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Electrification for “Under Grid” households in Rural Kenya

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ABSTRACT

In Sub-Saharan Africa, 600 million people live without electricity. Despite 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. In this paper, we present high-resolution spatial data on electrification rates in rural Kenya in order to quantify and visualize energy poverty in a novel way. Using our dataset of 20,000 geo-tagged structures in Western Kenya, we provide descriptive evidence that electrification rates remain very low despite significant investments in nearby grid infrastructure. This pattern holds across time and for both poor and relatively well-off households and businesses. We argue that if governments wish to leverage existing infrastructure and economies of scale, subsidies and new approaches to financing connections are necessary.

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 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.

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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 m 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.[1] 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; Khandker et al., 2012; Kitchens and Fishback, 2013; Lipscomb et al., 2013; Barron and Torero, 2014). 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 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.[2] 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."[3]

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 1700 MW) comes from non-fossil fuel sources such as hydro and geothermal. Furthermore, there are plans to build an additional 5000 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 II provides a brief background on rural electrification in Kenya. Section III describes our data collection strategy. Section IV provides a summary of the leading patterns that emerge from our dataset. Section V discusses the implications of our results.

1.1. 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.[4] Over the next few decades, 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 8436 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

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[1] 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.

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

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

[4] 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.

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%.[5] 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.

2. 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 m 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.

2.1. 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.[6] 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.[7]

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 10 constituencies ranging from 8 to 23.[8]

Table 1
Comparison of socio-economic indicators between sample region and nationwide counties.

	Sample region	Nationwide county percentiles		
		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	44.6	37.0	42.4	45.2
% with secondary education	10.4	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	32.5	21.8	29.0	43.7
% with piped water	6.3	6.9	14.2	30.6
Total public facilities	1,288	356	521	813
per capita (000 s)	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.

2.2. Sample representativeness

Table 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

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[5] 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/).

[6] 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.

[7] 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.

[8] 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.

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 1000 people, which is slightly above the nationwide county-level median of 0.75. 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.

2.3. 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 m of the central transformer and to determine whether the structure had a visible electricity connection at the time of the visit.[9] 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.

2.4. Data visualization

We create a series of maps, presented in Fig. 1 (and Figs. A1–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 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 m 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 Fig. 1 (and Figs. A1–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).

3. 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.

3.1. 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.[10] 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.[11]

This high cost could potentially be justified if many of the surrounding households and businesses were connected to the grid.[12] The majority of households in our sample region are willing to pay for an electricity connection. Based on a random subsample 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.[13] By dividing the 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 $2427. Yet if every structure within each transformer

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[9] 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.

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

[11] 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.

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

[13] 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.

Fig. 1. Visualizing the proportion of households and businesses that are "under grid". *Note*: In these maps, the white circle labelled "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. Maps of 18 additional transformer communities are presented in Figures A1 to A3 in the Appendix.

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.[14]

In Fig. 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 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.

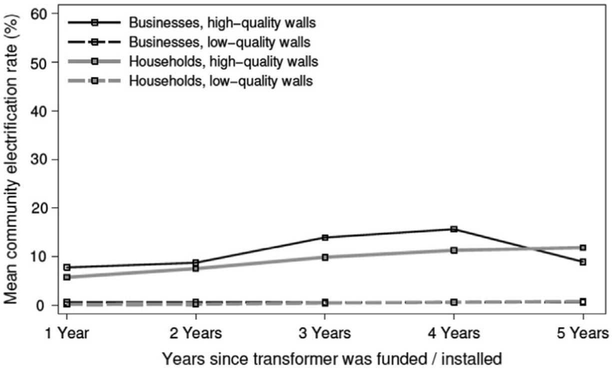

Fig. 2. Mean transformer community electrification rates by structure type and fund-ing/installation year. *Note*: Transformer communities are grouped by REA project year. The REA project year is the fiscal year in which each project was nominated and funded for electrification. Structures with high-quality walls are defined as those made of brick, cement, or stone. Structures with low-quality walls are defined as those of mud, reed, wood, or iron.

In our sample of 2824 businesses, 33.6% are visibly connected to power. In Table 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

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

Table 2
Electrification rates for businesses of various types.

	% (1)	*N* (2)
All businesses	33.6	2824
Small retail	36.2	1163
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.

motors. Similarly, connectivity for welding, carpentry and workshops is relatively low at 39.2%.[15]

3.2. *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.[16] 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 Fig. 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.

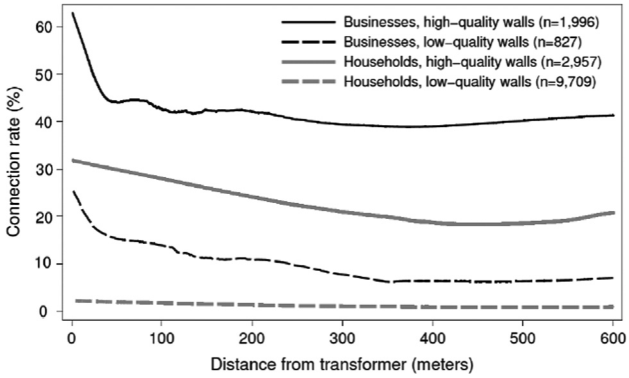

Fig. 3. Connection rates by distance to the central transformer. *Note*: We plot locally weighted regressions (bandwidth 5) of the connection status on the distance to the transformer for businesses and households with high and low quality walls. As in Fig. 2, high quality walls ad defined as those made brick, cement, or stone. Low-Quality walls are defined as those made of mud, reeds, wood, or iron.

Table 3
Predictors of electrification.

	Households			Businesses		
	(1)	(2)	(3)	(4)	(5)	(6)
Distance	-0.69^{***} (0.18)	-0.14^{*} (0.08)	-0.19^{**} (0.09)	-2.71^{***} (0.91)	-2.08^{**} (0.93)	-1.37 (1.41)
Years		0.34^{***} (0.08)			0.82 (1.23)	
Walls		16.51^{***} (3.87)	16.70^{***} (3.73)		18.31 (11.53)	22.25^{*} (11.57)
Walls × Distance		-1.60^{***} (0.57)	-1.56^{***} (0.57)		0.47 (1.10)	0.04 (1.29)
Walls × Years		2.56^{***} (0.88)	2.44^{***} (0.83)		3.18 (3.01)	1.60 (2.92)
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)–(6) report results for businesses. Definitions: (a) Distance is the straight line distance to the central transformer (in 100 m 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).

* $P < 0.10$
** $P < 0.05$
*** $P < 0.01$.

In Table 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

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

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 m 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 m away than if it is 200 m away. In comparison, at 200 m, 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

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[15] 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.

[16] 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.

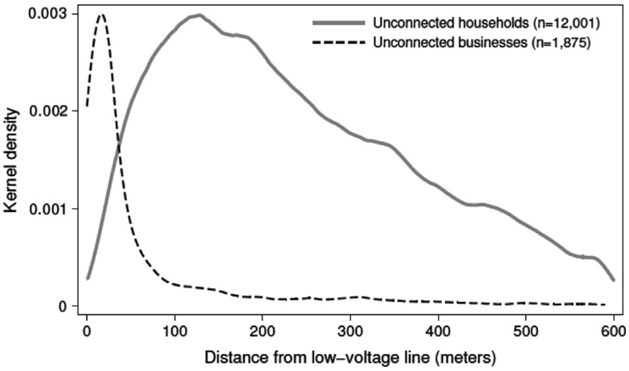

Fig. 4. Kernel densities of unconnected households and businesses by distance from low-voltage line. *Note*: We plot epanechnikov kernels (bandwidth 12). The horizontal axis represent the distance of the unconnected household or business to nearest connection point or transformer. The vertical axis scale applies to household density only. The peak density for businesses is 0.016.

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 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 1737 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.[17]

3.3. *Half of the unconnected households in our sample are "under grid," or clustered within 200 m 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-m 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 Fig. 4, we plot the density of the 12,001 unconnected households and 1875 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 m of a low-voltage line, and the mass of unconnected businesses is within 50 m 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.[18]

According to REA, service poles are required for every 50 m of line; three or four service poles would therefore imply a maximum distance of 150–200 m. We conservatively estimate the incremental cost of supplying an electricity connection to a single household 200 and 100 m 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.[19] Once connected, households pay the utility an electricity tariff that is structured to cover the cost of additional power generation.

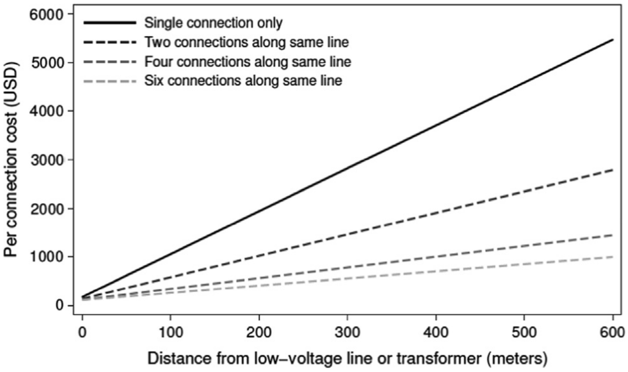

Fig. 5. Economies of scale in the cost of providing household electricity connections. *Note*: Cost estimates are based on actual assumptions used by REA for budgetary purposes. The horizontal axis can be interpreted as either the distance to the nearest low-voltage line or the distance to the central transformer.

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 Fig. 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 m, respectively. These neighboring households can be located as far as 30 m 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

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

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

[19] 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 m away from a transformer.

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.[20] 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 m 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.

4. 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 m 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 potential opportunity for millions of new connections.[21]

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.[22] 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 2013). 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 hundreds of millions of African 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.

Acknowledgments

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Appendix

See fig. A1–A3

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[20] 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.

[21] 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.

[22] 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.

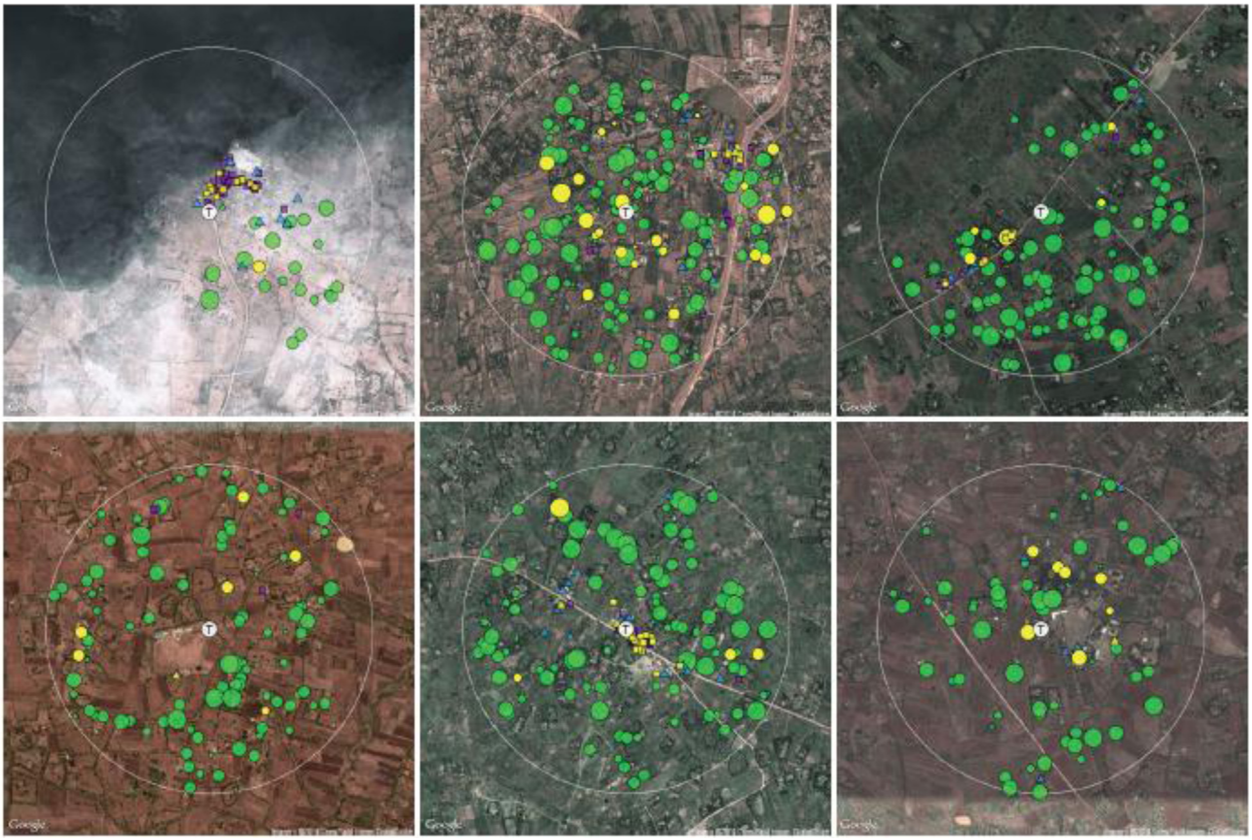

Fig. A1. Maps of transformer communities 1–6. *Note*: The white circle labelled “T” in the center identifies the location of the REA transformer. The larger white outline demarcates the 600-meter radius boundary. Green circles represent unconnected households; purple squares represent unconnected businesses; 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.

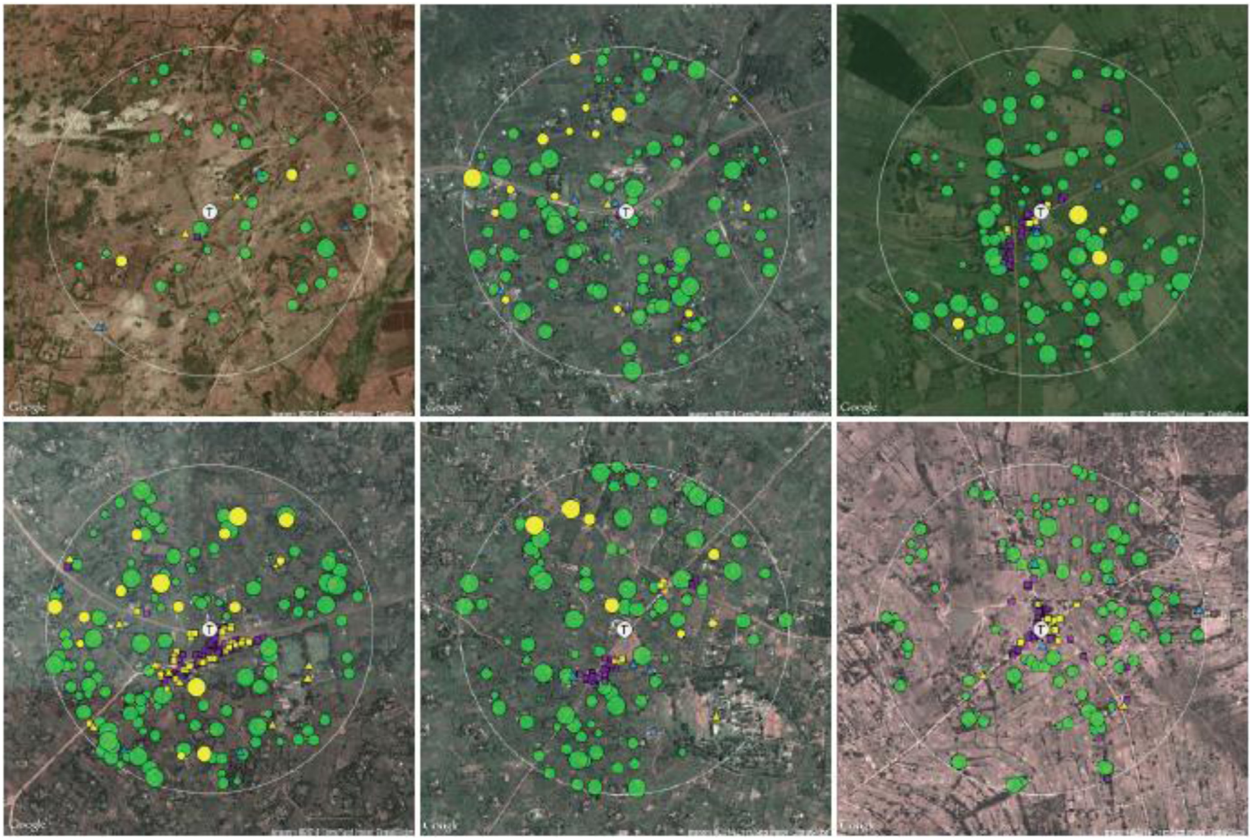

Fig. A2. Maps of transformer communities 7–12. *Note*: The white circle labelled “T” in the center identifies the location of the REA transformer. The larger white outline demarcates the 600-meter radius boundary. Green circles represent unconnected households; purple squares represent unconnected businesses; 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.

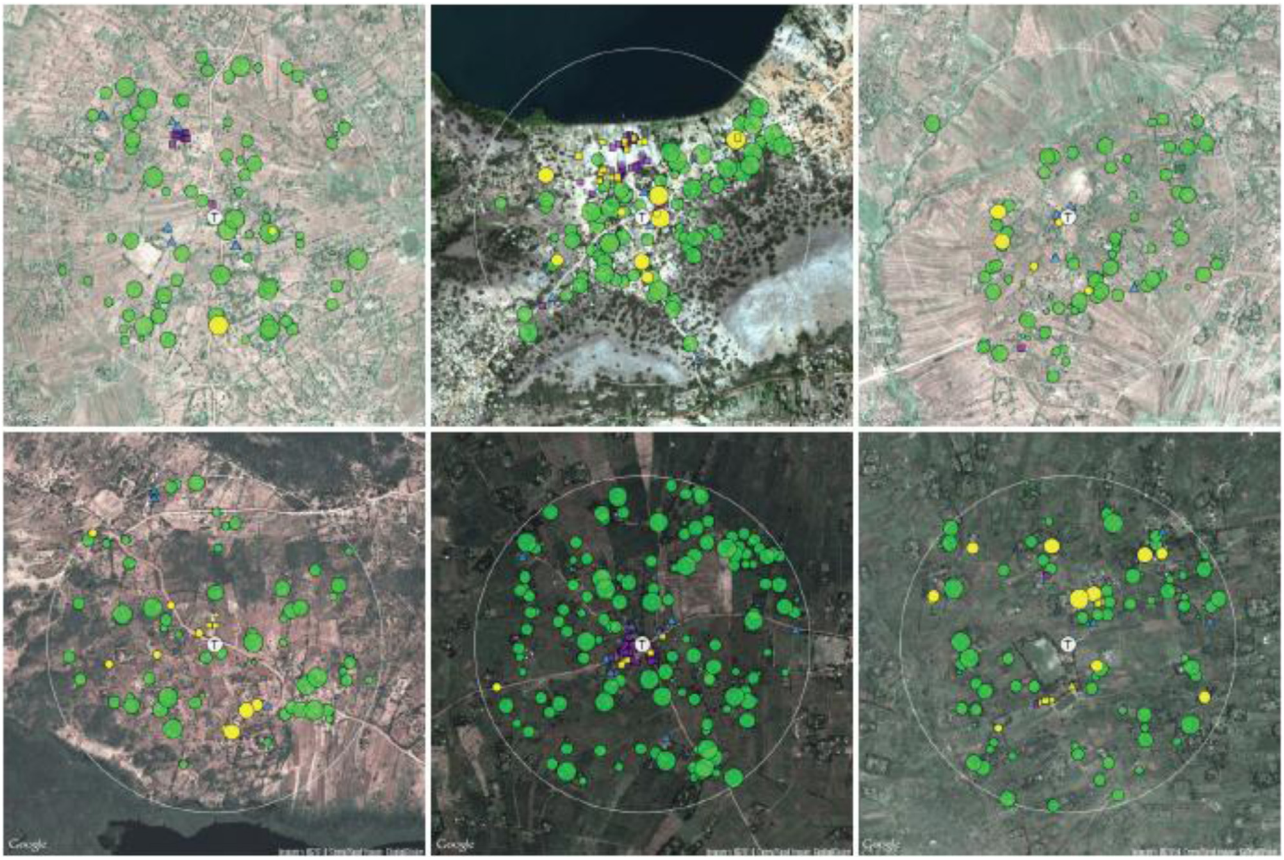

Fig. A3. Maps of transformer communities 13–18. *Note*: The white circle labelled "T" in the center identifies the location of the REA transformer. The larger white outline demarcates the 600-meter radius boundary. Green circles represent unconnected households; purple squares represent unconnected businesses; 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.

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