Lighting Up Tanzania:

Affordable Electrification for All

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Abstract

In Africa, almost 60% of people live in the dark due to the lack of electricity in villages. New technology such as mini-grids and solar home systems offer a credible, cheaper, and faster alternative for bringing electricity to people who live far from the main grid. Tanzania, in eastern Africa, needs the expansion of electrical energy, and only 38% of its population has access to electricity. The goal of this research is to find a model to analyze and expand electrification efforts by finding the most cost-effective way to continue Tanzania's electrification process. The output can be used by the government as a blueprint to formulate the short term and long-term plan in a particular region.

In this research, we are calculating the cost of giving electricity access to identified unelectrified populations in Tanzania. By taking account for region typology such as: urban, suburban, and rural. Estimating the electricity demand for each household to find the most optimum technology between main grid, mini grid, or solar home systems to electrify unelectrified Tanzania households.

Keywords: Electricity, Affordable, Main-Grid, Mini-Grid, Solar Home

Introduction

In Africa, almost 60% of people live in the dark due to the lack of electricity in villages. New technology such as mini-grids and solar home systems offer a credible, cheaper, and faster alternative for bringing electricity to people who live far from the main grid. A persistent challenge for African rural electrification is finding and prioritizing communities that can be viably connected to electricity.

Tanzania, in eastern Africa, needs electrical energy, and only 38% of its population has access to electricity. The rural areas use biomass collected from Tanzanian forests to meet about 80% of their energy needs, such as burning wood for cooking and heating, further worsening habitat degradation.

Tanzania gained the attention of political leaders worldwide when a drought in the late 2000's challenged the hydroelectric-reliant grid. Since then, Tanzania has progressed by relying more on natural gas. We can find a model to analyze and expand electrification efforts throughout Africa by finding the best way to continue Tanzania's electrification process in a particular region.

However, Tanzania is supposedly one of the many African countries with the highest CSP (Concentrated Solar Power) and PV potentials through a study based on Geographic Information System (GIS). It has the estimated potential of producing a TWh, but research shows that Tanzania only installed solar power of only 26 MW at the end of 2020, which is far less than the estimate projected by the indicated study. Approximately only 38% of people in Tanzania have electricity, which means about 37 million people in Tanzania live without it. With the provided loan and funding, we are trying to examine cost-efficient ways for Tanzania to electrify instead of relying heavily on thermal gas or diesel power plants.

Background

There has been various research about Tanzania's need for aid in electrification and ongoing projects to set appropriate goals for its development in the energy sector. Wide grids primarily provide electricity throughout Tanzania; a project was funded from 2008 to 2013 by the Millennium Challenge Corporation (MCC). The group highlighted how vital it is to connect households to the national grid and consider rural electrification since the connected rate was exceptionally lower in rural areas.

The article also stresses the importance of implementing renewable energy since it is 30% cheaper to use those instead of fossil fuels. Organizations like The Tanzania Renewable Energy Association (TAREA) are committed to increasing access to electricity and other energy sources with renewable energy technologies. The Lighting Rural Tanzania project also helped low-income households access energy in 2018 by installing solar lanterns and solar home systems. Different ideas and reforms were mentioned, but all served the same main purpose.

For the future, ongoing projects are focusing on a similar goal: increasing connectivity to 50% by 2025, increasing power generation capacity to at least 5,000 MW by 2020 and ensuring that 70% of the population has access to electricity by 2030. Despite extending efforts to make this happen, Tanzania's total power installed capacity remains at 1,602 MW, not even directly close to the 5,000 MW goal. How would existing future projects plan to meet their goals at this state? Many research mentions the great energy potential Tanzania has and mentions high-scale goals that aren't quite up to its words yet. This project intends to address the cost-efficient approach Tanzania can take for individuals and non-individual groups, running spatial analysis and exploring grid lines associated with funding for different types of grids or solar panels appropriate for its population (urban, suburban, rural).

Methodology

The objective of our work is to use data science & urban informatics skills to create a plan for least cost electrification of Tanzania. This plan can be used by Government of Tanzania as well as private organizations to calculate the investments required to provide electricity to every household.

The proposed solution is a bottom-up approach crafted for the residential population of Tanzania as of 2021. Our methodology as outlined in the flowchart below [Figure 1] in the appendix can be broadly summarized into four main steps:

1. **Identifying unelectrified population of Tanzania:**
    a. We use the population settlements data and overlay the electricity grid data obtained from World Bank on top of it.
    b. Based on external research we identified that settlements within 3 miles of the grid are usually connected and have electricity. Using this assumption, we separate all the population settlements within 3 miles of the electricity grid on either side and classify them as 'electrified' settlements. Settlements beyond this boundary are regarded as 'unelectrified' settlements. [12]
    c. The average household size of Tanzania in 2021 is 4.4 [1]. Using this information, we estimate the number of unelectrified households in Tanzania:
    d. $Unelectrified\ households = \frac{Unelectrified\ population}{Average\ household\ size}$
    e. The percentage of unelectrified households calculated using this methodology matches the 37.7%, obtained from external research.
2. **Classify unelectrified households into urbaneness categories**
    We classify households into urban, suburban and rural categories as electricity

consumption is different for each category. The detailed steps for this classification can be found below (Section 4.ii)

3. **Calculate electricity demand by household**
   Using the categories generated in the previous step, we estimate electricity demand per household. Urban households have more devices that consume more electricity as compared to rural settlements. The details for demand estimation for every household are in (Section 4.ii)
4. **Determine optimal technology per household**
   a. For our analysis, we have considered three types of technologies that are either predominant or have the most potential for impact. The suitability factors for each of the chosen technologies are listed below:
      i. *Grid connections* (Section 4.i) make most sense for households that are in large, dense settlements with high demand for electricity such as downtown areas of cities. Also, extension of grid is very expensive, so it would be most economical to consider settlements that are already close to the electricity grid.
      ii. *Mini-grid connections* (Section 4.ii) are best suitable for households that have dense populations but are located away from the current electricity grid. These systems can support communities using clean sources of energy such as wind, hydro, solar or biomass. There is a future potential to link these systems to the main grid and utilize the excess generated electricity for other regions.
      iii. *Solar home systems* (Section 4.iii) have the highest environmental impact and have a very high potential in Tanzania. Utilization of solar technology is suited for households that are scattered in rural areas across the country, far away from the main grid, where the population density is also low.

   b. For each household, the cost of electrification by either connecting to main grid, setting up a mini grid or installing solar panels is calculated and the most optimal technology is chosen. The methodology for cost calculation with respect to each technology is outlined below in Section (4.i)

i) Main Grid connection cost analysis:

   a. Connecting a house to an electricity Grid comprises of two costs:
      i. *Fixed costs* (per household)*: [3]*
         Costs involved in setting up the infrastructure and the equipment required for connecting a house to the electricity grid.
         From external reports, we identified that the average fixed costs per connection is 300 USD
      ii. *Variable costs* (per settlement)*: [4]*
         Costs involved for extending the existing electricity grid such as setting up poles, digging trenches, labor costs, equipment & infrastructure costs. From external reports, we identified that these costs amount to approximately USD 20000 per km of line extension. This cost is cumulative for each settlement and not per household as once electricity line is extended to a settlement, each household can get access by paying the fixed cost.

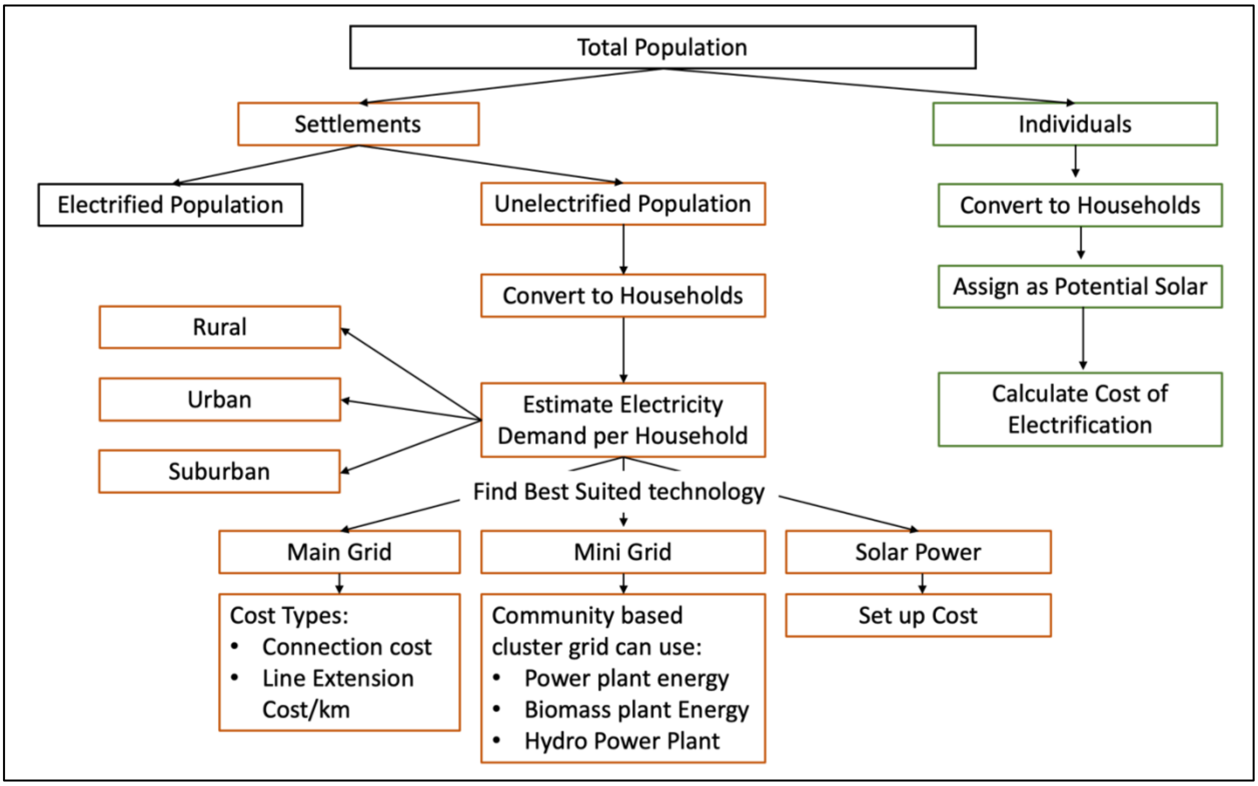

Figure 1 Flow Chart of the process followed to implement the project

a. For each *unelectrified settlement*, we calculate the distance to nearest electricity grid (in kms) using geo-distance between settlement polygon and electricity grid polygons.
b. For each of the household in this unelectrified settlement, the cost of connecting to main electricity grid is:
c.

$$Grid\ connection\ cost\ per\ household = Fixed\ cost + \frac{Variable\ cost\ per\ km * Distance\ of\ household\ from\ grid\ (in\ kms)}{Number\ of\ households\ in\ settlement}$$

d. Using this formula, we obtain the cost of connecting every unelectrified household to the main electricity grid by extension of the grid.

ii) Mini-grid connection cost analysis:

There are many components affecting the price of the mini grids, however this research will simplify the cost component and focus on the fixed cost of mini grid interconnection installation and the average power generation cost from several energy sources. Here are some of the components.

Levelized cost of electricity (LCOE) for each kWh for each household.

Using the reference of LCOE shared by the USAID, the cost of energy technology that might be used for mini grids is as follows:

Table 1 Relative Cost of Energy Across Mini-grid Technologies

Resource	**LCOE – low ($/kWh)**	**LCOE – high ($/kWh)**
Wind	.043	.076
Hydropower	.057	.070
Biomass	.085	.125
Geothermal	.043	.053
PV	.058	.143
Solar thermal	.177	.373
Nuclear	.096	.104
Natural Gas	.052	.148
Coal	.103	.196

Number of households: The number of households is used to estimate the electricity demand in the area.

Fixed installation cost: As reported by the USAID, the installation cost for mini-grids infrastructure varies between $200 up to $1,000 for each household. This cost includes the labor, the cable, and the infrastructure to be installed in each house. We are using $500 for the estimated fixed installation cost

Electricity demand: As the cost is dependent on the electricity demands for each household, we count the cost based on the urban cluster type. There are three separate classes of cluster: urban (6 kWh), sub-urban (4 kWh), and rural (2 kWh) for each household.

Mini Grids Cost Calculation:
Total cost = (Average of Energy Cost x Electricity Demand) + (Fixed Installation Cost x Number of Households)

iii) Solar power connection cost analysis

When calculating the viability of solar energy, we must address the demand for power and the costs associated with it. According to figures from the US office of Public Affairs, Tanzanians use on average 260 Wh of energy per day, or 1.2 kW for an average family of 4.6 people.[2] However, many families have limited or nonexistent access to energy in Tanzania. If energy access was widespread, per capita usage would correspondingly increase. With that in mind, we can calculate that those in the countryside who previously have not had much access to electricity will only need 2 KWh on average per day per household, while those in more energy intensive urban areas will need closer to 6 kWh on average per day per household.

- The costs of solar electrification is easier to predict in Tanzania, because there is no need to build out a complicated series of power lines and maintain them. Instead, families, or a denser cluster of neighbors can receive solar panels and a batter from the government with instructions on use.

- There are currently several different types of portable solar panels and batteries at different price points on the market, but a good price estimate for a bulk order is $100 for every 100 W of maximum power for a solar panel.
- 200 W solar panels will on average generate 1.5 kWh of energy based on the average weather conditions nationwide, and we can use that figure to estimate the necessary solar panels+batteries to meet energy demand.
- Using this calculation for cost and demand we can see how much money you would save by relying on solar panels over the grid, assuming that everyone needs electrification. The quantile map below displays what this might look like.
- **Data Visualization:** Refer [Figure 3] in the appendix.

Results

To identify the most appropriate solution to electrification, the analysis is performed on the unelectrified population in Tanzania. Of the 40 million population residing in the region, nearly 24.4 million remain unelectrified. As the scale and size of the population vary according to the regions, electrification solution is measured on the identified clusters. Of the 35620 clusters, 82% of the region has no access to main grid connections. The statistics manifest that majority of the region still highly relies on the daily use of non-renewable energy sources for lighting. The figure [Figure 4] in the appendix, highlights regions having access to electricity connections while a majority of the area remains in the dark.

The detailed examination of these clusters showcases varying population densities in the unelectrified regions. The density ranges from 2 persons per hectare to 200 persons per hectare. Hence the clusters were further classified into urban, rural, and suburban settlements. The Tanzania National Bureau of Statistics states that 33% of the population in Tanzania live in urban areas. Therefore, as per the stated urban threshold, the clusters classified in the urban area inhabited more than 70 persons per hectare. Similarly, population density in areas classified as suburban and rural settlements ranged from 10-70 persons and below 10 persons per hectare respectively.

Further, the classification shows that more than 70 percent of the unelectrified regions are categorized as rural and suburban (rural with the highest share of 47%). Surprisingly, the classification reveals that 27% of the regions having a population density of more than 70 persons per hectare (classified as urban) have no access to electricity. The figure [Figure 5] in the appendix shows a spatial representation of the unelectrified clusters.

Table 2 Electrification costs according to different methods

Cluster Type (Cost in millions)	Grid Cost	Mini Grid Cost	Solar Cost
Urban	$7,958.89	$1,478.04	$2,119.35
Suburban	$8,730.97	$789.73	$769.42
Rural	$21,566.26	$1,038.81	$616.72

According to the electrification costs derived in the [Methodology] above, costs are computed to electrify the identified clusters. The [Table 2] above presents the cost to electrify clusters in Tanzania as per the identified figures. The results show that if the Tanzania government decides to electrify the region by providing main grid connections, they will have to develop a electricity capital plan of $38,256.12 million by investing $7,958.89 million in urban areas, $8,730.97 million in suburban and $21,566.26 million in rural areas. The further classification for the proposed electrification methods can be seen in the table [Table 2].

Undoubtedly, opting for mini grid and solar will lower the electrification cost marginally for the government. However, adopting a hybrid selection approach will provide a more feasible solution to the problem. The most optimum electrification solution is computed according to the cluster's electricity demand and the resources available nearby. Clusters with closest distance to the main grid are moreover provided extensions to the main grid. Whereas regions with high exposure of wind and water streams are majorly provided by mini grids. However, population density also plays a role in determining an optimal solution as per the least cost incurred. The figure [Figure 6] below shows spatial presentation of a hybrid solution.

The hybrid solution found that electrifying 72% of the clusters by solar, 26% by providing a mini-grid and the remaining 2% by connecting to the main grid will reduce the electrification cost from the initial derived option of sticking to a specific method. The hybrid solution will lower the electrification cost by 21 percent which will account for the government to ultimately save approximately 675 million dollars in the capital investments.

Discussion

For scaling this analysis into the future, we would need to consider population increase by different regions across the country and people migration patterns from rural areas to urban areas. Electricity demand changes over time as technology evolves and costs associated with energy generation technologies would also change in future. Currently, this is beyond the scope of our analysis.

To make this analysis more nuanced, we need to incorporate electricity demands for commercial, industrial, and agricultural activities in Tanzania, which is potentially an area for future research work.

Lastly, we have assumed that the current electricity grid can generate electricity to support the new households we suggest in our solution. Similarly, we have assumed that the demand for new solar panels and mini-grid infrastructure can be met by the existing resources in Tanzania. This is a limitation of our analysis which essentially paves way for a separate project on increasing the generation capacity of Tanzania's electricity grid as well as checking feasibility of infrastructure supply.

Conclusion

Based on the analysis and cost calculation that has been done. The following conclusions was drawn:

- Most suburban and rural areas in Tanzania are more effective to be electrified with a solar-based energy source as it is more expensive to extend the main grid line to reach the remote rural area. This result is aligned with the fact that Tanzania is a region with rich Concentrated Solar Power to power the solar panel.
- For areas with urban type classification, a better alternative of main grid extension is mini grid with the proportion of 67.70%. However, further detailed feasibility analysis is needed to decide which technology is the most suitable for the region, such as hydropower near a riverbed or natural gas for an area with easy access to the resource.
- To meet the electrification target, the government can focus first on electrifying areas with higher density areas with mini grids as it will impact more people. Later, Tanzania's government can cooperate with international donors to build several solar panel plants in remote rural areas. To focus on giving electricity access to the unelectrified population with cheap and accessible electricity for all.

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Appendix

Below includes are the diagrams and maps from the study:

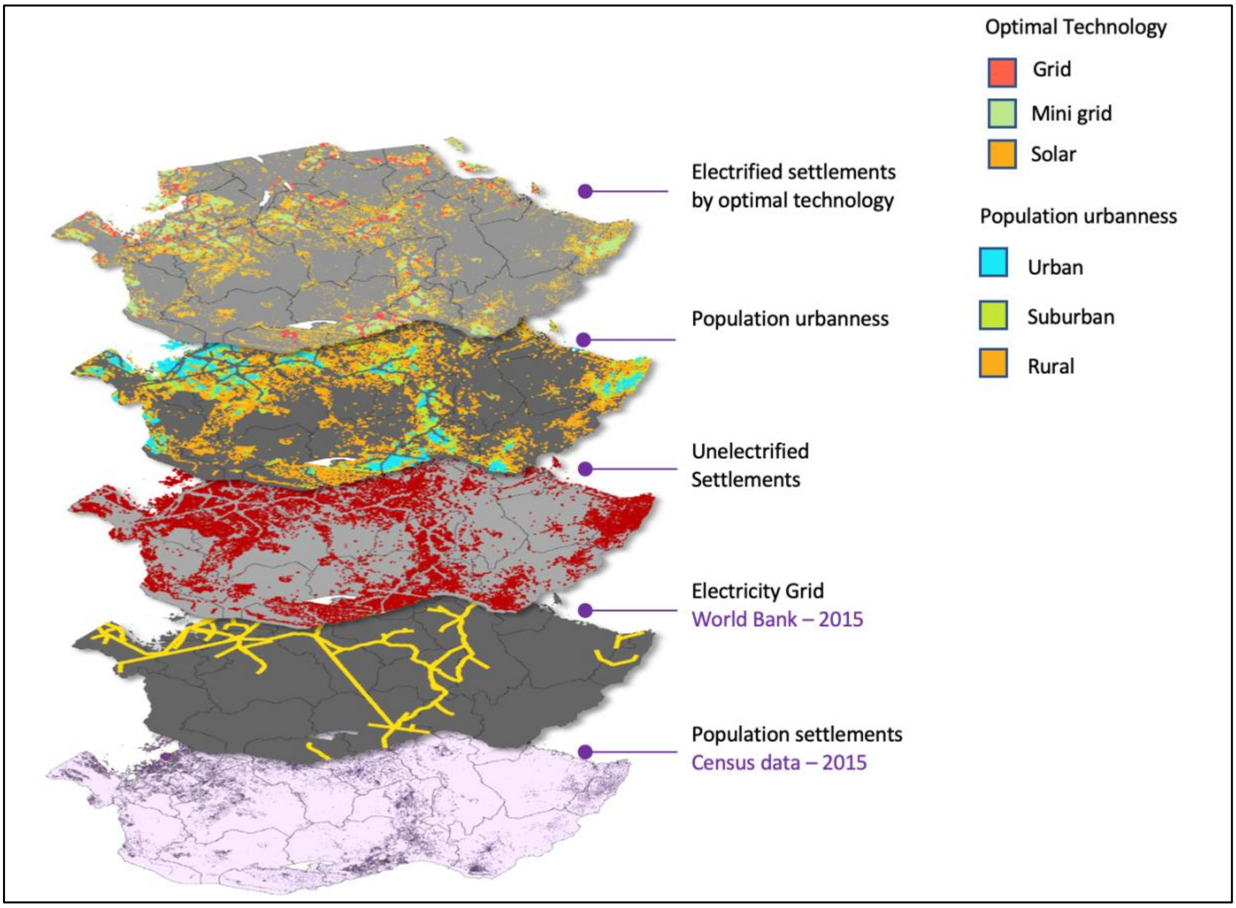

Figure 2 – Layered View of steps followed to get the optimized electrification result

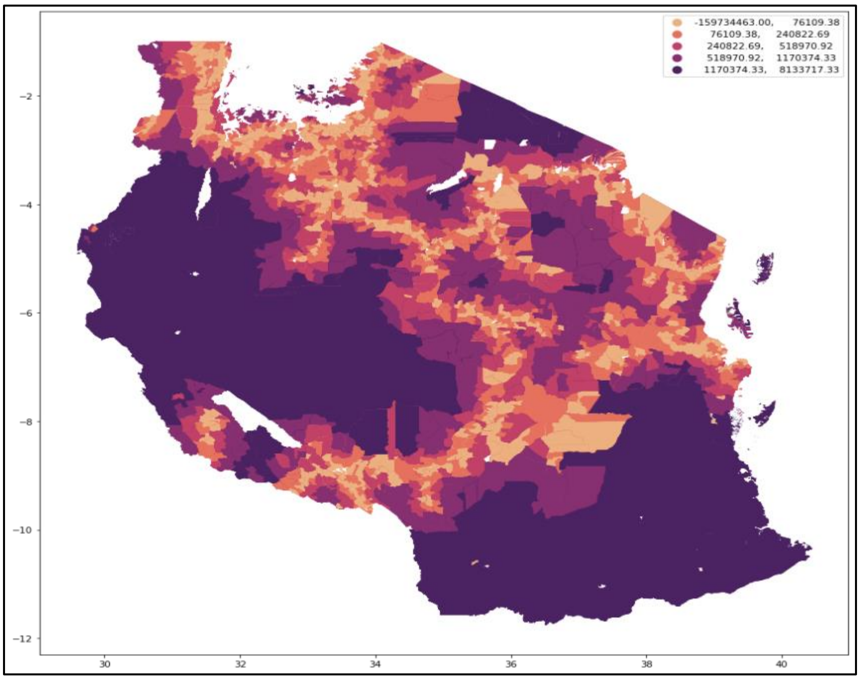

Figure 3 Quantile map of money saved if adopting solar panels

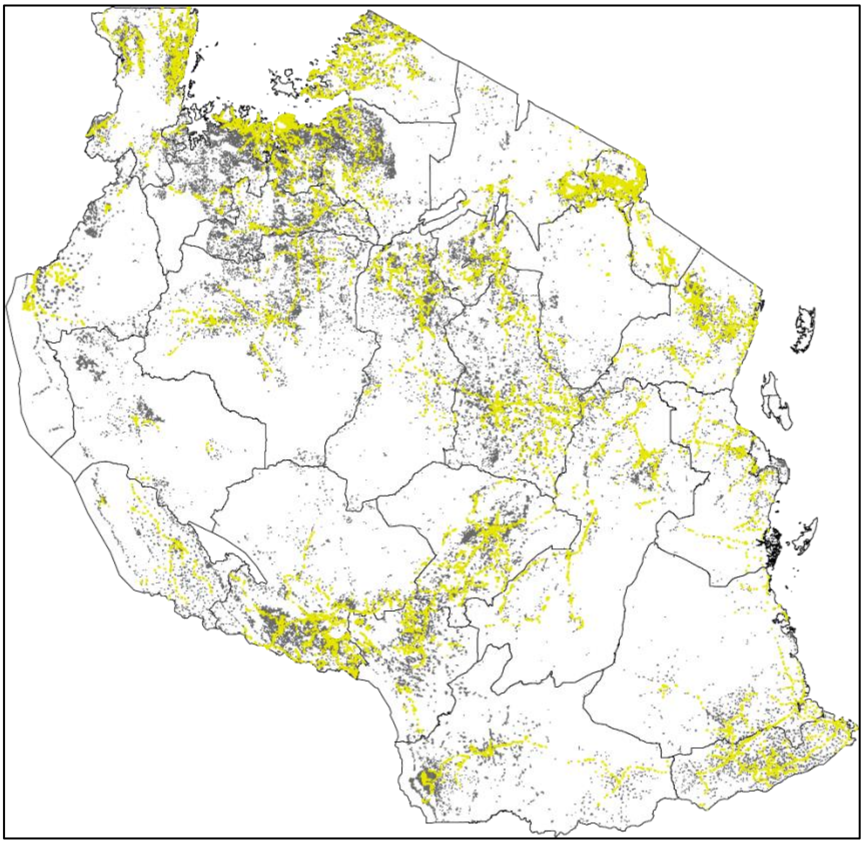

Figure 4 Population having access to electricity

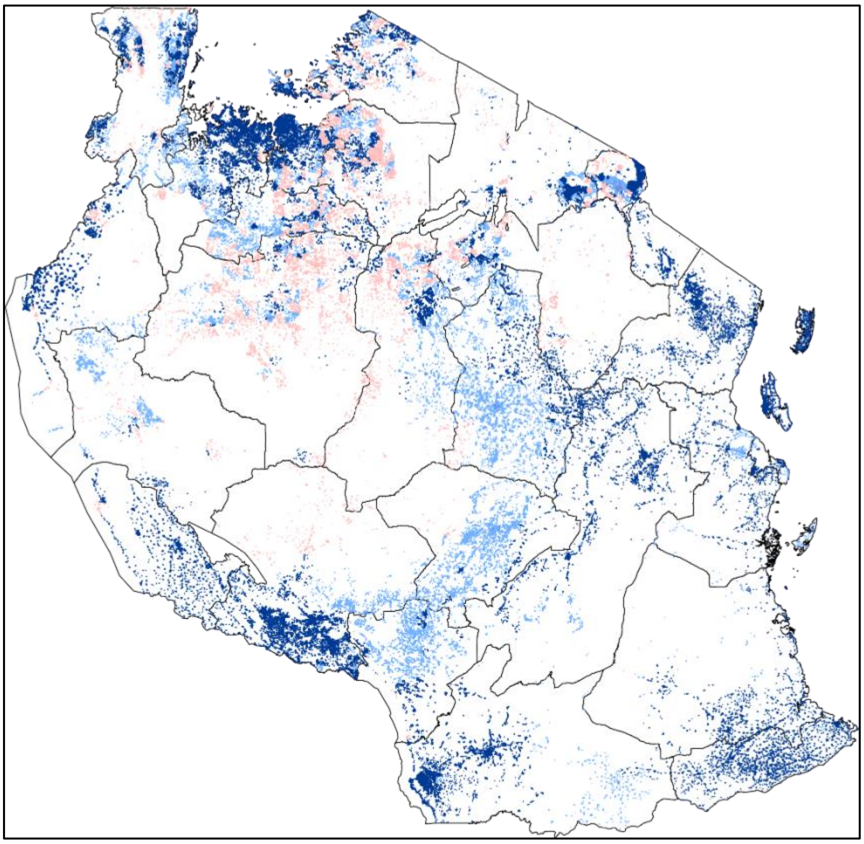

Figure 5 Cluster Classification - Urban, Suburban, Rural

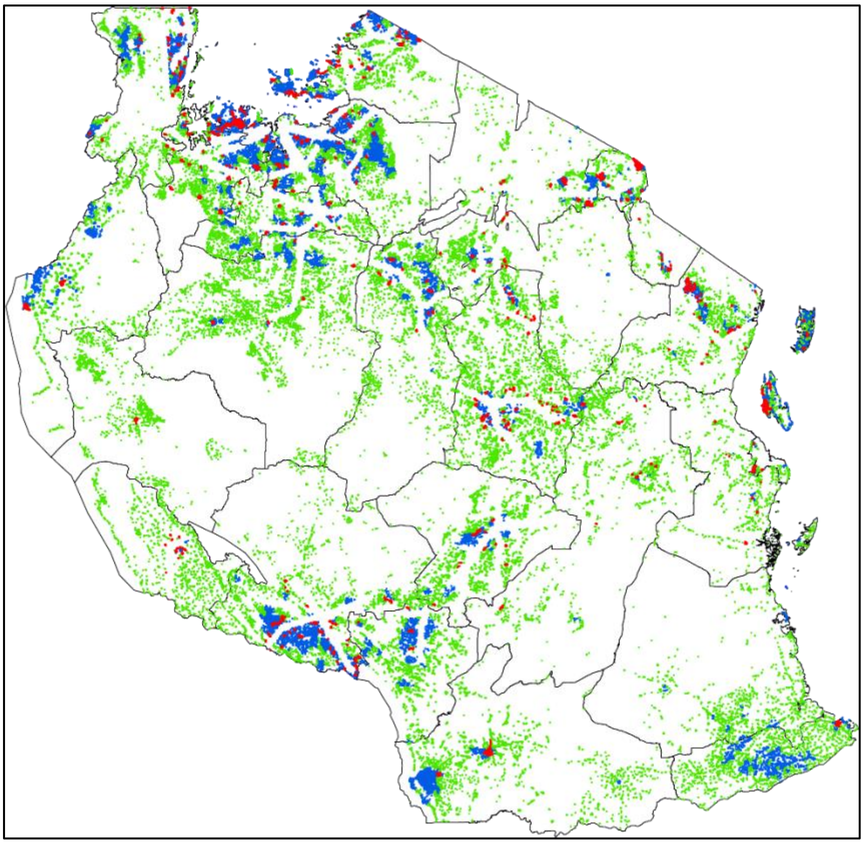

Figure 6 Hybrid Solution to electrification

Team Contribution

A. **Sonam Sonam (ss15624)** – Data preparation and Cost calculation for main grid connections. Completed the write up sections of – Methodology & Discussion.
B. **Suraj Sunil (ss14449)** – Electricity consumption and demand calculation, cluster (urban, rural, suburb classification). Completed the write up section of – Results
C. **Hanfie Vandanu (hv480)** – Cost calculation for mini grid connections. Completed the write up section of – Abstract, Mini Grid Calculation and Conclusion
D. **Max Magid (mmm9940)** – Cost calculation for Solar power for small clusters and far-flung areas. Completed the write up section of Introduction
E. **Wonchan Lee (wcl311)** – Data collection for Tanzania and background literature analysis for project. Completed the write up section of background.