Determining Viability of Interconnected Solar Home Sytems

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***Abstract*— Using data from a rural area of Kenya, we use data analytics to determine how efficient it would be to interconnect homes using solar home systems. We make use of data profiles of several homes and assign these to many locations. We then pick locations to analyze and create theoretical connections to surrounding homes. The cost of wiring and value of excess electricity are compared.**

Keywords—Solar Home Systems; electrical infrastructure; Off-grid rural communities

I. INTRODUCTION

In many developing countries, access to electricity is a continuing challenge. While large electrical grids can often connect vast numbers of people to large power generating sources like power plants, it is especially challenging for people living in rural areas of these countries to obtain access. Even if a majority of those living in urban areas have access, it is common for rural individuals to have no access. The reasons for this vast difference are mostly economic. In urban areas, people are often located close together, so it is not expensive to expand the grid to reach them. Additionally, it may be easier to construct and operate power sources near cities. On the other hand, it is very expensive and inefficient to connect disparately located rural houses to the grid.

One solution that exists to address the need for rural electrification is mini-grids. These mini-grids connect a smaller number of homes to smaller generation sources. The creation and operation of a mini-grid does require some organization and expertise. Further, they are only possible in areas where populations are dense enough to support them.

A second solution to rural electrification is solar home systems. These systems are typically paid for by their users (rural individuals) in installments and are owned after these payments are completed. They frequently consist of a solar panel (for power), a battery and regulator, and some devices such as light bulbs, phone chargers, radios, and television sets. An advantage of these systems is that they do not require any interaction with other individuals (they can be used anywhere) and after they are purchased, users no longer need to pay for electricity.

However, there does exist a major drawback in using these systems: the amount of electricity that can be utilized is inherently limited. At most, the user can use whatever power is generated by the panel during the day plus however much energy can be stored by the battery during the night. Therefore, these systems could be made stronger if more electricity could be used.

A suggested solution to this problem is to interconnect various homes using solar home systems. This would allow those who are not presently using electricity to provide access to their neighbors' electricity who require it, and other sharing. This combines the concept of the mini grid with the infrastructure of the solar home system. However, the maintenance required would be significantly less than in the mini-grid case, and the users would own their own electricity sources.

II. EXISTING LITERATURE

A. "Solar Energy Centre"

Roche and Blanchard suggest the idea of a "solar energy centre" in their paper, "Design of a Solar Energy Centre." This center would be privately owned and use several SHS to charge lights and other appliances, which could be rented to the local community at night [2]. Other services could include photocopying and televisions. Local entrepreneurs own and operate the business, which allows for a system with no subsidies or grants. Local individuals who want lights or other appliances can get temporary access to them, without the commitment or upfront costs of purchasing their own.

The process begins by first evaluating locations, including by using simulation software to determine the best system design. An energy usage survey was provided to the test community. The authors noted that, in this particular case, since the solar systems were being used by a local area community, there existed the potential for electricity usage for economic activity and water purification purposes. We will not consider these uses in our research.

These researchers determined that it is possible to use a commercially purchased hub to connect significantly more lamps at a time; this allowed them to charge a maximum of 35 lamps at one time with one panel.

The researchers showed that it is economically feasible to use this solar energy center to power a community. While we are focusing more upon individual households, the concept of SHS sharing has been proven.

Additionally, the researchers provide estimates of how much electricity is valued. They estimate that the Levelized Cost of Electricity provided by home batteries is \$2.72/kWh for batteries and \$2.67/kWh for lighting. Meanwhile, they estimated the grid pricing in that particular area of Kenya to be \$3.45/kWh. Additionally, houses have to pay a large connection fee of \$147 and pay for their own appliances when connecting to the grid.

B. Policies

In "…What policies may be required?" by Bhattacharyya et al., the authors address what policies may be best for mini-grid and off-grid electrification [2]. The authors note that over 1 billion people worldwide lack electricity access. They discovered that existing research proves that rural electrification (extending grids out to poor, rural people) is ineffective and unaffordable. Additionally, it will not be possible for governments to fund necessary infrastructure projects to provide electricity to people on their own, which necessitates both alternatives like solar home systems and private investment.

In mini grid examples, concern was expressed that tariffs would become unbearable. In the case of connecting solar home systems, this should not be an issue since the electricity is privately owned by the homeowners. The authors strongly recommend integrating with livelihood projects such as education, agriculture, and health; a shared solar home system network may provide the necessary power to work towards these achievements.

One recommendation that the researchers made was that one size (scale) does not fit all; in certain cases, solar home systems will certainly be the right fit. The authors recommended "locally adapted support to off-grid electrification." In a case such as rural Kenya, it would be necessary to have the right microfinance structure and perhaps SHS operation and maintenance to ensure success. Another recommendation was to link with rural development activities, such as education and water.

While the authors seemed to be focusing upon mini-grids, the concepts can be applied to connecting a few solar home systems. People living in rural Kenya cannot expect that the government will connect them to the grid and will likely need to use alternative connection methods, which they will need to at least partly fund through private investment. Linking these systems, if efficient, would provide the opportunity for livelihood improvement for a local community.

III. DATA UTILIZED

Before presenting our data, we first note our estimate for electricity value in Kenya. While Roche and Blanchard above calculate a very high LCOE in their research around \$3/kWh, we do not believe users would be able to or willing to pay rates this high. We instead assume that electricity in Kenya may be valued close to the tariffs currently charged by Kenya Power and Light Company (KPLC). As of November 2018, the tariff for average residential users was 10 Kenyan Shillings, which is roughly \$0.10/kWh [3].

We make use of two datasets in order to address our problem. Each of these is in "pickle" format. The first of these is geographic data points of about 50 thousand homes in Homa Bay County, Kenya. Homa Bay is in the western part of the country near Lake Victoria; most of the county is rural. The data we use is in a box located with corners at .74 degrees South, 34.02 degrees East, and .54 degrees South, 34.42 degrees East. This area is about 1000 square kilometers.

The second dataset contains consumption and production data for homes with solar home systems. This dataset from 29 homes features consumption and production data at 10-minute intervals, over a 6-month period. This is obviously a vast trove of data, which will require us to take averages when we make our analysis.

IV. PROCESS

In order to analyze the data, we use the python programming language. Python has unique libraries that are useful for this process. For instance, we utilize geopandas in order to manipulate and present our data.

A. Creation of A Random Box

Our first step is to create a randomly-sized box in order to make measurements within the box. The amount of data, over 50 thousand homes, is simply too large to make use of efficiently. The box allows us to make measurements within the smaller box, so that we can notice and track similar behaviors within a smaller area. The randomness of the box size and location means that we will not have biased data due to box location or size. Making use of the *intersects* function in geopandas, we can determine the number of locations that are within the randomly-generated rectangle. This data is entered into a Boolean list indexed to each location.

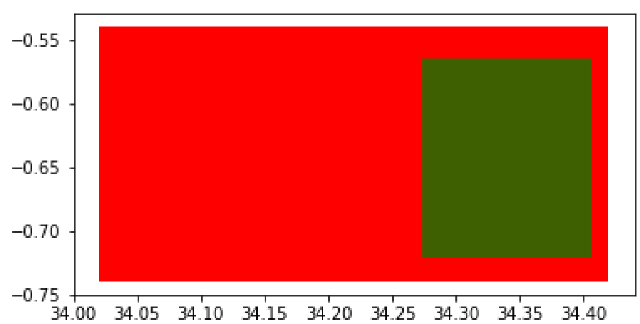

Fig. 1. Example of A Randomly Generated Rectangle

Figure 1 demonstrates an example of these randomly generated boxes. The outer red rectangle is the total area that is within the scope of our data, while the green box is the randomly generated rectangle within the red rectangle. The random rectangle should always appear within the bounds of the red rectangle, though its dimensions and size will vary. To obtain data that reflects all of the Homa Bay area, 10 boxes were sampled, each with 1,000 points selected randomly within the green box for analysis. The 10,000 total data points selected can be seen below in figure 2.

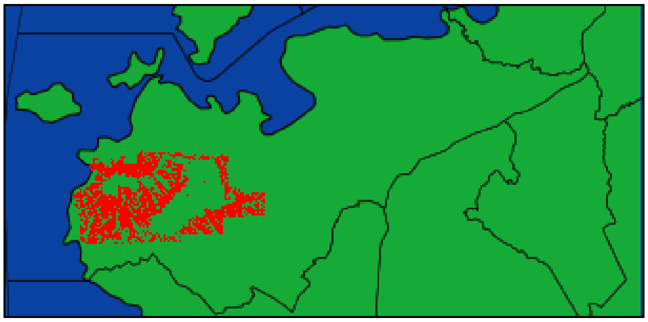

Fig. 2. 10,000 Randomly Selected Data Points used by Model within 1,000 km² area of Homa Bay, Kenya

B. Modeling Solar Home System Interconnection from Randomly Selected Structures

Within each of the ten green boxes made in *part A* above, 1,000 structures are randomly selected and are representative of a center location for a solar home systems to be interconnected to. For simplicity of the algorithm, it would be assumed that all houses would be connected directly. Figure 3 below shows how transmissions lines are drawn as a simple line where the blue point is the selected house, the red points are the nearby structures (<40m away), and the grey lines are the transmission lines.

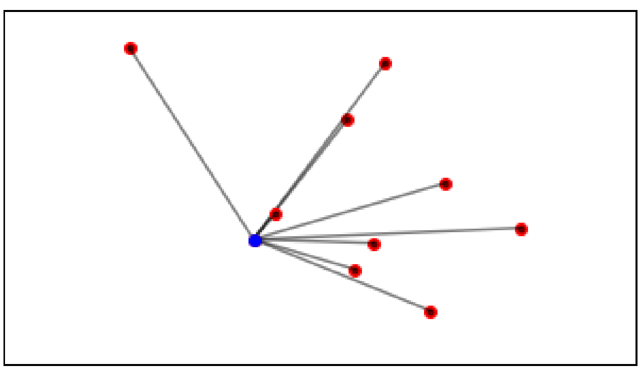

Fig. 3. Demonstration of How Transmission Lines are Drawn in Model. Blue = Chosen Structures, Red = Structures within 40m radius

From the model created in Figure 3, the total amount of wiring from the center point to all of the nearby structures within the radius is calculated by using the summation of distance. As the locations provided to us are in geographic locations (degrees), it is necessary to undergo a conversion to obtain physical distances. To accomplish this, the Haversine formula is used. The Haversine formula uses trigonometry to factor in the curvature of the earth in order to obtain physical distances in kilometers that could be used in a 2-dimensional setting, such as the situation in this paper. The formula is used to find the distances between all locations within the box, and then a double indexed list is used to store the data for all these locations.

Due to a lack of geographic data, it was not possible to determine whether geographic hazards such as hills, structures, rivers, and other effects would impede the ability to connect two houses or whether the effective distance of connection would be greater. Nevertheless, the purpose of this project is to obtain an estimate of the effective uses of connecting homes with solar home systems, which will still be possible.

C. Determining Line Cost From Distance

To determine the total cost of interconnection between structures, the total distance from each point within in the radius to the chosen center location was used. The price per meter that Kenya Power and Electric pays for 5 gauge wired used at 11 kV is $10/m [4]. Since the solar home systems we are modeling are running at much lower voltage and current, we can assume the cost per meter is much lower and the estimate of $5 a meter was used based on the significant drop in wire price as gauge increases. To determine cost of interconnection within a node the total distance of wire needed is multiplied by the price per meter of wire.

D. Averaging Use Data and Assigning Behaviors to Homes

There were total of 29 different energy profiles that could be assigned to each structure within a radius. Data for the for the 29 homes included measurements of current in, current out, IMEI, temperature and voltage recorded every 10 minutes for a 6 month period. From this data the average production, consumption, and net energy for each structure was produced. When a radius was produced and the structures within 40m of the center point are found, each structure was randomly assigned one of the energy profiles.

After energy profiles have been assigned to each of the structures within the radius, the summation of all energy data is taken. Those values are then stored into the main dataframe as well as how many structures are in the radius, distance and cost of wire, and the coordinates of the center point that was selected. By calculating energy profiles for 10,000 different radii and for tens of thousands of structures, a very statistically significant data can be produced.

E .Comparing Line Costs to Gained Energy Value

To determine if it would be economically viable to create interconnections as proposed, values needed to be placed on the price of interconnection of houses as well as the financial benefit of pooling excess produced energy. The price of interconnection was simply the price of wiring determined in *part C* above. The value per meter includes cost such as interconnection into a system, cost of wire, cost of necessary poles for the wires to be spread a longer distance. This cost would be much lower than the previous $10/m since the wire used would be much higher gauge and therefore cheaper [4].

To set a value of on the excess energy that would be pooled together by interconnection, a value needed to be determined on a per Joule basis. Since interconnection would allow for the harvesting of excess power much more efficiently, scaler values of the energy produced (assuming the same level of consumption) to see how adding more production to the system would further increase the economic efficiency interconnection.

The financial gain of electricity was calculated by using the levelized cost of electricity (LCOE) of a solar home system with a battery at $2.72 per kWh [1]. At this rate, that would translate to $\$(7.55 \times 10^{-4})$ per kJ. The net excess energy after consumption is then multiplied by this rate to determine the financial gain of the electricity shared in the system. Using LCOE we are able to see the full economic affect that sharing excess electricity can do for an area.

V. RESULTS

Sampling the 10,000 randomly selected structures resulted in a fairly skewed population of structures contained in each radii as seen in figure 4. The bulk of radii produced three or fewer structures within the 40 meter radius. This strong statistical correlation seen by number of structures within a set radius of 40m is indicative of how feasible it would be to connect more than several structures together, any further farther distance would result in a line voltage drop that would be too large.

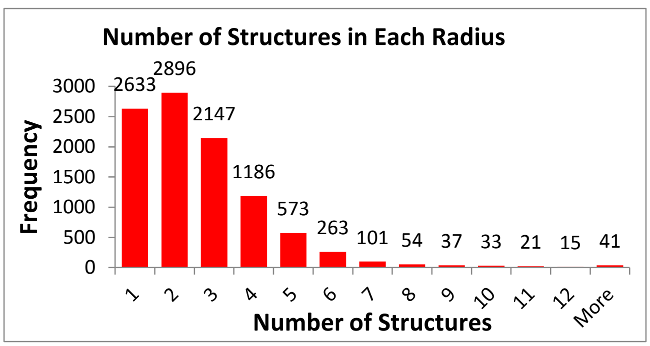

Fig 4. Histogram of Number of Structures used by Model in Run

As would be expected, a linear growth is seen in the excess amount of energy produced as the number of structures is increased seen in figure 5. Resulting graphs of net production show a very close relationship between number of structures and excess net energy. With many data points' radii with three or less structures, there is almost no variation between this linear relationships.

Adding more production to each structures on magnitudes of two and three times the original production results in a much higher slope for this linear relationship. We see very little change in the net energy produced when dealing with the bulk of three or less structures, some differences forming between four to seven structures, and with eight or more structures within a radius we see large differences of the different levels of production magnitude. Increased production on the scale of even three times has little to no effect on the most common scenario of three or less structures within a 40m radius.

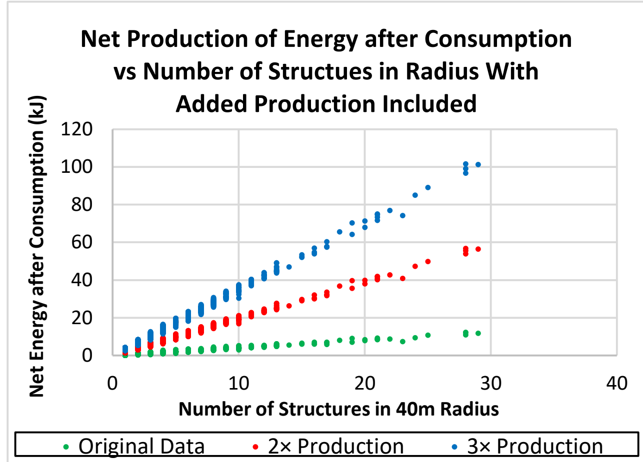

Fig 5. Excess Produced Energy with Production Multipliers vs Number of Structures

There is a clear relationship between number of structures within a radius and overall economic benefit of interconnection of the solar home systems as seen in figure 6. Adding more solar home system to an interconnection has a linear drop off in the overall economic effect on those connected together. The cost of wire and establishing a network between solar home structures decreases at a very rapid linear rate as the total distance that is covered by the wiring is increased. This can be seen with an increasing number of structures as well as within the span of a set number of structures. Our model uses distance as the determinant of the total price of interconnection, therefore when structures are farther away or many more structures need to be connected together (therefore more distance of wiring needed), the total benefit is reduced drastically.

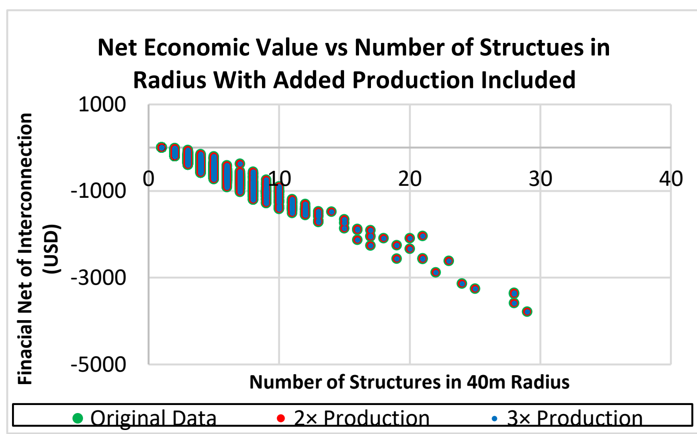

Fig 6. Net Economic Gain vs Number of Structures

VI. ANALYSIS

Though the total economic benefit may look as if there is no positive results, there are many. LCOE was used to calculate the total economic gain of excess production over the course of six months for interconnected solar home systems. It is noted that when three or less structures are connected to one another and especially when those structures are close together, there is close to a $0 net gain of interconnection. This means after the six month period, the interconnection has paid for itself. Any net excess energy in the time period after this six months would then be counted as a profit since the LCOE of excess energy would not need to be put towards the cost of interconnection. Figure 6 shows the where the investment stands after 6 months of interconnection vs the number of structures.

Over the course of time, all these interconnections would theoretically net to zero, but those with a very large gap will not likely do so in their rated life span. Therefore the situation that makes the most economic sense for interconnection would be the situation where three or fewer structures that are very close together would make the most sense.

This model serves the for a great purpose for basic estimation of interconnection, but the primitive graphing function used to directly connect all nodes to the center node may contribute to the great inefficiencies seen as the number of interconnections grow. Figure 3 demonstrates this greatly with 10 structures within the radius. Long lengths of wire are needed to connect structures far away from the center node. If a path of least resistance algorithm was used such as Dijksra's method, it would result in only a connection entering and leaving each of the structures with exception of the beginning and end structures. This would result in far less wire being used and distance covered, resulting in a lower cost for more structures within a radius and potentially structures that are far apart in a radius. This algorithm was not used in this model due to the large computational demand of a more advanced connection algorithm than what our group was capable of performing.

VII. Conclusion

Our study concludes that connecting solar homes together for the purpose of surplus energy is not efficient. The low amount of surplus energy a single house outputs, coupled with the cost of connections, and limited distance that these connections can be made, means that the cost of connections cannot be recovered by creating enough surplus to add a new system. However, our study is limited to networks made entirely of independent solar homes; the results will likely differ when including solar homes design to produce a surplus (I.E. full roof paneling) and dedicated power plants are included in the data.

Acknowledgment *(Heading 5)*

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