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Identification and Evaluation of Cost Optimal Technology Options for Improvement of Electricity Access in Rural Kenya

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ABSTRACT

With around 12% of Kenya's rural population having access to electricity in 2014, rural electrification's progress has been conspicuously slow over the years. The purpose of this study is to identify and evaluate cost optimal technology options for improvement of electricity access in rural Kenya, on a geographical information system platform. Based on a one-year scenario, the study uses site suitability and cost distance analysis to conduct a mapping exercise based on four pre-chosen technologies. The results indicate that these technologies have the potential to reach around 2.1 million households increasing the national electrification rate by 28 percentage points to stand at around 94% from the current reported figures of 66%. Grid extension has the potential to reach 1.6 million households, followed by the solar photovoltaics and solar photovoltaics/wind hybrid mini-grids reaching 167,925 households while solar home systems extends to 315,844 households. Geographical information systems can be useful to energy planners, regulators, investors and users, as they aid in decision-making through the intersection and integration of information on multiple levels. Further research is also identified.

KEYWORDS

Kenya, Electricity access, Rural electrification, Rural electrification planning, Spatial analysis, Geographical information systems.

INTRODUCTION

Energy is a vital component in the social, technological and economic development of human beings that has become an intrinsic part of modern day-to-day lives. Energy has been labelled as the "oxygen" of the economy and the "life-blood" of growth as it is crucial to nearly all services and goods in the modern world [1]. Every advanced economy can attribute its development and success, to reliable access to modern energy [2]. While there is no single definition of modern energy access, in almost all the variable definitions, there are some commonalities such as household access to minimum level of electricity, household access to safe and sustainable cooking and heating fuels, access used to deliver public services such as electricity in health facilities and access that allows for productive economic ventures [2].

Considering the Kenyan case, the energy sector is primarily supplied with biomass at 68%, petroleum products at 22% while electricity stands at 9% of the total energy consumption and other forms such as solar and wind take up the remainder [3]. Electricity for lighting is not widespread. It is found mostly in the central and western parts of the country which host most of Kenya's urban population with majority of the households (estimated at 64%) using paraffin through tin lamps or lanterns, while fuel wood is used mostly in the northern part of the country where majority of the population are pastoralists [4, 5]. Similarly, the most common cooking fuel is wood at 56%, followed by charcoal at 17% while electricity is at 0.4% amongst many other fuels [5]. This energy mix calls for integration of more sustainable forms of energy.

Although Kenya's electricity demand has more than doubled from a peak demand of 785 MW in 2002/03 [6] to 1,650 MW recorded in March 2017 [7], the electricity consumption per capita has had a much slower progress. In 2003 it was recorded at 128 kWh growing to 167 kWh in 2014, compared to the Sub-Saharan (SSAs) regional value of 483 kWh in the same year [8]. Likewise, the country's performance on increasing access to electricity has been sluggish with the national electrification rate rising with around 25 percentage points over twenty years. As of 2014, 36% of the population had access to electricity with an urban electrification rate of 68.4% while the rural electrification rate stood at 12.6% [8]. The slothful progress of Rural Electrification (RE) suggests that specific focus needs to be accorded to this sub-sector if universal access is to be achieved.

RE can be described as electrifying rural and remote parts of a country. The objective of electrifying rural areas is faced with many challenges such as low load density due to low population densities, poor load factors characterized by evening peaks, remote areas with rough terrain as well as high capital and operation costs for grid extension. In addition, people living in these areas tend to be poor with agriculture as their main economic activity, which limits productive uses of electricity. To address electricity access under such diverse situations, there is need to take advantage of innovative and successful off-grid approaches that use renewable energy applications such as Solar Home Systems (SHS) or hybrid mini-grid systems using Renewable Energy Technologies (RETs) or in combination with diesel-powered rather than rely on grid electrification alone [9].

It therefore, suggests that RE planning requires a creative and coordinated strategy that enables decision makers at the macro-level to choose economically sound electrification technologies that consider the social and environmental effects at the micro-level. Spatial analysis carried out on Geographical Information System (GIS) platform, offers such an innovative approach, such that in RE planning, it would include modelling relationships between elements such as population density, distance to the main grid, available local renewable energy resources to generate new interactions. In turn, this would provide new knowledge and results that can influence the solutions needed to provide suitable electrification options.

LITERATURE REVIEW

The rudimentary levels of infrastructure performance in terms of quality, quantity and access in SSA are a major impediment of growth and productivity in the region. According to the Global Competitive Report, 2018, SSA scored 46.3 out of a possible 100 points, ranking it last globally [10]. Additionally, there has been minimal addition of electricity generating capacity over the last 20 years in the region, increasing by 0.01 MW per 1,000 people in 2012 from 0.03 MW in 1990 [11]. Many factors contribute to this trend. Therefore, the lack of electricity infrastructure in rural areas is not surprising because RE is seen as an enormous infrastructure project, economically unattractive for private developers as well as for governments that must optimize the limited resources that they have: making it more complex than urban electrification [12]. This paper focuses on infrastructure development, namely RE and its strategic planning in order to improve access of electricity in rural Kenya.

Traditionally, electrification is seen as a national government prerogative where grid extension and densification has been the preferred way of increasing electricity access in most countries [13] and Kenya is no exception [14]. Beforehand, small-scale renewable energy solutions were not largely considered due to the barriers they exhibited such as cost-effectiveness, technical barriers, market barriers, social and environmental barriers [15]. However, the tide has changed and technologies such as solar Photovoltaic (PV) systems and small-scale wind systems have become more competitive against grid extension due to technology improvements and cost reductions [16]. Moreover, the growing dependence of countries on fossil fuels and its price volatility has prompted countries to safeguard their energy security [17], thus increasing the economic attractiveness of RETs, which additionally contribute to mitigating global warming and in the abatement of greenhouse gas emissions [18].

RE projects are unique because they require diverse financial, institutional, technical and organization approaches from the conventional methods. Additionally, as they occur locally, it is prudent to take advantage of their specific geographic qualities such as local renewable energy resources, population distribution to attain their full potential [19]. RE projects are usually cost intensive due to the remoteness and dispersed nature of the un-electrified communities, their socio-economic status, low demand as well as low load factors [20], which is reflected in the high cost of provision of electricity, the low affordability and in their overall sustainability. Creation of RE programs as an institutional response can contribute to a significant increase in RE rates. These programs can allow for national governments, donors and private sector to work together in the planning, financing and implementation of the RE programs. Brazil, Ecuador and Bolivia have some notable success RE projects [21].

RE planning for grid extension and off-grid applications can take three major forms:

- Separation;
- Uncoordinated;
- Coordinated approach.

In the first approach, the two main strategies are handled separately in policy-making and in resource allocation. Although, the approach seems simplified, the demarcation may hinder the prospect of grid extension to off-grid areas in the future [22]. Additionally, if done purely on financial viability, the poor population may lack the service altogether or be exposed to paying higher tariff cost [23]. In the second approach, the strategies are carried out without any regulation and integration into the country's main goal. As with the first approach, its flaws may include maximizing profits while marginalising poor consumers, overlapping or duplication of electricity services such as when the national grid expands into off-grid areas, affecting the readiness of private sector involvement. Such is the case in Kitonyoni, Kenya where a 14 kW solar PV hybrid mini-grid with (diesel backup) was constructed in 2012 and three years later the grid arrived [24]. Although the community did not connect to the grid, it is clear case of duplication.

The coordinated approach is where off-grid electrification and grid extension are carried out simultaneously: focusing on their complementary financial, economic, technical, environmental and social elements rather than their competitive ones. As RE programs require both public and private sector participation, the national governments can proactively support the private sector by creating market incentives, transparent regulation and targeted subsidization both on the supply and consumer side [25]. For instance, a strong and integrated policy framework that successfully incorporates off-grid technologies with clear licensing, tariff-setting and rights of concessions guidelines, can create favourable conditions that protect private investors and provide opportunities for both the private investors and the national utility [26]. This study makes a case for the coordinated approach where electricity planning looks at both grid extension and off-grid electrification pathways simultaneously.

Given the complexity and magnitude national electricity planning represented by increasing population, low electrification rates, increased electrification options and the intricacies of rural electrification, there is need for comprehensive planning tools. These tools aim to synthesize aspects of the current and proposed future energy system to determine cost effective electrification options. This study presents a GIS-based electrification planning exercise, complemented with energy system simulation and optimization tools. Bertheau *et al*. [27] claim that only few such tools exist and their application is rare but this slowly changing as GIS-based tools are proving to be useful in RE planning and in supporting decision-making [28, 29].

Electricity planning requires combining the various aspects of the target areas such electricity demand, topographical characteristics such as terrain and elevation, distance from the main grid, resource potential, while aggregating the cost of technology and of the electricity to end user [30]. The use of geo-referenced data can hardly be practical without the use of a GIS [31]. Although in Africa, there are limited GIS-based comparison analysis for use in electrification planning due to deficiency of relevant energy-related information such as current energy use, potential of renewable energy resources [32], such deficiencies have been managed either by either acquiring remote-sensed data when the budget allows or using open-sourced data to fill in the data gaps. Such data in acceptable levels of detail, can still inform policy makers where, when and what type of technology is to be deployed to rural areas [28].

Some studies have been carried out for electrification planning by allocating pre-chosen electrification pathways to serve un-electrified communities. Kemasour *et al*. [33] used a GIS supported software called NetworkPlanner to explore the cost-effective electrification options under 100% penetration rate[*] in Nigeria. They found out that grid extension was most cost effective for 85% of the un-electrified communities, with mini-grids serving 8% and stand-alone systems serving the remainder. Bertheau *et al*. [27] derived a least-cost electrification plan at cluster-level via a GIS platform which resulted in allocating grid extension, PV-hybrid mini-grid and SHS to 57.1, 12.8 and 2.8 million people, respectively. Cotterman [34] applied a Rural Electrification Model (REM) to Kayonza, Rwanda where allocation of electrification options was according to the load profiles of the buildings, the distance to the grid and having the least cost of investment. Due to the extent of the grid, the study concluded that most of the population are grid-compatible while those further away fell into the off-grid options. Parshall *et al*. [35] used an algorithm based on Kruskal’s minimum spanning tree to determine demand nodes that met the least-cost criterion deemed appropriate for grid expansion while the remaining nodes were allocated to off-grid application, according to their relative costs.

On the other hand, GIS has also been used to select the optimal site for various RETs intended to serve the off-grid compatible communities such as those derived in the studies mentioned above. On a continental level, Herman *et al*. [36] used GIS to estimate the technical potential of solar, wind and bioenergy in Africa where the sites with the highest potentials were derived as well as their potential energy output. This study was unique because they looked at biofuels harvested from three crops: sugarcane, soybean, Jatropha rather than residual crop or woody biomass as seen in Hiloidari *et al*. [37] or in Kaudinya *et al*. [38]. Jahangiri *et al*. [39] applied GIS to find optimal site in the Middle East for wind-solar PV hybrid large-scale power plants while Kling *et al*. [40] used a GIS-based methodology to identify attractive regions for small-scale to large-scale hydropower development in West Africa. Kaijuka [41] used GIS as visualization tool to prioritize un-electrified communities through a benefit points allocation formula in

[*] Penetration rate is electrification of every household in each community.

Uganda. The novelty of the approach in this study is that the allocation of electrification options are prioritized where it is economically feasible to do so. For instance, with the grid extension option, high and low priority areas are delineated as well as the optimal sites to set up the off-grid options. Additionally, with the help of a simulation tool, a site allocated the mini-grid option is verified by calculating the break-even grid distance and proving whether the option chosen is ideal.

Recently, a GIS-based electrification planning exercise was carried out under the Least Cost Geospatial Electrification Plan (LCGEP) of the Kenya National Electrification Strategy [42]. The Plan's main objective is to achieve universal access by 2020 and assist in further network development through 2030. Our study is similar to the LCGEP study in that both our models aim to achieve the 100% electricity access but differ many aspects namely in the cost criteria and thresholds as well as the study area examined. In the LCGEP report, they look at the economic value criterion while this paper deals with the infrastructure cost of extending the grid in terms cost per connecting household and cost per meter of Medium Voltage (MV) line as the deciding factors. Additionally, they look at grid densification and only solar PV mini-grids while this study overlooks grid densification because the national utility was doing it at the time of writing this report and not only includes solar PV but also solar PV/wind hybrid mini-grids and SHS.

Moreover, the results achieved in this study are not comparable with those in LCGEP report. In the LCGEP, they allocate 837,000 households to grid extension, 590,000 households to grid densification and 34,000 households to solar PV mini-grids. These differences occur because firstly, the study area differs considerable, in the LCGEP report analysis is carried out in 98,000 km² while this study looked 126,976 km² for grid-compatible population. Secondly, they used a maximum threshold of EUR 1,735[†] while this study used a value of EUR 1,245 for the cost per connecting household. Lastly, the methodology in the LCGEP report is not properly documented making it hard for closer examination while this study uses site suitability and cost distance analysis. This study also differs from other studies where the clustering of demand nodes is done after the grid-compatible population is analysed unlike in Bertheau *et al*. [27] where it is done before and for all un-electrified population. This is because grid extension is likely to occur to those people near the infrastructure and not necessarily in a cluster unless it is uneconomical to do so.

METHODS

The research employed two main methods: qualitative and quantitative methods to sufficiently comprehend the research problem and achieve the research objectives, which fell into two major categories: carrying out a RE planning exercise for Kenya and understanding the environment that RE operated in. The methodology for RE planning exercise used in this study employed spatial analysis on a national level via a GIS platform. The pre-chosen electrification options included the conventional grid extension, solar PV mini-grid, solar PV/wind hybrid mini-grid and SHS. While there are many other electrification technologies, these four were chosen because they are mature technologies, are locally appropriate and due to the availability of their spatial data. The analysis takes place at a national level and therefore, the maps will cover the extent of the country's boundaries without further aggregating the information to county or constituency level. This is largely attributed to the research objective that looks at analysing RE as a single national component. Additionally, most of spatial data acquired was not disintegrated into smaller administrative boundaries thus also influencing the form of analysis.

[†] Reported as USD 2,000 and converted to euros at an exchange of USD 1 = EUR 0.867624 [42].

Further elaborated in the analysis section, the expanse of estimated demand was done through a site suitability analysis, which incorporated five criteria: population density, distance from existing grid, land use, protected areas and elevation. The potential demand was then clustered into households and the cost per connection per household was simplified and based in literature. The cost comparison of the electrification options was done through creation of a cost raster that determined the extent grid extension and whereby mini-grids were further allocated using geospatial location of wind and solar resource potential as one of the main criteria. SHS were allocated by exclusion. Grid densification was not included in the study. Figure 1 shows the conceptual framework developed for the spatial analysis of the electrification options and Table 1 shows a summary of the input data used, type, sources and date of the data

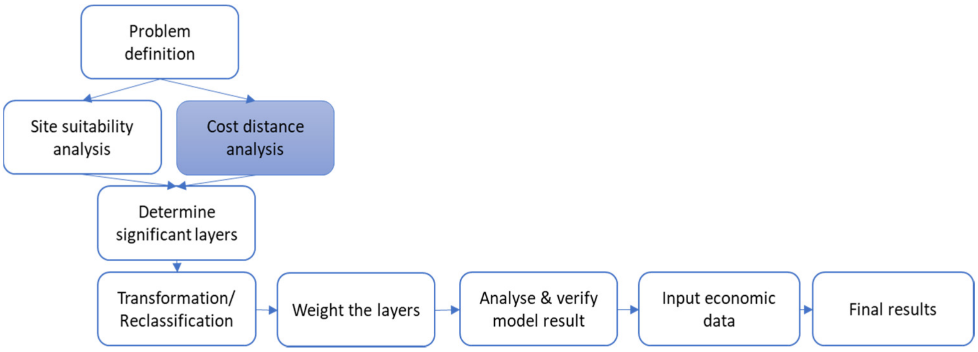

Figure 1. Conceptual framework for electrification options

The assumptions and limitations of the study are explained here. The spatial analysis carried out is based on a one-year scenario and does not include any projections for demand or cost and has no component of temporal data included. As the study was data-intensive, some of the data acquired had different datums thus proved difficulty to align together in the GIS platform, limiting the extent of geoprocessing functions being carried out successfully. Another challenge encountered was that some of the data, mainly vector data, was of low quality, containing slivers, overshoots and undershoots necessitating the use of less accurate but relatively better quality, open-source data.

Allocation of SHS to the population that was not electrified by either the grid extension or the mini-grid applications was largely subjective as Kenya is regarded as one of the most vibrant SHS market in Africa with approximately 300,000 units reported to be present [43]. A report by Lighting Africa indicated that on average less than 50% of the rural population would have access to SHS due to its higher price compared to that of solar lanterns despite the projected price declines in solar products and increased access to finance innovations [43]. Therefore, it was assumed that 50% of the remaining population (after grid and mini-grid allocation) had absolutely no access to electricity prior to the analysis and thus would be allocated SHS.

Table 1. Input data and sources

Dataset description	Type of data	Source
Country boundary	Feature	[44]
Population density	Raster	[45]
Land use cover	Raster	[46]
KPLC mini-grids	Feature	[47]
Existing grid lines	Feature	[47]
Elevation	Raster	[48]
Protected areas and national parks	Feature	[49]
Solar irradiation	Raster	[50]
Wind speed	Raster	[51]
Constituency boundary	Feature	[47]

The Illemi triangle, a disputed triangular piece of land in north of the country Kenya and situated at the north-western side of Lake Turkana bordering Kenya, Ethiopia and South Sudan, has not been included in the analysis due to data processing procedures as well as for impartiality purposes. The number of people in the triangle excluded from the analysis is also unknown as Kenya includes the triangle's data together with Turkana County as one entity.

ANALYSIS OF ELECTRIFICATION OPTIONS

In this section, the location of priority areas for grid extension and mini-grids are evaluated with the grid extension option being categorized into high and low priority areas while mini-grid potential sites are categorized according to the settlement size of target population. Their associated costs together with those of the SHS option are also appraised.

Grid extension option: location of priority areas (site suitability)

In this option, two major aspects were dealt with the location of priority areas (site suitability) and the cost allocation to connection per household. The location of priority areas to electrify through grid extension is a valuable aspect as it offers an initial decision support with the use of GIS software, through a method often referred to as site suitability analysis. As per the nature of study, the site suitability analysis was considered a Multi-Criteria Evaluation (MCE) where there are many different criteria and only one objective.

Selection of criteria considered are of a cost-effective nature due to the financial sustainability that they offer for grid extension. The first of five criteria considered was the distance from the existing grid. This criterion has an impact on cost of connection in that, the farther away the target population is, the higher the capital cost of the investment tends to become due to the need to erect longer transmission/distribution lines and the higher the energy losses experienced in these long lines effectively raising the cost for delivery of the electricity [52]. Due to the Last Mile Connectivity Project (LMCP) currently carried out by Kenya's national utility company, a 600 m buffer has been excluded from the analysis as KPLC is working to electrify the households within this distance. In the analysis, a 10 km threshold is used as the upper limit, but this is subjective and can be changed accordingly.

The number of people to be connected is another cost-related critical factor. Higher cost of connection per household is likely for low population densities as the total costs are distributed over fewer people than for areas with higher population densities, in addition to, having increased distribution losses due to the low load density if long transmission lines are present. The third criterion was land use as it is important to consider the current land uses to avoid conflict. It is also impractical to erect gridlines in water bodies or flooded areas thus such areas were excluded in the analysis. Protected areas and national parks were also excluded in the analysis, in line with Kenya's Wildlife Bill 2011 [53], in a bid to safeguard these areas and minimise cases where the distribution lines run across such areas. In effect, a 150 m buffer was drawn around these areas. Lastly, elevation is also a key factor when it comes to costs because it would be less expensive to erect gridlines and associated infrastructure in a relatively flat surface than it would to do that in a hilly or mountainous region attributed to additional costs to access the area and associated construction costs.

The weights of the five criteria mentioned above were done with the weighting-by-ranking method. Distance to the grid was deemed most important thus given rank one and subsequently the rest of the criteria followed to elevation with rank five as seen in Table 2. The value of 1.5 was chosen for the parameter (p) following a sensitivity analysis experimented using different values of p. It is noteworthy to mention when p = 0, all criteria have the same weight while with increasing values of p, the distribution of the weight is skewed to have the first two important criteria gaining more weight while the other criteria become obsolete.

Table 2. Weights for the five criteria for site suitability

Weighting by ranking (rank exponent)				
			p	1.500
		Exponential weight		
Criteria	Rank	Weighted exponential $(n - r + 1)\ p$	Normalised weight	Normalised weight [%]
Distance to grid	1	11.180	0.396	40
Population density	2	8.000	0.284	28
Land use	3	5.196	0.184	18
Protected areas	4	2.828	0.100	10
Elevation	5	1.000	0.035	4
Total		28.205	1.000	100

A site suitability model was created in the ModelBuilder using ArcGIS software. The proximity to the existing grid lines and to protected areas was first carried out using Euclidean distance tool, then the reclassify tool was used for four of the elements and the scale used was 1 to 10 with 1 being the least suitable and 10 being the most suitable. Euclidean distance is the straight-line distance of each cell to the closest cell of the source dataset, in this case the existing grid lines and protected areas. Thereafter, their outputs were overlaid using the weights mentioned above. The land use dataset was fed directly to the weighted overlay tool, because it contains unique values (has a nominal scale) which were assigned various scores depending on the land use type. The output was a grid extension suitability mask.

Cost analysis for grid extension. The cost analysis for grid extension was done by using a euro cost raster through carrying out a cost distance analysis, a form of spatial analysis that measures how costly it is to travel over a surface [54]. The cost distance analysis determines the least-cost path to choose to extend the grid for each of the source cells (areas with un-electrified population) in the study area. As seen in Figure 2, the euro cost raster (red circle) is based on two criteria namely cost per single-phase connection per household and cost per construction of MV line (straight-line measurement) in euro cost measure. The criteria chosen are simplified, the average cost of connection per rural household is estimated at EUR 1,245[‡] [55] which includes not only materials such as conductor and pre-paid meter for the service drop but also the low voltage network extensions from the distribution transformer. It is also assumed that it does not include the cost of construction the MV line.

Other studies have reported higher figures such as that of Parshall *et al*. [35] reported the cost per connection to be EUR 1,548 (USD 1,784) but this cost was chosen to reflect the low-cost design approaches that KPLC have adopted in the recent past. The other criteria chosen, was cost of construction of 33 kV 25 mm Single Wire Earth Return (SWER) MV lines at the cost of EUR 7.3 per meter [56]. Each of the criteria was given the same weight and mimics the 2nd phase of the LMCP where areas are selected based on the distance from the existing grid lines and the population density with an aim to maximize the number of new connections per invested shilling [57].

[‡] Reported as USD 1,435 converted to euros at the exchange rate of USD 1 = EUR 0.867624.

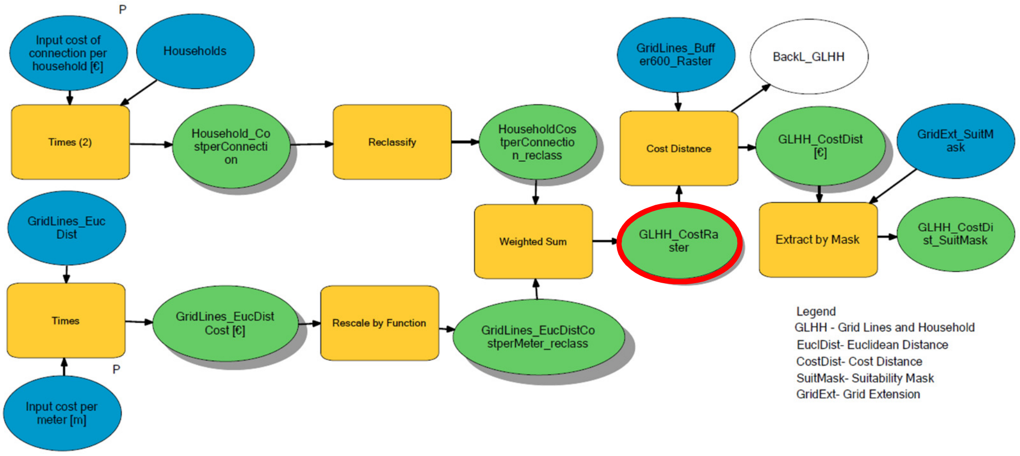

Figure 2. Cost distance model for grid extension

Generally, in the euro cost raster, the lower values are preferred as they indicate the total accumulative least-cost units over the cost surface, unlike in the site suitability model where the reverse is true. Once the cost distance raster was created, it was passed through the suitable-areas mask for grid extension that had been created in the previous section creating a cost distance map (see Figure 3). This map shows how costly it is to extend the grid taking into consideration the cost per meter of extending Grid Lines (GL) and cost per connection per Household (HH). It was noted that the suitable-areas mask fitted within the range where it was the less or equal to 20,000 EUR in the euro cost raster.

The first elimination procedure was done through the euro cost raster such that the areas demarcated for grid extension were those that did not exceed a euro cost of EUR 20,000. The euro cost was used as the threshold assuming that the finances were constrained, although this can be adjusted depending on the available budget. The euro cost was guided by a study done by Lee *et al*. [58] that reported the median cost of a Rural Electrification Authority (REA) project was KES 2.5 million (EUR 20,833). These areas were further divided in two categories: high priority areas with population density of equal or more than 150 inh./km² and low priority areas with a population density of less than 150 inh./km². The areas that were outside the suitable-areas mask were analysed for either the mini-grid or the SHS option.

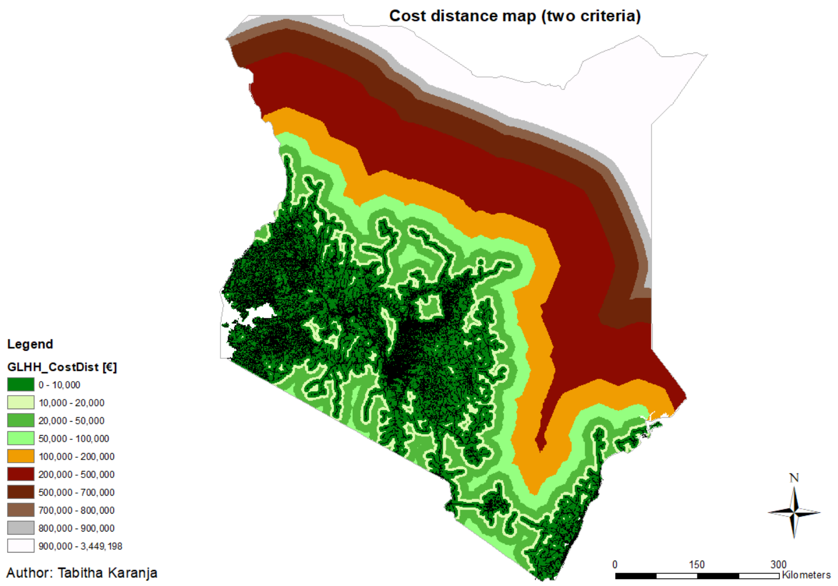

Figure 3. Cost distance map for grid extension

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The mini-grid option: site selection

The first step in this analysis was to create an off-grid mask. This included the areas that had a euro cost greater EUR 20,000. Apart from the cost criteria, the other criteria used for deciding if an area was optimal as a mini-grid site were population density and the renewable energy resources available. In this case, only solar and wind were used but the model can incorporate other RETs dependent on datasets availability.

Approximately one third of Kenyans live in the northern part of the country and are sparsely settled from the east to the west [59]. Taking this fact in to consideration, it was important to group the population in to settlements depending on the size of population, making it the first and altogether significant criterion that was used. Further processing of the population size was carried out through a settlement model, making four distinct categories, settlements with:

- Over 600 households (~ over 3,000 people);
- Between 301 and 600 households;
- Between 100 and 300 households;
- Between 30 and 100 households as shown in Figure 4. A household size is taken to be 5 [60].

Such a categorization was used for easy identification of those areas with more households that innately suggest that there would be potential of higher demand for the power generated by the mini-grid. Although, 30 households seem to be on the lower side, there have been cases where a mini-grid has been erected to serve such a small number of households, but due to economic sustainability, generally, more demand is preferred. Thereafter, the wind and solar resource data was matched up with the remaining sites to assign which technology which would be more suitable at each of the locations.

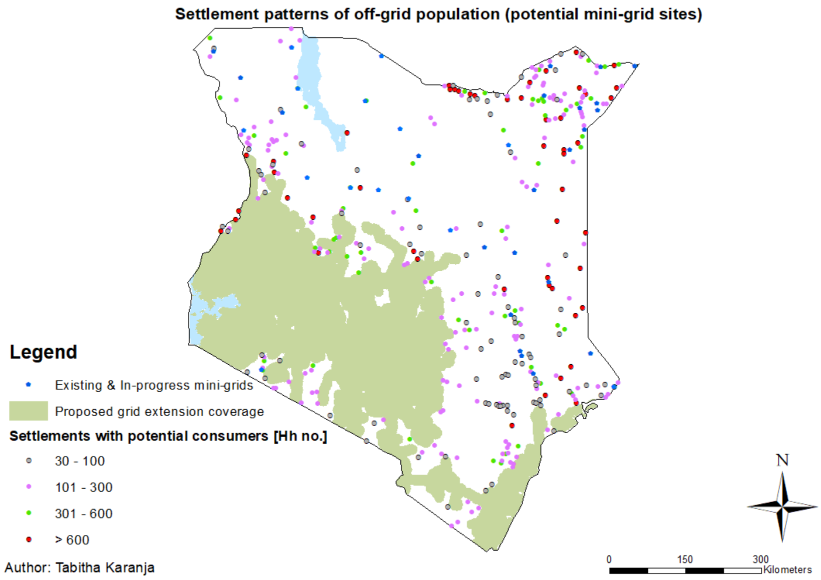

Figure 4. Settlement patterns of off-grid population (potential mini-grid sites)

For the wind resource data, a wind-speeds dataset of average wind speeds, recorded at a 50 m hub height with a spatial resolution of 1 km from the Global Atlas-International Renewable Energy Agency (IRENA) website was used [61]. For the analysis, the wind speed of 5 m/s and above was chosen as the speed at which the wind energy could be considered for the mini-grid site. The solar dataset used was the yearly average of Global Horizontal Irradiation (GHI), downloaded from the Global Solar Atlas website published by Energy Sector Management Assistance Program (ESMAP) [62]. Kenya is situated astride the equator and therefore, receives high irradiance, with the western and northern part of the country receiving the highest amount of irradiation. This implies that solar-powered technologies can be used all over the country with more success in some parts more than others can. An amount of 1,400 kWh/m² was chosen for the analysis to differentiate the areas with higher irradiance but the figure can be altered to suit different desired outcomes.

For both the wind and solar resources, the assumption taken is that, the higher energy output expected by having better renewable energy resources, would significantly contribute in the overall cost of the life cycle cost of the mini-grid installation. This implies that in the case of a hybrid installation with diesel, less diesel would be required in a plant with higher renewable energy penetration, to site an example. Nonetheless, the data is used for initial site selection but more comprehensive resource assessment ought to be done once the site has been selected, as mini-grids are site-specific. A combination of these three criteria (settlement pattern, wind and solar resources) was used to select the areas where it would be more suitable to put up solar PV or wind mini-grids or a combination of both.

Cost analysis for mini-grid option. The capital costs for mini-grids can hardly be generalized because of the distinctive characteristics and components that make up each installation. However, numerous studies carried out in Kenya have come to similar findings as seen in other parts of the world such as: the cost per kW installed of a mini-grid decreases as the system size increases. One such Kenyan study by Carbon Africa *et al*. [63] highlights that the general trend of decreasing costs and depicts clearly solar PV technology to be less cost intensive for smaller capacities but with increasing capacities, the competitiveness of wind and hydropower increases as well. Additionally, following a study done by National Rural Electric Cooperative (NRECA), of over 120 solar PV mini-grid installations planned for Kenya, the cost per consumer was derived as EUR 1,190[§] [56]. In a bid to derive indicative costs of all the mini-grid sites that were achieved in this analysis, this cost per consumer was used as an assumptive figure to calculate the total costs of the proposed mini-grids, clearly dependent on the number of potential consumers calculated.

Solar home systems

The SHS option was assigned to the population that did not fall either into the grid extension area or into the mini-grid sites by means of elimination. The analysis carried out was to calculate the number of population that was left from the previous electrification options and compute the costs that would be expected if this population was served with SHS of about 30 Wp which is the average solar PV system size in Kenya and whose typical cost is about 10 EUR/Wp installed [64].

RESULTS AND DISCUSSION OF COST OPTIMAL ELECTRIFICATION OPTIONS

The final site suitability maps and costs for the electrification options analysed previously are presented here together with validation the results in form of a case study.

Grid extension option: final site suitability map

Figure 5 shows the final site suitability map, which is a composite map that incorporates all the chosen criteria and produces the priority areas to be electrified. The map is overlaid with the existing gridlines for ease of comprehension and to show the findings accurately. The number of people within the suitable area region is around 8.1 million distributed over an area of 126,976 km², which is about 22% of the country's

[§] The cost per consumer was averaged between 121 solar hybrid (diesel) mini-grid installations based on a 10-year projected growth.

total area as can be seen in Table 3. With an estimated household size of five, that would translate to approximately 1.6 million households. The number of households currently connected to the grid as per the analysis is around 5 million against KPLC's figures of 5.5 million as at April 2017 [60]. The difference may occur to the nature and quality of the datasets as explained earlier but also due to the difference in the period of the creation of the datasets and date of the reported data tallied from the utility.

In a red-amber-green colour scheme, the results are presented in an easy-to-understand manner where the green colour shows the areas that are most suitable, with scores ranging from nine to five. On the other hand, red shows the areas that are least suitable with scores of two and below. The weight overlay tool has an output score of zero to mean that the area in question is not suitable at all. It is important to mention that an output can have the score of zero when scale values are set to 'restricted' because the value assigned to that cell is the minimum value of the evaluation scale set, minus one [65]. In this case, as one was the least score given in the overlay tool and subtracting one would result in a zero score as displayed in the suitability map.

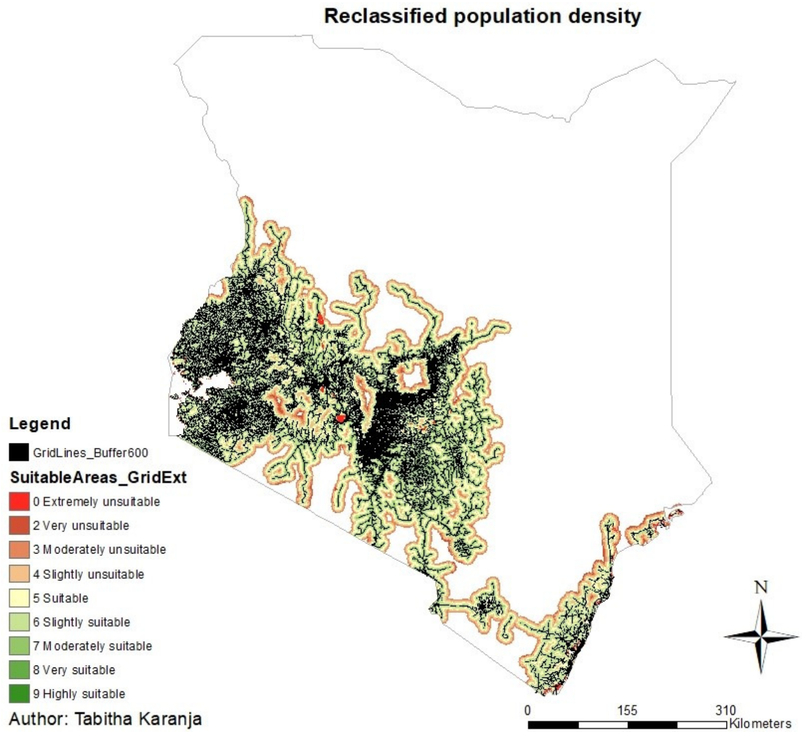

Figure 5. Site suitability map for grid extension

Table 3. Site suitability map statistics

Site suitability map statistics				
	Area [km²]	% of country's total area	Population	No. of households
Study area (incl. gridlines)	184,515	32%	33,156,040	6,631,208.00
Area with gridlines	57,539	10%	25,007,783	5,001,556.60
Suitable areas (mask)	126,976	22%	8,148,257	1,629,651.40

Such a map is important as a first decision-making support because it combines the relationships of the weighted criteria to come up with the suitable areas, where the land use conflicts are minimal, where the slope is relatively flat, not too close to protected areas, all within 10 km from the existing grid. It is noteworthy to mention that this composite map does not include any economic considerations as they are incorporated in to the cost analysis map in the next section.

Results of cost distance analysis. It is evident that the Lake Victoria region in the western part of the country has the highest potential for grid extension as most of the high priority areas are situated there (see Figure 6). Areas in the central part of the country and some areas in the coastal region follow this pattern. Similar findings were documented by Lahmeyer International [66]. The areas of low priority areas are just as important because even though they have a population density of less than 150 inh./km², as they are still within the threshold of project costs of less than EUR 20,000.

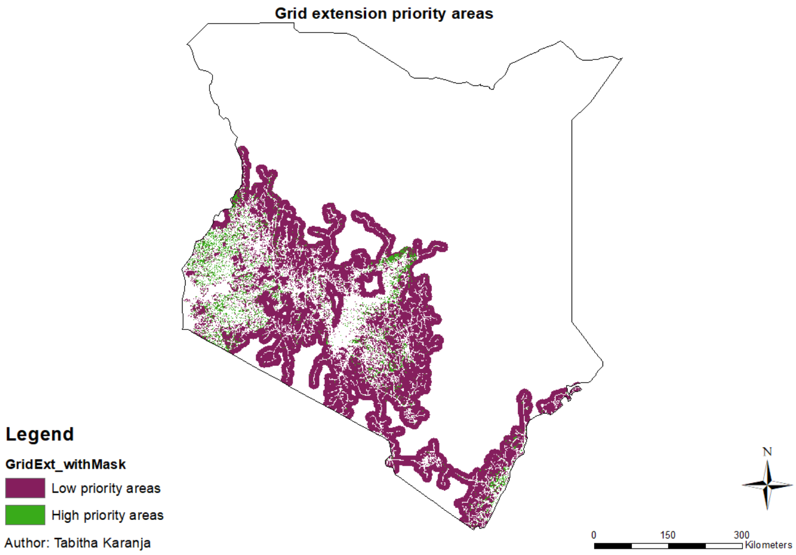

Figure 6. Grid extension priority areas map

With the assumption that no other electrification option such as mini-grid or SHS are deployed within the suitable-areas mask, the projected cost for grid extension amounts to around 2 billion euros in total as shown in Table 4. The household numbers derived in the site suitability map and the final figures in the cost distance map differ slightly with 0.001% owing to the different processes that have been passed through the datasets.

If an additional 1.6 million household (8.1 million people) were connected to the grid, this would increase the national connectivity rate to 88% from the current figure of 66% [7], although the current figure has been disputed and the actual figure is claimed to be much lower. Nonetheless, a report from KPLC, rightly acknowledges that there are over 1.3 million potential households living near the main grid, although no exact distance in kilometres is mentioned [57]. The KPLC report collaborates the results of this study.

Table 4. Grid extension potential households and projected capital costs

	Households	Projected capital cost [EUR]
High priority areas	971,125.60	1,209,051,372
Low priority areas	661,110.20	823,082,199
Total	1,632,236	2,032,133,571

As can be seen from the cost figures, grid extension is a capital-intensive exercise. As showcased here, a GIS platform can be used as part of a strategic and integrated planning process to identify and prioritize areas for implementation. This is an important aspect for planning because it not only shows what financial resources are needed but also directs where the highest efficiency of those funds can be achieved. Another benefit is that, it would be clear to the stakeholders what the government intended to do and how much in terms of people and area coverage was being considered [33]. From a funding perspective, it would benefit the government to know how much funding is needed and what would be the potential impact for the required funding. Additionally, the actual project implementation could be phased out and done over a period, as and when finances became available.

Furthermore, RE planning inherently involves many stakeholders. The capability of using GIS platforms and tools, presents an opportunity to accommodate and assimilate the various objectives from each of the stakeholders. The decision criteria chosen for grid extension are crucial as they determine the results and could change the circumstances in which grid extension is chosen and up to what point the extension be carried out. Therefore, it is paramount to have robust criteria in place because such a decision-making process renders RE planning to be administered objectively and efficiently. Essentially, RE planning can become a national-level planning strategy, through a coordinated approach that seeks to utilize all the resources available, from all institutions involved, in a more efficient and effective manner. The institutions that will benefit from such a coordinated process are not just REA and KPLC, but also Kenya Electricity Transmission Company (KETRACO), county governments and even the private sector.

From a private sector perspective, it would be beneficial to energy entrepreneurs to know where and what degree, the grid was going to extend for them to efficiently plan, where they could channel their investments [22]. In addition, for those mini-grid owners already within the range, such information would help them strategize what their next course of action would be, when the grid arrives. Although such a course of action is dependent many other things such as the policy, regulatory, legal and financial framework within which the mini-grid operates within, the information would nonetheless, be useful.

Mini-grid option: final site suitability map

From the analysis, the south-eastern part of the country is suitable for wind/solar PV hybrid mini-grids, because of the good wind resource found in this region as seen in Figure 7. Additionally, wind/solar PV hybrid mini-grids are also prevalent in the north-western part of the country in the surrounding counties near Lake Turkana as well as in the south-western part of the country bordering Tanzania with most sites situated in Narok West County. The north-eastern part of Kenya is suitable for solar PV mini-grids although there are a few sites where wind energy is also adequate to have wind/solar PV hybrid mini-grid. The sites designated for solar PV indicate that wind energy at the 50 m hub height is not as favourable and, in such sites, diesel can be used to complement the system or even storage options such as batteries can be employed.

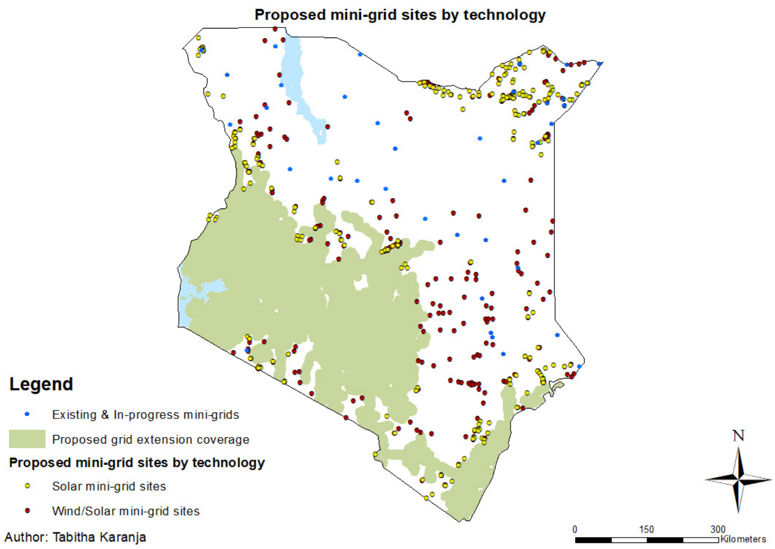

Figure 7. Proposed mini-grid sites by technology

Despite the northern part of Kenya having good wind resources and due to fewer households present in the area, which is characteristic of the region, there are fewer mini-grid sites set up. This low density can be attributed to aridity of the area as it is part of the Arid and Semi-Arid Lands (ASAL), has a dispersed population scattered over a relatively large area in small settlements and the communities that live in these regions are mostly nomadic in nature [67].

Mini-grid cost results. From the two technologies chosen in the analysis, a further 2.2% of the population would be served by the mini-grid installations at a projected capital cost of close to 200 million EUR. Each of the different types of sites mentioned in Table 5 have more than 30 potential households to cater for, with some even having over 600 potential consumers to serve. The area covered by the mini-grids is relatively small, amounting to 0.8% of the total area of Kenya. As is also evident in Table 5, the solar PV sites costs are much higher than the wind/solar PV hybrid sites. This is not to suggest that one technology is cheaper than the other is, but rather it shows solar PV mini-grids are more prominent than the solar PV/wind mini-grid, attributed to their geographical locality. Additionally, the solar PV sites cater for many people and as the cost is averaged by the cost of connection, it is understandable that the overall project costs are also higher.

The three criteria used for site suitability analysis for mini-grids are not exhaustive as they leave out the other parameters such as effective demand assessment, potential productive uses of the power generated and state of security as some of the areas are known to experience unrest, which need to be considered when it comes to choosing the sites to implement.

Table 5. Mini-grid households and projected costs

	Population	Households	Area [km²]	Projected cost [EUR]
Solar PV sites only	436,320	87,264	2,550	103,844,160
Wind/Solar PV sites	403,306	80,661	2,240	95,986,828
Total	839,626	167,925	4,790	199,830,988

Case study of proposed mini-grid site in Lorengipi ward, Loima Constituency. Following a cluster analysis to derive settlements that could be deemed mini-grid compatible, a site within Lorengippi ward having around 100 households was chosen to verify the results from the above section. Due to lack of empirical data, it was estimated that there were additionally 10 small commercial businesses, 3 public facilities and 1 anchor facility totalling an electric load of 165.44 kWh/day[**] with a peak of 14.13 kW when simulated using the community load option in the Hybrid Optimization of Multiple Energy Resources (HOMER)[††] software. The GIS map on site location, the assumptions for electricity consumption of the different consumers, cost assumption on the mini-grid system and grid extension used for this study can be found in accompanying supplementary information at the end.

The system was designed to run on solar PV and batteries, incorporated to act as a backup and provide flexibility due to the intermittency of the solar irradiation. A 55 kW solar PV system with 120 batteries having a usable nominal capacity of 486 kWh and autonomy of 70.5 hours were modelled to meet the demand. The system was modelled to meet almost all the demand (deficiency of 0.08%) but as a compromise, it generated excess electricity of 10,980 kWh/year (12.7%) with a small capacity shortage of

[**] Estimated electricity consumption per consumer can be found in the supplementary information at the end.

[††] It is software that allows a user to design and evaluate on-grid or off-grid power systems, both financially and technically for remote, stand-alone and distributed generation applications [68].

102 kWh/year (0.17%). The levelized Cost of Energy (COE) is 0.4480 EUR/kWh with the total Net Present Cost (NPC) of the system amounting to 427,302.70 EUR, which includes the O&M and salvage costs. These costs do not include costs for the erection of distribution network nor the construction of powerhouse or for logistical purposes.

The solar PV mini-grid site was then compared to the option of extending the grid to the same site. HOMER calculates the break-even grid extension distance, which is the distance where the NPCs for the stand-alone system (mini-grid) would be equal to the NPC of extending the grid [68]. The breakeven distance for grid extension was found to be 24.75 km. However, the proposed mini-grid site is 42.4 km away from the current main grid connection point, including the 600 m buffer expected to be covered by KPLC during grid densification. Moreover, even with the proposed grid extension coverage done in this study, the site would still be 32.9 km away from the closest grid connection point thus reinforcing the proposition that a mini-grid installation at the site would be a favoured solution.

Table 6 compares the total capital costs for both the grid extension option and the mini-grid option. It is evident that the mini-grid costs are much less and the cost per consumer amounts to 4,186.87 EUR/consumer against that of grid extension amounting to 5,608.77 EUR/consumer. Additionally, the cost per kW of the mini-grid amounts to 8,678.23 EUR/kW (8.67 EUR/W) which is relatively high but is expected given the size and configuration of the system. According to the IRENA [16], the total system costs can range between 2.17 and 9.46 EUR/W, for mini-grids that rely heavily on solar PV and have a battery. The prohibitive cost per kW can be attributed to the system configuration because it has no diesel generator component and instead, batteries were increased to cover the entire backup. The system can be customized further to meet the consumers' needs, which could increase or decrease the capital costs. Some suggestions include:

- Including a diesel generator for backup which would reduce the amount of batteries and thus capital costs for the batteries keeping in mind its capital cost;
- Reduce the hours of autonomy;
- Allow some unmet demand, which could be regulated either by demand-side management strategies or by load shedding among other possibilities.

Table 6. Comparison of electrification options for proposed site in Lorengippi ward, Loima constituency

Cost breakdown	Grid extension	Mini-grid option (55 kW)
Grid equipment cost [EUR]	589,399.48	-
Solar PV, battery cost [EUR]	-	427,302.70
Distribution network cost [EUR]	50,000.00	50,000.00
Total capital cost [EUR]	639,399.48	477,302.70
Cost/consumer [EUR]	5,608.77	4,186.87
Cost/kW [EUR]	-	8,678.23

Source: Author's own

Solar Home Systems

From the analysis, around 3.1 million people are outside the grid extension area as well as the mini-grid proposed sites, meaning that around 631,687 households are spread over an area of approximately 391,620 km². If 50% of these households can be facilitated with ways to access a SHS of around 30 Wp at an estimated cost of 300 EUR for the system, this option would require an additional investment of around 94.8 EUR million for around 1.5 million people (~315,844 households).

CONCLUSIONS

The main objective of the thesis research was to identify which electrification options would be cost optimal to improve electricity access in the rural areas of Kenya. Based on population density and the distance from the main grid, grid extension was found to be a suitable and cost optimal way to electrify an additional 1.6 million households within a 10 km threshold from the main grid. Such an addition would increase the national electrification rate by 22 percentage points but would require investments of around 2 billion EUR. Solar PV mini-grids have the potential of improving electricity access for an additional 87,264 households while and solar PV/wind hybrid mini-grids have the potential to reach an additional 167,925 households amounting to a total about 2.2% of the total population at a capital cost of approximately 198 million EUR. SHS have the potential to reach an additional 315,844 households estimated at a capital cost approximately 94 million EUR. In total, the four electrification options have the potential to reach around 2.1 million households increasing the national electrification rate by 28 percentage points to stand at around 94% from the current reported figures of 66%.

Case studies in both the grid extension and mini-grid options were used to verify the results achieved. It was found that when Meru County was analysed for the grid extension option, an additional 98,802 households could be grid electrified at a capital cost of 123 million EUR. This grid extension together with the LMCP project would increase the county electrification rate to 97%. On the other hand, for the mini-grid option, a site in Lorengippi ward, Loima Constituency, Turkana County was chosen. The verification was done via HOMER software where the break-even grid extension distance was calculated. The break-even grid extension distance was found to be 24.75 km against the actual distance of 42.4 km of the proposed site to the existing main grid. Even with the proposed grid extension coverage done in this study, the site would still be 32.9 km away from the closest grid point thus reinforcing the proposition that a mini-grid installation at the site would be a favoured solution. Furthermore, comparing the total capital costs for both the grid extension option and the mini-grid option, against assumed system configurations, the mini-grid capital costs were much less.

Further research includes incorporating other electrification options that include other RETs or multiple combination of RETs/hybrid systems depending on their availability locally. Although the analysis assumes a one-year scenario, further studies can include projection of future demand, dynamics of population growth and movement as well as variations of connection cost over a period of years.

NOMENCLATURE

Abbreviations

CostDist	Cost Distance
EuclDist	Euclidean Distance
GIS	Geographical Information System
GLHH	Grid Lines & Households
GridExt	Grid Extension
HOMER	Hybrid Optimization of Multiple Energy Resources
IRENA	International Renewable Energy Agency
KPLC	Kenya Power and Lighting Company
LGCEP	Least Cost Geospatial Electrification Plan
LMCP	Last Mile Connectivity Project
MV	Medium Voltage
PV	Photovoltaic
RE	Rural Electrification
REA	Rural Electrification Authority
RET	Renewable Energy Technology
SHS	Solar Home Systems
SuitMask	Suitability Mask

SWER	Single Wire Earth Return
Wp	Watt Peak

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Supplementary information for case study of proposed mini-grid site Lorengippi ward, Loima Constituency

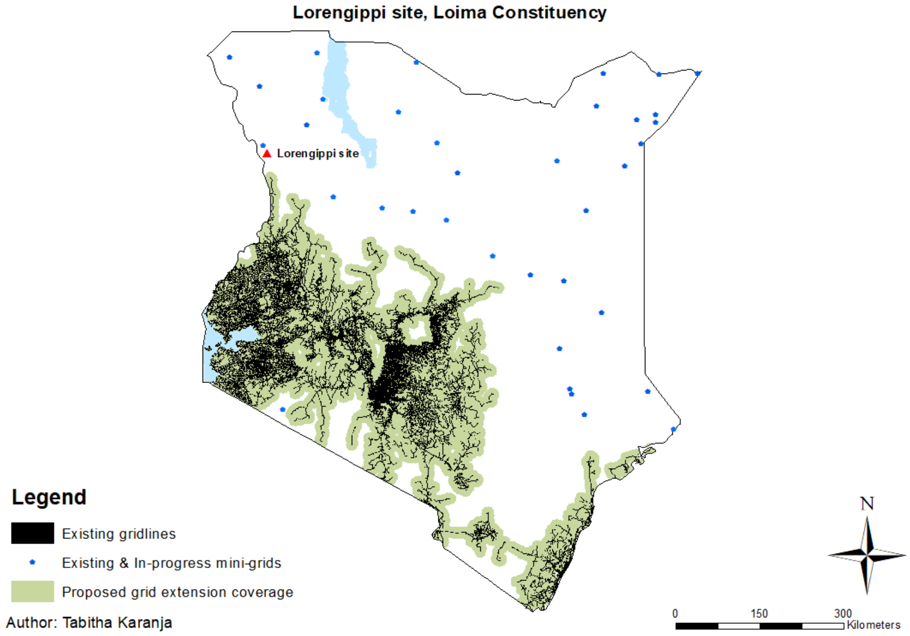

Figure 8. Proposed site in Lorengippi ward, Loima constituency (red triangle) (source: Author's illustration, map data [47])

Table 7. Estimated electricity consumption per consumer

Consumer	[kWh/day/consumer]	Source
Household	0.95	[63]
Small commercial	4.32	[63]
Public facility	6.8	[63]
Anchor load	10	Own assumption

Table 8. Cost assumption taken for proposed mini-grid site

Assumptions	Value	Source
Economics		
Discount rate [%]	10	[69]
Inflation rate [%]	7.47	[69]
Project lifetime [years]	20	[70]
Equipment	Value	Source
Solar PV capital cost [EUR/kW]	2,526	[70]
Converter capital cost [EUR]	800	Own assumption
Battery capital cost [EUR]	1,500	Own assumption
PV & Battery O&M cost [% of investment cost]	2	[70]
Assumptions	Value	Source
Grid extension		
Capital cost [EUR/km]	7,261	Data used for MV line (33 kV) [56]
Grid power price [EUR]	0.20	Averaged from [71] for a post-paid payment plan
Grid extension O&M cost [% of investment cost]	2	Own assumption
Distribution network cost [EUR]	50,000	Own assumption

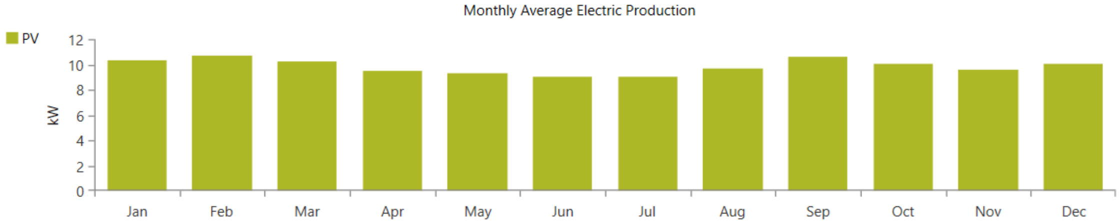

Figure 9. Monthly average electric production for proposed solar PV mini-grid (source: author's own)

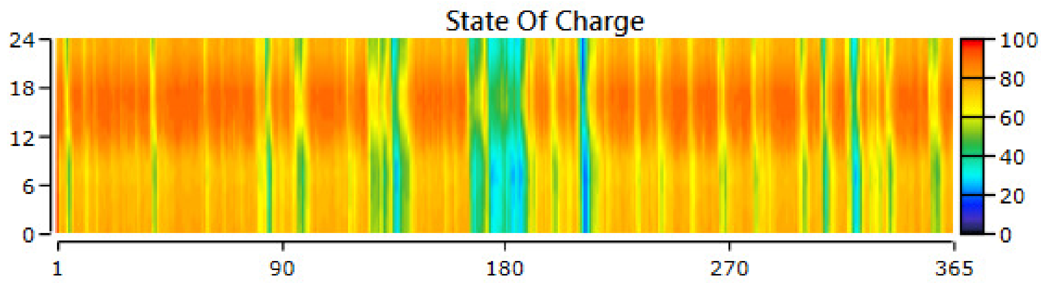

Figure 10. State of charge of batteries (source: author's own)

Figure 11. Breakeven grid distance for proposed site in Lorengippi ward, Loima constituency (source: author's own)