether they would still accept if required to complete the upfront payment in six weeks. Figure 3.9, Panels B and C plot the net present value and take-up results corresponding to offer 6 and the average for offers 1 to 5 (which are very similar), assuming a discount rate of 15 percent.

Table C11—Summary of selected historical national rural electrification initiatives

			Electrification rate					
			National		Rural		GDP per capita	
Country	Period	Government authority	Start	End	Start	End	Start	End
Kenya	2008 - present	Rural Electrification Authority	<20%		<5%		939	
China (I)	1949 - 1978	Maoist era of central planning	n/a	63%	n/a	53%	n/a	292
China (II)	1978 - 1998	Ministry of Water and Power, Rural Electricity Department	63%	98%	53%	97%	292	1,512
Vietnam	1975 - 2009	Vietnam Electricity (EVN)	10%	96%	3%	95%	376	1,235
Tunisia	1972 - 2001	National Rural Electrification Commission (CNER)	37%	95%	6%	88%	1,524	3,092
South Africa	1995 - 2001	SA National Electrification Programme (NEP)	30%	66%	21%	49%	5,321	5,811
USA (I)	1935 - 1940	Rural Electrification Administration	68%	79%	13%	33%	9,102	11,847
USA (II)	1940- 1955	Rural Electrification Administration	79%	98%	33%	94%	11,847	19,974

Notes: There is very little reliable data available from China in 1949. At that point, rural electrification rates were likely to be < 1 percent.

Note C1—Community selection process

In August 2013, local representatives of REA provided us with a master list of 241 unique REA projects, consisting of roughly 370 individual transformers spread across the ten constituencies of Busia and Siaya. Each project featured the electrification of a major public facility (market, secondary school, or health clinic), and involved a different combination of high and low voltage lines and transformers. Projects that were either too recent, or classified as not commissioned, were not included in this master list. Since the primary objective was to estimate local electrification rates, projects that were funded after February 2013 were excluded to ensure that households in sample communities had had ample opportunity to connect to the grid.

In September 2013, we randomly selected 150 transformers using the following procedure: 1) in each constituency, individual transformers were listed in a random order, 2) the transformer with the highest ranking in each constituency was then selected into the study, and 3) any remaining transformers located less than 1.6 km (or 1 mile) from, or belonging to the same REA project, as one of the selected transformers, were then dropped from the remaining list. We repeated this procedure, cycling through all ten constituencies, until we were left with a sample of 150 transformers for which: 1) the distance between any two transformers was at least 1.6 km, and 2) each transformer represented a unique REA project. In the final sample, there are 85 and 65 transformers in Busia and Siaya counties, respectively, with the number of transformers in each of the ten constituencies ranging from 8 to 23. This variation can be attributed to differences across constituencies in the number of eligible projects. In Budalangi constituency, for example, all of the 8 eligible projects were included in the sample. As a result of this community selection procedure, the sample is broadly representative of the types of rural communities targeted by REA in rural Western Kenya.

Note C2—Experimental design notes

Sampling—Households were identified at the level of the residential compound, which is a unit known locally as a boma. In Western Kenya, it is common for related families to live in different households within the same compound.

Surveying—The majority of the baseline surveys were conducted between February and May 2014. However, 3.1 percent of surveys were administered between June and August 2014 due to scheduling conflicts and delays.

Sample of connected households—Since electrification rates were so low, the sample of connected households covers only 102 transformer communities; 17 communities did not have any connected households at the time of census, and we were unable to enroll any connected households in the remaining 31 communities, for instance, if there was a single connected compound in a village and the residents were not present on the day of the baseline survey.

Randomization—For the stratification variable market status, we used a binary variable indicating whether the total number of businesses in the community was strictly greater than the community-level mean across the entire sample.

Note C3—Unexpected delays during the wiring phase

Kenya Revenue Authority (KRA) identification certificates—Households applying to Kenya Power are required to have (1) a National Identity Card (NIC), (2) a KRA Personal Identification Number (PIN) certificate, and (3) a completed Kenya Power application form. 42.0 percent of household heads requesting a connection did not already have a KRA PIN certificate, which could only be generated on the KRA website. Since most rural households do not regularly access the Internet, project enumerators provided registration assistance for 96.6 percent of the households lacking KRA PINs. At the time of the experiment, KRA PIN registration services were typically offered at local Internet cafes at a cost of $5.69 (500 KES).

Spelling mistakes on wiring certificates—Households connecting to the grid are required to have certificates that the wiring is safe. The ready-board manufacturer provided wiring certificates that needed to be signed by contractors after installation. We encountered delays when the spelling of the name on the certificate did not precisely match its spelling on the NIC or KRA PIN certificate.