A Geospatial Framework for Electrification Planning in Developing Countries

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***Abstract*—In efforts to achieve universal electricity access, geospatial factors, particularly the distribution of populated places and other electricity demands, are fundamentally important in determining the relative costs of competing grid, mini-grid or home system electrification options. Research presented here goes beyond broad metrics such as population density to instead consider patterns of aggregation and distances between communities to produce geographically specific cost estimates for medium and low voltage line. This analysis considers these factors at two geographic scales. First, it presents localized investigations of several rural locations in sub-Saharan Africa, at the scale of tens of kilometers, using household-level location data from GPS surveying and high-resolution satellite imagery. This work resulted in broad classification of village landscapes and suggested cost-effective electrification with different technologies depending upon inter-community and inter-household distances as proxies for medium and low voltage line lengths. Second, the analysis draws upon larger scale planning studies and data, at the scale of thousands of kilometers, in developing countries targeting electricity access for millions or tens of millions of unserved households, relying on coarser geospatial population datasets. A key observation of this analysis relates to the manner in which electrification planning can respond to cost tradeoffs between grid and non-grid electrification options in areas with different settlement patterns.**

Keywords—electrification, access, planning, geospatial, GIS, algorithm, Africa, developing countries

I. Introduction

Global electricity access goals, particularly Sustainable Development Goal 7, focused on ensuring access to modern energy, target poor, underserved populations, often in rural areas. While generally instructive, the basic metric of population density lacks crucial information regarding settlement patterns that is essential for planning electrification on a large scale. More geographically specific estimates of electrification costs require localized information regarding settlement patterns, such as the aggregation versus dispersal of households, villages, and other electricity demand points. These local settlement patterns have decisive impacts on cost tradeoffs between networked (grid and mini-grid) and non-networked (household) electricity systems. Distances between communities are crucial for estimating medium-voltage grid line costs, while patterns of household spacing establish low-voltage line costs. Some academic analyses have addressed this subject both in general and in specific countries [1, 2, 3, 4, 5, 6, 7]. Crucially, localized settlement patterns can vary substantially in a manner that is not necessarily related to overall population density, complicating efforts to determine cost-effective electrification strategies.

This paper examines these issues quantitatively for multiple geographic contexts and different spatial scales, using examples from several years of rural electrification planning in a range of developing countries. First, the paper presents a quantitative analysis of settlement patterns – specifically the spacing of households and communities – in sample rural areas from several countries of sub-Saharan Africa. This analysis is at a highly localized scale – tens of kilometers – and draws upon data for household locations drawn from a combination of GPS ground surveying and high-resolution satellite imagery. Second, the paper presents results from national or regional planning efforts or data for existing systems, at the scale of hundreds or thousands of kilometers, using coarser data, at the community level, obtained from national censuses or similar efforts. For both contexts, data and assumptions about unit costs for electrification are used to create cost estimates for electrification of different landscapes using different technologies to illustrate the impact of geospatial factors.

II. Population density and aggregation metrics, examples from sub-Saharan Africa

Population density is a useful, though very general, metric for understanding electricity demand distribution. Figure 1 below shows population density for nine countries in sub-Saharan Africa at two scales: a 10 x 10 km area, and a "single village" (a smaller area within this 10 x 10 km square, locally defined as one village).

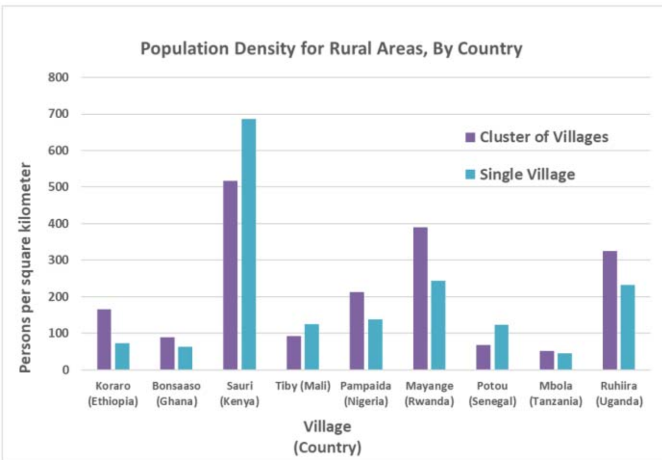

Figure 1: Population density for selected rural areas of nine countries in sub-Sahran Africa

The three countries with the lowest values, below 100 persons per square kilometer, are in selected areas of rural Tanzania (TZA), Ghana (GHA) and Ethiopia (ETH); mid-range values, between 100 and 200 persons/km^2 are found for selected rural areas in Mali (MLI), Nigeria (NGA), and Senegal (SEN); and in a third group of rural areas relatively near the Rift Valley Lakes of East Africa – southern Uganda (UGA), Rwanda (RWA) and western Kenya (KEN) – population density values are substantially higher, above 200 persons/km^2. An electrification cost analysis based only on population density would predict that costs of grid electrification per household connection will be relatively high in the first group of low-density countries (ETH, GHA, TZA), intermediate in the second group (MLI, NGA, SEN); and substantially lower in the higher density countries (RWA, UGA, KEN). While these estimates based on population density are broadly helpful, a key cost driver for electrification planning is local scale settlement patterns, namely the spacing and aggregation of village communities and individual households.

This analysis used the following approach to investigate settlement patterns as a cost driver. Inter-household distance, used as a proxy low-voltage line length per household (LV/HH), was estimated by calculating "nearest neighbor" distances between rooftops identified in satellite imagery using a combination of GPS-located households and identification from satellite imagery (plus a "correction factor" to account for the fact that not all structures are dwellings). Next, medium voltage line length per household (MV/HH) was estimated by algorithmically aggregating these household points into household "clusters", then calculating the minimum distance to connect all clusters using a "minimum spanning tree" algorithm.

Local settlement patterns – household and village spacing – were analyzed for 10 x 10 km rural areas throughout sub-Saharan Africa. These metrics – MV/HH and LV/HH – for these examples are provided to illustrate types of settlement patterns, as well as a methodological approach to develop quantitative metrics beyond simple population density. However, it is critical to note these examples are not intended as representative values for all areas within a given country or region. Due to space constraints only two cases are presented in detail due to space constraints.

A. Example: Rural Mali (Ségou Region)

Figure 2 below shows an example of settlement patterns in a rural area in Mali, in the Ségou Region, near the town of Ségou, within about 5 km of the Niger River. The overall population density in this area is about 100-125 persons/km^2. This figure shows rooftops identified in satellite imagery (red points) versus households identified by ground-level GPS surveying (white and blue boxes) against a satellite image background. This area is characterized by very closely aggregated households, with structures spaced often less than 10 meters apart, in adjoining compounds that often share adobe boundary walls.

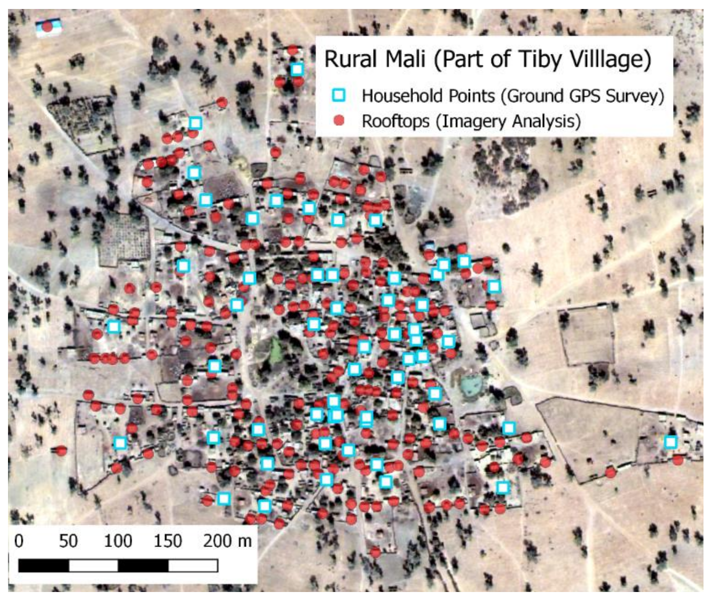

Figure 2: Rural Mali (Ségou Region, part of Tiby village area, ~1 km x 1 km): Rooftops and household (GPS) points against a satellite image background

Household points like those in this figure were used to compute a key analytical metric: the average distance between individual households, which is important for estimating the length of low voltage line needed per household (LV/HH) – a key input for estimating both grid and mini-grid network costs. The first step in this calculation was computation of the distance between every rooftop point using a GIS "nearest neighbor" calculation, then summing these individual distances to create a total inter-household distance for all rooftops. Then the number of rooftops was converted to an estimated number of households using a "conversion factor" which was established by comparing the number of rooftops for a given area with the number of GPS points for actual households collected by ground surveying performed by field staff. Finally, the total distance computed in the first step was divided by the estimated households, yielding an approximate low voltage line length per household (LV/HH).

Figure 3 below shows this same part of rural Mali at a larger scale (10 x 10 km). This figure focuses on clusters of households, and shows four key features: a) structure rooftops as identified from satellite imagery (red points); b) central locations around which rooftop locations were algorithmically clustered (yellow points); and c) the 1,000 m radius limit used for clustering (yellow circular areas). These yellow cluster points and circular areas serve as estimated central locations and coverage areas for a local electricity source, such as a grid transformer or mini-grid generation system, from which low voltage lines extend to connect households. The figure also contains a fourth feature, d) yellow lines illustrating a simple minimum distance required to connect all "village cluster" centers, using a "minimum spanning tree" (MST) algorithm.

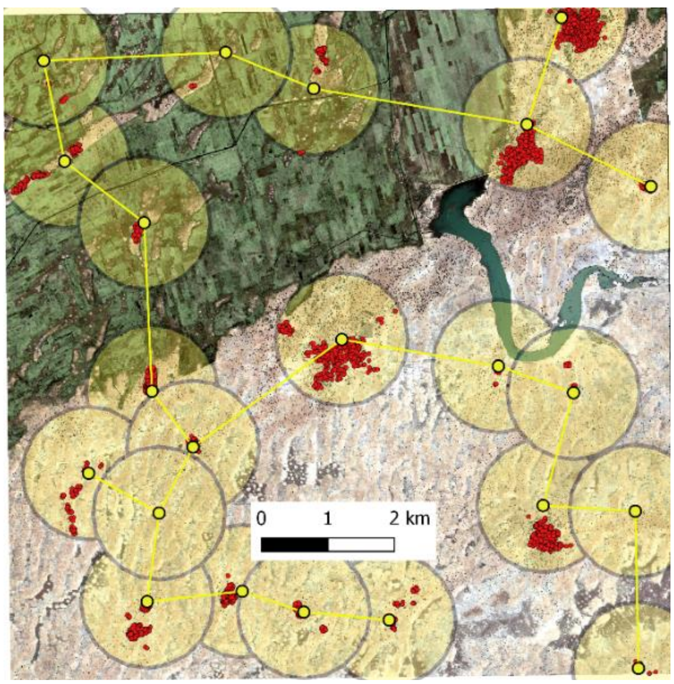

Figure 3: Rural Mali (Ségou Region, full Tiby village area, 10 km x 10 km): 2,496 rooftops (red points) identified in satellite imagery (~770 HHs) in 22 clusters with 1000 m radius (yellow points and circles) connected by ~37 km MST (yellow line).

Dividing this minimum total distance by the total number of estimated households yields another key analytical metric: an estimate of medium voltage line per household (MV/HH). This is helpful for understanding costs for electrifying all households and clusters identified in these rural locations.

The mean distance between households resulted in an estimate of 16 m of low voltage line per household (LV/HH), and median of 13 m LV/HH. The sum of the segments (yellow lines in Figure 3) required to connect all household clusters (yellow points) is ~37 km. This total, divided by the total number of households, yields an estimate of ~48 m of medium voltage line per household (MV/HH).

The settlement pattern in this part of rural Mali can be described as very closely aggregated homes in dispersed communities. The close aggregation of households suggests that systems that are locally networked (with low voltage lines between households in a grid or mini-grid) will be relatively cost-effective. However, since the clusters of households are relatively distant from one another, the medium voltage line costs to span distances between communities in this area are relatively high per household.

B. Example: Rural Ethiopia (Tigray Region)

Figure 4 below shows an example of a rural area in Ethiopia (Tigray Region, near the town of Hawzien) with rooftops (red points) and household GPS points (white and blue boxes) against a satellite image background.

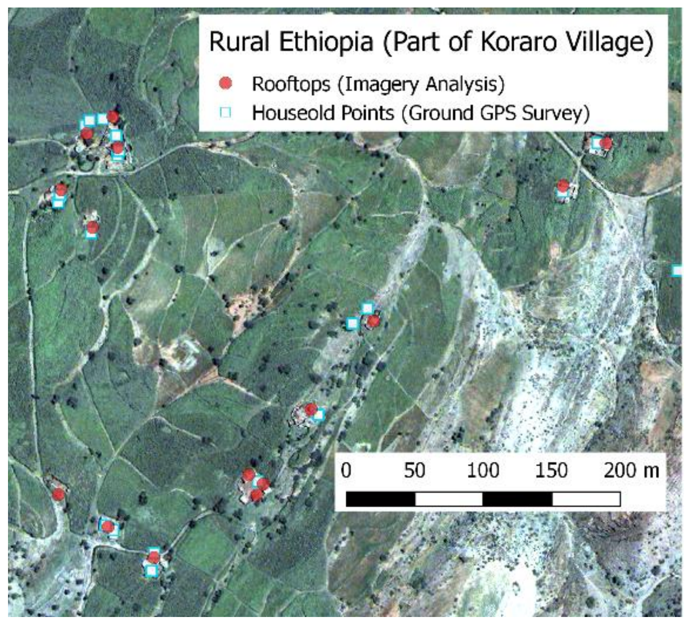

Figure 4: Rural Ethiopia (Tigray Region, part of Koraro village area, ~1 km x ~1 km): rooftops and household (GPS) points against a satellite image background

The overall population density of this area is about 72 persons/km^2. This area is characterized as having both a low overall population density, but also large spacing between households, with inter-household distances often reaching 100 meters or more.

As with Figure 3 presented previously for Mali, Figure 5 below shows this area of rural Ethiopia at larger scale (10 x 10 km) with households (red points); household cluster centers (yellow points); and the 1,000 m cluster coverage areas (yellow circles), and yellow lines illustrating the shortest distance required to connect all cluster centers.

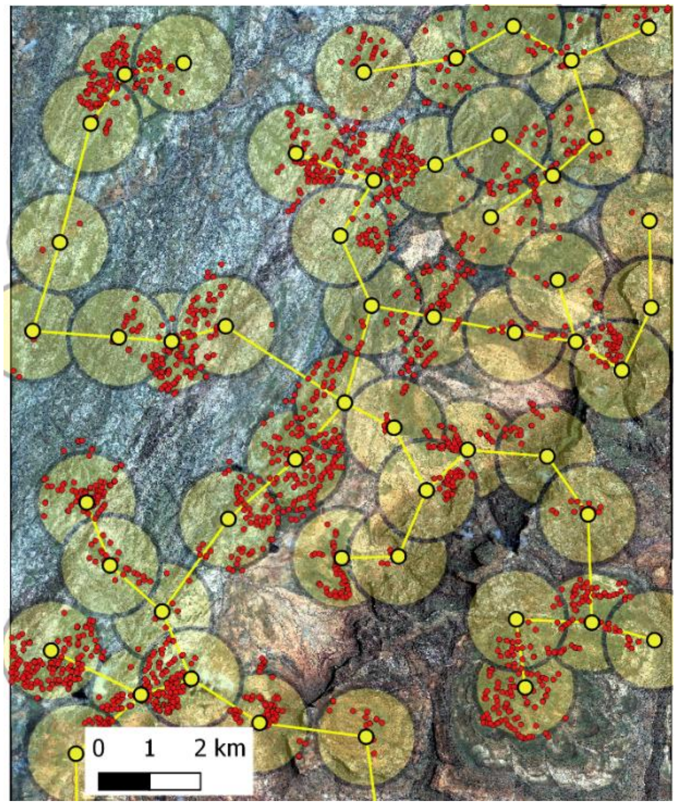

Figure 5: Rural Ethiopia (Tigray Region, Koraro village area, full 10 km x 10 km area): 2,096 rooftops (red points) identified in satellite imagery (~2,100 HHS) in 54 clusters with 1000 m radius (yellow points and circles) connected by ~83 km MST (yellow line).

For this rural part of Ethiopia, the mean distance between all households is ~68 m LV/HH, and the median is ~49 m LV/HH. The sum of the distances between all household clusters (yellow points) is ~83 km. This total, divided by the total number of households, yields an estimate of ~39 m of MV/HH. The settlement pattern has MV/HH values similar to Mali, but much greater inter-household distances. This pattern can be characterized as disaggregated homes in dispersed communities.

This strongly suggests that systems with local low voltage networks (grid or mini-grid) will cost significantly more to serve this settlement, and also suggesting systems with no network at all (such as solar home systems) may have the greatest cost advantage.

Figure 6 below provides quantitative support for the broad observation made previously, that the Mali sample area has very closely spaced homes. The figure is a histogram of the distribution of "nearest neighbor distances" using two vertical axes. The left axis indicates the number of households with a given nearest neighbor distance and the right axis shows the percentage of households, while the horizontal axis shows the distance. For this part of rural Mali, nearly 30% of the households (~400) are 10 meters or less from a nearest neighbor, over 80% are 20 meters or less, and well over 90% of the area households are within 30 meters, leaving very few remaining households at larger distances.

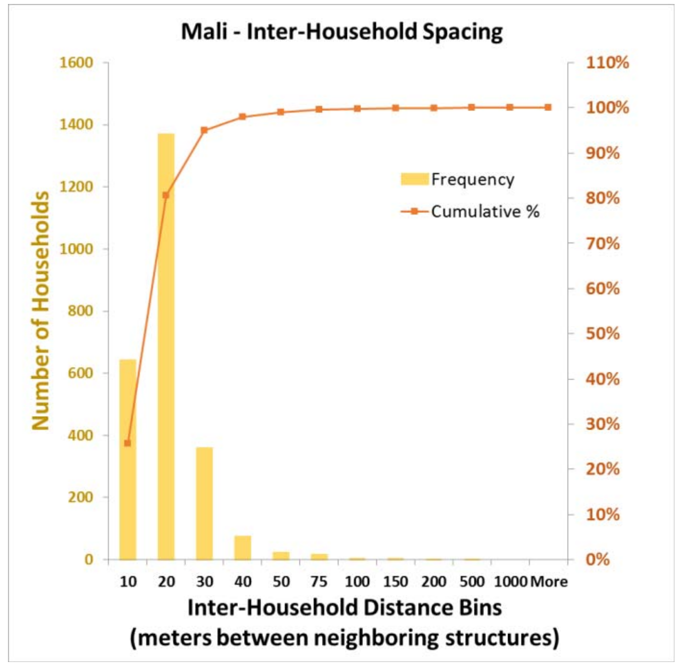

Figure 6: Histogram of "nearest neighbor" distances for households in sample rural areas of Mali

Similar patterns of closely aggregated households can be found in rural areas of many west African countries (MLI, GHA, NGA, SEN). These communities are likely to be good candidates for systems with local, low voltage networks connected to either central generation (as a micro-grid) or a transformer connected to the grid. Which of the two is preferable, grid or micro-grid, depends on distances between and sizes and total demands of communities, factors that are not displayed here.

Figure 7 below shows similar household spacing data for the selected area of rural Ethiopia. The figure shows that this area is characterized by very disaggregated households, with only about 35% of all households having an "nearest neighbor" distance of 30 meters or less. Roughly half of the area households are 50 m or more from the closest neighbor, and around 20% are further than 100 meters.

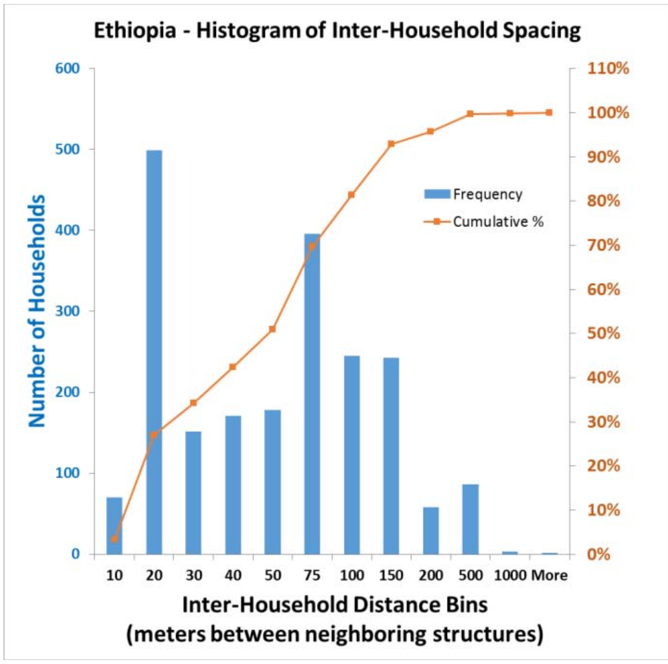

Figure 7: Histogram showing "nearest neighbor" distances for households in sample rural areas of Ethiopia

Similar patterns of very dispersed households can be found in less dense parts of East Africa, particularly rural parts of Tanzania that are distant from Lake Victoria. These communities are likely to be difficult to cost-effectively serve with networked systems due to unusually high costs of low voltage lines. This does not necessarily preclude grid or mini-grid service for these areas, but it suggests that these systems will have inherent cost disadvantages, and that cost savings may be achieved by supplying substantial fractions of these communities with off-grid technologies such as solar home systems.

III. A GEOSPATIAL FRAMEWORK FOR ELECTRICITY PLANNING

Previous sections showed rural settlement in sample areas, first, from rural Mali, as an example of closely aggregated homes in widely spaced communities, compared with a sample area in rural Ethiopia showing very disaggregated homes and communities in a sparsely populated landscape.

The key metrics for local settlement patterns – MV/HH and LV/HH – for these two examples, as well as several others examined in a similar manner, are presented in Figure 8 below. These examples, it should be stressed, are not intended as representative of all rural areas these countries, but rather to display a wide range and variety of rural settlement patterns.

The blue points in this figure show two values: The y-axis shows the estimated mean medium voltage length per household (MV/HH), which is simply the sum of all distances between household clusters, divided by the total number of households. The second, on the x-axis, it the estimated mean low voltage line length per household (LV/HH), which is the average of all distances between point locations identified in the 10 x 10 km areas. The red points in the figure show results the impact of excluding unusually small household clusters or unusually distant households in order to, in effect, reduce the influence of geo-spatial "outliers" on electrification costs. The specific approaches and results will be discussed in later sections.

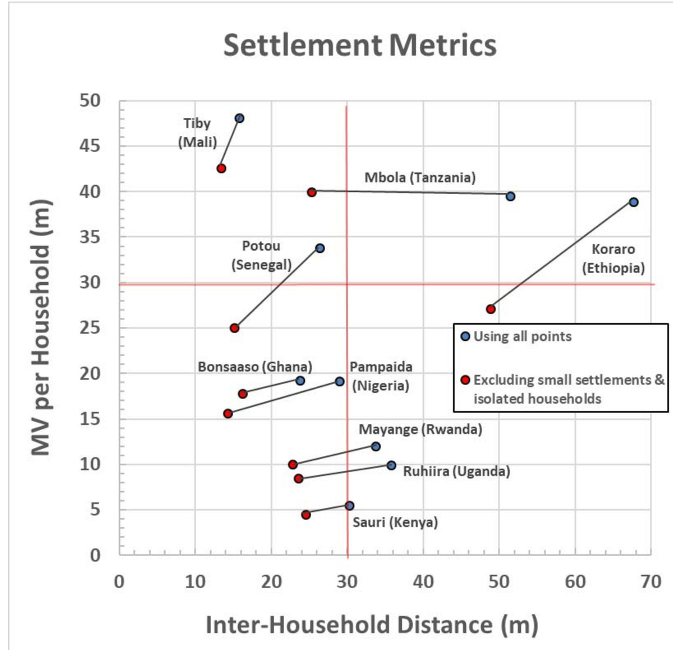

Figure 8: Key settlement metrics -- MV/HH and LV/HH -- for rural sample areas in nine sub-Saharan African countries.

The results displayed in this figure suggest some broad observations about how settlement patterns impact costs and practical considerations of electrification in a variety of real-world planning contexts.

A. Types of dispersion and aggregation of communities and households

A key observation of this work is that, beyond simple population density, electrification planning should consider settlement patterns, specifically the degree of dispersion vs. aggregation, which can be quantified with two geo-spatial factors:

- Distance between communities, which determines MV line costs
- Distance between households, which determines LV line costs

In addition to the points for specific rural settings, Figure 8 shows two red lines (chosen somewhat arbitrarily at 30 m for both LV/HH and MV/HH) to establish a rough typology useful in explaining how these two factors typically influence the outcomes of electrification planning.

In general, grid electrification is most cost-effective when both households and communities are closely aggregated (lower-left quadrant). This pattern prevails in many higher-density areas, including urban and peri-urban areas, as well as rural areas with small, closely-spaced farms.

In the opposite situation (upper-right quadrant) where both communities and households are widely spaced, off-grid technologies such as solar home systems are likely to be least-cost. The previous example from rural Ethiopia is of this type, as well as other rural parts of East Africa (including a sample area for rural Tanzania, not shown in detail due to space considerations) and parts of Highland Papua New Guinea, where farms are larger and homes are widely spaced.

Where households are closely spaced, but communities are small and/or widely spaced (upper-left quadrant), micro-grids tend to be least-cost, since they forego costly medium voltage extensions between communities while having relatively low cost for local low-voltage lines. The prior example from rural Mali follows this pattern, as do other examples from rural West Africa (including a specific location in rural Senegal, not shown in detail due to space considerations). In other parts of the world, this pattern of closely aggregated communities, but with communities scattered across the landscape, can be common in various low-density landscapes such as mountain areas, where households cluster in valleys, on coasts, where fishing livelihoods focus settlement near the shore, or along roads or rivers that serve as aggregation sites for households.

Finally, situations where households are widely spaced but communities are closely spaced (lower-right quadrant) are relatively rare, since higher overall population density tends to push both households and communities close together. In this analysis, some examples from rural areas near Lake Victoria (western Kenya, western Uganda, and Rwanda) fell just on the borderline of this and the first category mentioned (the lower-left).

B. Approaches to controlling grid costs by removing the most dispersed households and communities from the network

The red points in Figure 8 above illustrate the impact of two simple methods to reducing the cost per household of network connections. The first is to reduce low-voltage line costs (LV/HH) by using the median (instead of the mean) inter-household distance, which reduces the statistical influence one kind of "outlier": very isolated households. The second is to reduce medium-voltage line costs (MV/HH) by removing another kind of "outlier": very small household clusters, those with fewer than 10 households. These specific approaches taken to reducing the influence of unusually small or isolated settlements are somewhat arbitrary, but are also supported by prior experience and common practice. For example, the cutoff value of 10 households for small clusters was chosen as a relatively conservative boundary to indicate the common practice of utilities that suggest that exceptionally small communities are more cost-effectively electrified with non-networked systems, such as solar home systems. The choice of the median inter-household distance, as an alternative to the mean, reflects the simple and robust statistical practice of using medians to reduce the influence of extreme "long tail" values.

The second of these two approaches is illustrated in two figures below which show a magnified area of the household cluster maps for Ethiopia with added numbers indicating total households represented by each cluster point. Figure 9 below shows MV connections if all clusters are connected.

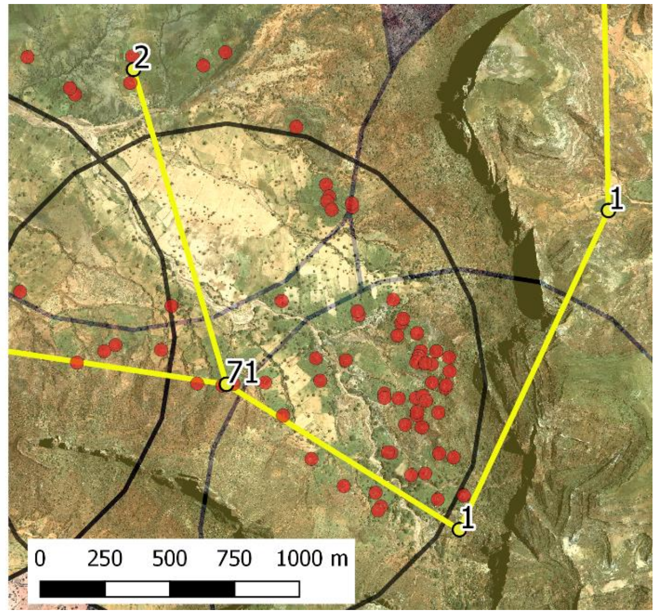

Figure 9: Potential MV line connecting all household clusters (Ethiopia)

In contrast, Figure 10 below shows an MV line excluding the clusters with fewer than ten households, resulting in a much shorter MV line path that still serves the overwhelming majority of homes served by the previous MV grid.

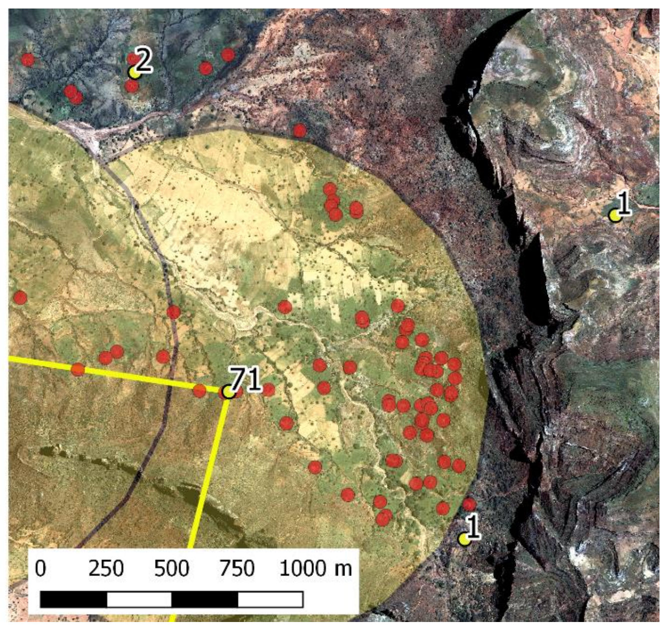

Figure 10: Potential MV line connecting all household clusters except those with fewer than ten households (Ethiopia)

Quantitatively, this exclusion of the smallest communities from the proposed MV grid results in a decrease in the average MV/HH from 83 m to 38 m, a decrease of more than 50%. This suggest potential for large cost reductions, particularly in very disaggregated areas.

Considering the impact of these cost-reduction strategies for a wide range of geographies: The black lines in Figure 8 connecting these pairs of blue and red points indicate the magnitude and direction of the change in these metrics as networked electrification strategies (using either grid or mini-grid) focus increasingly on the most aggregated populations. Quantitative values used for the figure are presented in Table 1 below.

Table 1: Quantitative data for Settlement Patterns: MV/HH and LV/HH metrics using all data points vs. removing outliers

	Connecting all clusters and all households		Connecting only larger clusters (those with more than 10 households)			Removing isolated households (to achieve median instead of mean LV/HH)		
Country	MV/HH (connecting all clusters)	Mean LV/HH: all HHs	MV/HH (only clusters w/ > 10 HHs)	Pct of HHs removed (clusters w/ < 10 HHs)	% change in MV/HH	Median LV/HH	Pct of HHs removed (to achieve median LV/HH)	% change in LV/HH
Koraro (Ethiopia)	38.8	67.8	27.1	3.5%	-30.3%	48.9	10.1%	-27.8%
Bonsaaso (Ghana)	19.2	23.9	17.7	1.3%	-7.5%	16.2	10.5%	-31.9%
Sauri (Kenya)	5.5	30.4	4.5	0.5%	-18.1%	24.6	12.7%	-19.1%
Tiby (Mali)	48.1	15.8	42.6	1.3%	-11.4%	13.4	9.4%	-15.1%
Pampaida (Nigeria)	19.1	29.0	15.6	3.6%	-18.2%	14.4	12.0%	-50.5%
Mayange (Rwanda)	11.9	33.8	9.9	0.4%	-16.7%	22.9	18.8%	-32.3%
Potou (Senegal)	33.8	26.5	25.0	1.8%	-26.1%	15.1	9.1%	-42.8%
Mbola (Tanzania)	39.5	51.5	40.0	21.9%	1.2%	25.3	16.7%	-50.9%
Ruhiira (Uganda)	9.9	35.8	8.4	0.9%	-14.9%	23.6	16.6%	-33.9%
Average	**25.1**	**34.9**	**21.2**	**4%**	**-15.8%**	**22.7**	**13%**	**-33.8%**

The figures in the table suggest that around 16 percent of cost for the medium voltage grid line could be saved, on average, by excluding only the smallest communities from the grid while in the process excluding only 4% of the households – a differential of 12%. This savings on grid line could provide funds for mini-grid or solar home system electrification to these communities. This differential could be dramatically higher (in the range of 20-25%) for specific rural areas, such as the village clusters in Ethiopia and Senegal, where removing small communities from the grid extension plan could save 26-30% of grid costs, while shifting less than 5% of the population to non-grid alternatives.

Excluding "isolated" households from the local, low voltage network used for grid or mini-grid, and instead providing solar home systems, offers another route to cost savings. This calculation compares low voltage line costs assuming, firstly, the mean inter-household distance for all households and, for comparison, the low voltage line costs for a network that excludes the most isolated homes to result in an average LV/HH equal to the median inter-household distance. This comparison suggests that around 34% of the low voltage grid cost could be saved by excluding the 13% of homes that are very distant – a differential of 21%. Again, the comparison is more substantial for specific geographies with very high numbers of isolated homes. For example, the rural part of Tanzania surveyed here, which has unusually dispersed households, offers a 51% savings on LV line costs by switching only 17% of the households from grid to solar home system – a differential of 34%.

C. *Using Data for Settlement Patterns to Predict Grid and Mini-Grid System Costs*

The data for settlement patterns described above can, with some assumptions about unit costs, be used to predict electrification costs for different technologies. This quantitative cost and technical planning was undertaken using a open source tool [8]. Table 2 below lists assumed unit costs and key technical metrics for a cost comparison of grid and solar micro- or mini-grid on a per household basis. These have been used, in combination with the geospatial information for MV/HH and LV/HH described previously, to create estimates of total costs – initial and recurring – under different scenarios for selected geographies.

Table 2: Unit cost and technical assumptions for cost comparison of grid and solar mini-grid systems

Unit Costs	Grid	Mini or Micro Grid	
MV	25	0	US$/m
Transformer	100	0	US$/kVA
Solar Generation (excludes network)	0	1.6	US$/Wp
Solar System multiplier	0	1.2	Wp/kWh-HH-yr
LV	15	5	US$/m
Service Line	100	0	US$/HH
Connection	200	50	US$/HH
Power	0.10	0.30	US$/kWh
Annual demand per connection	200	200	kWh/HH-yr
Life / Years of Power	5	5	yr

The first cost estimation scenario, shown in Figure 11 below, shows all costs – initial and recurring – for grid and solar mini-grid connected households, summed over a five year timespan, assuming the unit costs in Table 2 above and an annual household electricity consumption of 200 kilowatt hours per household per year (kWh/HH-yr). The cost differential between grid and mini-grid systems can be seen in the difference in height between the stacked bars representing grid connection costs (stacks with blue bars) versus those for mini-grids (stacks with beige bars).

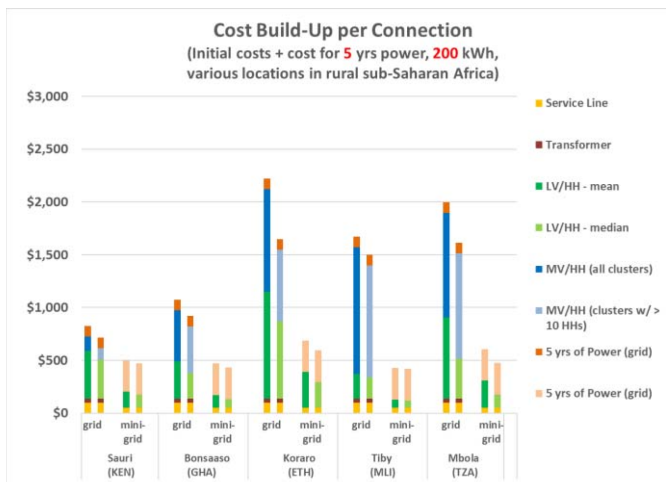

Figure 11: All costs – initial and recurring – estimated for grid and solar mini-grid electrification assuming 5 year duration and 200 kWh/HH-yr demand.

These results show that, at this demand level, over a five-year lifetime, solar mini-grids are more cost-effective for all communities in the five rural geographies analyzed. The lifetime cost savings offered by mini-grids relative to grid connections is highest for the areas with the most dispersed communities (i.e. rural Ethiopia and Tanzania) where MV line costs per household are expected to be high.

The second example, in Figure 12 below, shows the cost impact of changing the assumptions for electricity demand and system life. This second scenario assumes a 15-year system life and a higher, though still relatively modest, annual household demand of 500 kWh/HH-yr. The results on the relative cost-effectiveness of grid and mini-grid electrification are consistent: Grid electrification is estimated to be more cost-effective in nearly every scenario. This is principally because the higher unit cost of electricity from solar generation (beige bars) outweighs the savings that mini-grids offer in initial costs as the system life increases.

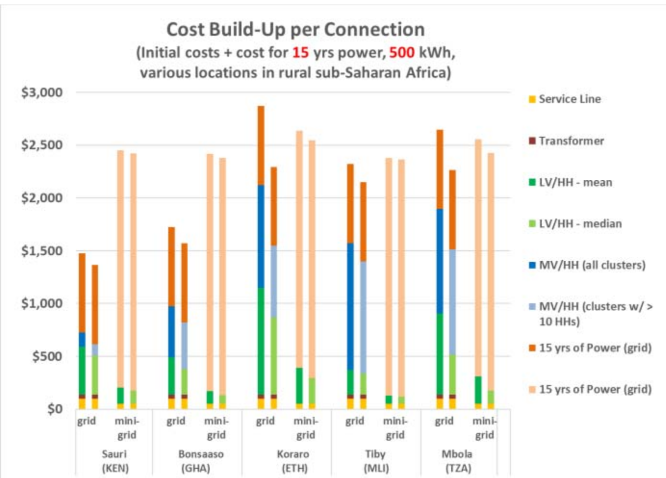

Figure 12: All costs – initial and recurring – estimated for grid and solar mini-grid electrification assuming 15 year duration and 500 kWh/HH-yr demand.

Note also that both of these preceding figures show two "stacked bar" cost indicators for grid, and two for mini-grid. In each pair, the higher "stack" represents costs for electrification of all households, while the shorter "stack" represents costs if geographic "outliers" (very small communities and isolated households) are assumed to be electrified with a third technology with no MV nor LV network, such as solar home systems or solar lanterns. The individual bars in each stack vary in color slightly to reflect the switch from higher MV/HH and LV/HH values to lower values when these costly homes are shifted to electrification by home systems of some type.

IV. GEOSPATIAL FACTORS IN LARGER-SCALE NATIONAL OR REGIONAL PLANNING: NGA, MMR, ONG, IND

The previous discussion has focused on detailed analysis, including specific household locations, for selected rural areas, on the scale of tens of kilometers. However, planning for universal access in entire countries or regions must address much larger areas, on the scale of hundreds or thousands of kilometers, typically including millions of potential connections. In these contexts, data with locations of individual homes is typically unavailable and can be costly to acquire. However, data for the locations of communities – ideally down to the level of individual villages or even clusters of homes – combined with empirically grounded estimates for household spacing, can be very useful in electrification planning.

The community level data provides an empirical basis for predicting medium voltage network requirements, and thus MV/HH and related costs. This information, in turn, serves as a basis for cost-benefit prioritization of grid construction (or "roll-out"). The following example, in Figure 13 below, shows map results of algorithmic, least-cost modeling of a utility-scale electrification planning study recently conducted in northern Nigeria. The grid extension portion of the access program is broken down into four phases, with extension to the lowest cost connections first, followed by extensions reaching more distant and smaller communities with higher per-household connection costs.

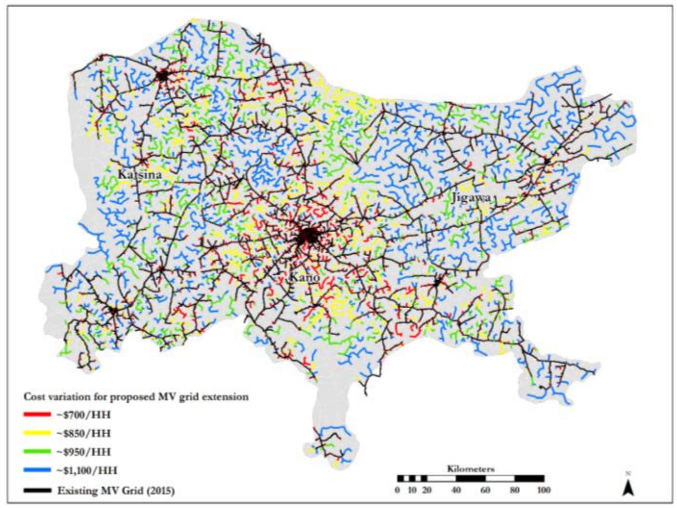

Figure 13: Prioritized grid roll-out in four phases for universal electricity access (Northern Nigeria)

Figure 14 below illustrates these changing costs from the same northern Nigerian utility as a chart. Reading from left to right, with 0% of households connected at the left edge, and 100% connected at the right edge, the figure shows that MV line needs, and thus household connection costs, begin at a low level, as communities in more densely populated areas near the grid are connected. Costs per connection then rise moderately and consistently as grid is extended to gradually more rural areas. Finally, as the last few percent of communities are connected – at the far-right of the diagram, beyond 95% completion of the extension program – rapidly rising MV line requirements to connect very dispersed communities cause costs per connection rise suddenly, increasing by a factor of 2-4 to connect what is, in fact, a very small number of homes (often the final 1-3%). In this example, a rapid increase in costs per connection (blue line) for the last 10% of homes – costs double from around US$1,000 per household at the 90% coverage level to over US$2,000 as the access rate approaches 100%. The medium voltage line length required per connection rises from around 15 m/HH to nearly 100 m/HH over this same portion of the grid extension program.

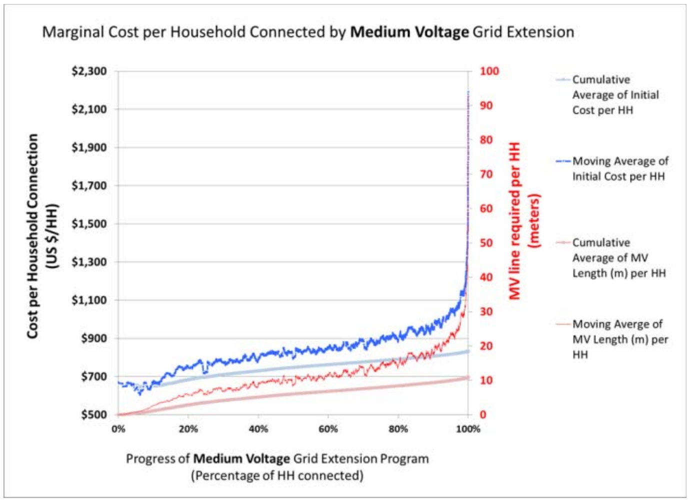

Figure 14: Increasing MV line and cost as prioritized grid roll-out proceeds (northern Nigeria)

While the previous example considers only one of the key geographic factors examined in this analysis, medium voltage line length per connection (MV/HH), the next example for Papua New Guinea also addresses the issue of household spacing, which determines low voltage line needs and costs.

This sort of visual inspection, complemented by other techniques, was carried out for rural sample areas in all provinces of Papua New Guinea. The results of this analysis established estimates of inter-household distances for every province (see Figure 16 below), which were used as a basis for estimating low voltage line needs and costs per connection.

This figure shows province names across the x-axis, and estimated mean inter-household distances (MID) as a proxy for LV/HH using three different methods: measuring distance between all households as single line (the "bulk" approach); using GIS to create a polygon surrounding a settled area and assuming even distribution of households within that area (the "area-based" approach); and a third method that estimated connections in two parts, including an overhead LV wire plus a "service drop" (this third approach is shown in Figure 15 below).

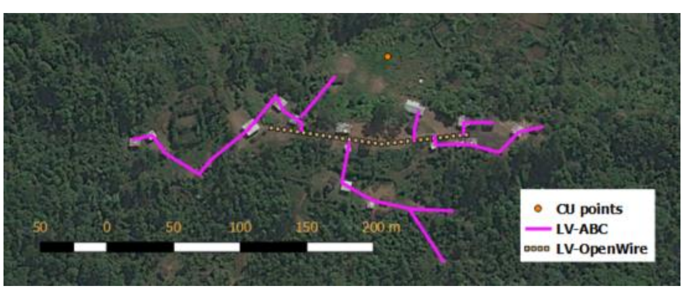

Figure 15: Use of high-resolution satellite imagery to estimate LV/HH needs (Papua New Guinea)

The three methods resulted in approximate comparable values in most provinces. The red frames around some bars indicate provinces with unusually high estimated inter-household distances, suggesting higher low voltage line costs per connection.

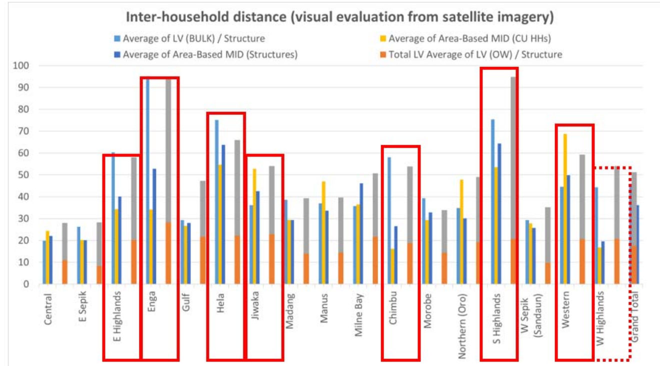

Figure 16: LV/HH estimates using three methods (for all provinces of Papua New Guinea)

This LV cost study formed one component of an estimate of all initial costs per household connection throughout a prioritized, national grid extension study for Papua New Guinea (PNG) shown in Figure 17 below. Unlike the Nigerian example, this analysis for PNG combines geographically specific estimates for both of the two key parameters of this analysis: inter-community spacing, which determines medium voltage line costs (MV/HH), and inter-household spacing, which determines low voltage line costs (LV/HH).

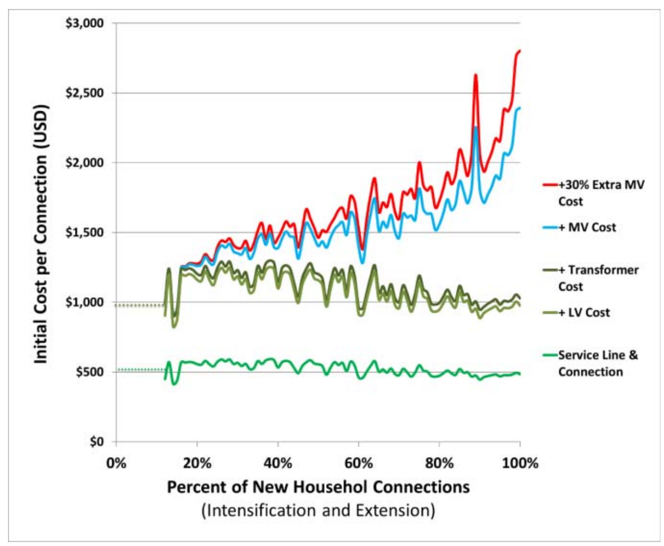

Figure 17: Rising initial costs per household connection for a sequenced grid extension program (Papua New Guinea)

In this PNG example, medium voltage line costs (red and blue lines) show a gradual upward trend, while low voltage line costs (olive green) show a slight decline. This combination of rising MV line costs and declining LV line costs throughout the grid extension program are due to historic patterns of grid extension in PNG. Provinces with large farms and widely dispersed households (higher LV/HH) happen to be nearer to the existing grid and so would be electrified first in a sequenced national grid roll-out program. Provinces further from the existing grid, to be electrified later in the sequenced grid roll-out program, tended follow a pattern more typical of coastal settlements, with higher inter-community spacing among communities accessed primarily by boat (thus higher MV line costs) but lower inter-household spacing in closely-clustered fishing communities (lower LV costs).

The preceding examples from Nigeria and Papua New Guinea show estimated values for future electrification. The following final example shows data for existing systems, specifically rural grid electricity access rates for states in India. Figure 18 below shows the percentage of rural households electrified in each state versus the medium voltage grid line length per connection for customers already connected.

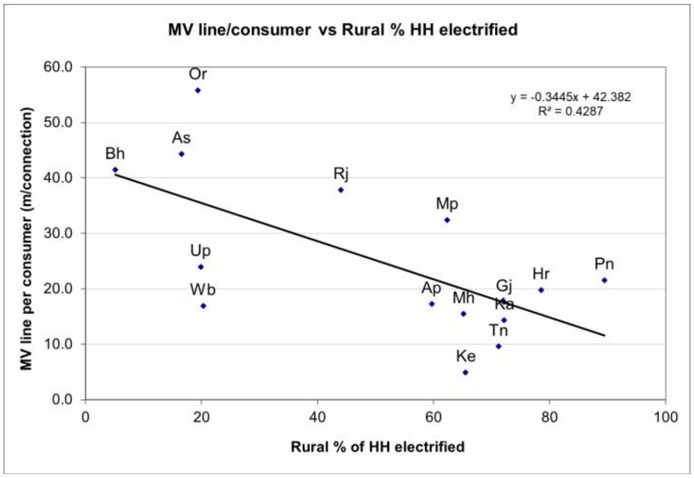

Figure 18: Rural electrification rates versus MV line length for states in India.

The data from these existing systems show a pattern that is consistent with the estimates from the broad geospatial observation that dispersed rural areas cost more to electrify, and thus show lower access rates. In the existing systems in India, there is an anti-correlation between the length of medium voltage line required to connect homes and the percentage of households connected. These data suggest that high access rates (above 60% or so) are most likely to occur in rural areas where medium line needs are below about 30 meters per connection. It is noteworthy that this MV/HH value of 30 meters is the value chosen for the division of four "quadrants" in the previous analysis of rural African settlement patterns presented in Figure 8 above. (Data was not available for LV/HH from Indian states, so the analysis of this dimension in network planning has not been assessed here.)

V. SUMMARY / CONCLUSIONS

This analysis has considered geospatial data for settlement patterns at different spatial scales to serve as a basis for cost estimates for electrification. Data for inter-community spacing (as a proxy for medium voltage line needs) and inter-household spacing (as a proxy for low voltage line needs) at local and national/regional scales provide a general geospatial framework for analyzing electrification costs for networked systems – grid and mini-grid. Results of geospatial analyses using this broad framework have been compared with results from larger scale costing analyses for universal electricity access programs in Nigeria and Papua New Guinea. Finally, data from existing systems in separate Indian states suggests that actual grid networks respond to these geospatial patterns, specifically in that rural areas with medium voltage line requirements below 30 meters per connection show substantially higher overall grid access rates.

Future directions of this work can focus on at least two areas: First, geospatial data at the household level, necessary for estimating inter-household spacing to determine the "last-mile" low voltage line costs, are currently somewhat limited. The analyses presented here are for small areas and have not been tested at larger scale. Additional analysis for larger areas, perhaps involving machine learning tools combined with statistical methods, may be fruitful in estimating costs for networked systems in areas with little or no electricity access. Secondly, empirical analysis can continue from the opposite direction through analysis of low and medium voltage line lengths and costs per connection for rural areas that are already electrified, following the example here using data for different Indian states.

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