Battery Storage: Comparing Shared to Individually Owned Storage Given Rural Demand Profiles of a Cluster of Customers

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Abstract:

In many low-income settings and geographies it's not immediately feasible to deploy central power generation with electric grids. In this context, off-grid approaches like solar home systems (SHS) are gaining wide acceptance. Since battery storage costs are the dominant costs, the value proposition of using a novel mini-grid with shared generation/ storage as opposed to SHS is examined. The relative merits are evaluated using time-resolved demand data from a cluster of small rural consumers. During the two-year operation of 9 SharedSolar systems in Uganda, nearly all the electrical demands were met as the systems were oversized for initial demand. This allowed us understand the actual demand (under commercial tariff payments) and estimate supply reliability for smaller optimal storage sizes post facto.

Using real time data, storage characteristics and HOMER simulations, optimal sizing for both approaches were established. The analysis reveals that customer diversity leads to considerable savings in storage requirements for same reliability when a shared approach is utilized. The study informs helps informs the economics of providing off-grid access to electricity.

I. INTRODUCTION

Access to electricity has shown to be a huge stumbling block for development in many countries. Without access to it, whole communities are at a severe disadvantage when it comes to competing in the modern world. When electricity is introduced in an area, it allows students to study in the evenings, and it allows businesses to pursue new entrepreneurial opportunities. Solar home systems, SHS, and isolated photovoltaic microgrids are two methods to increase electricity access in remote regions of developing countries. Both energy solutions will play an important role in providing electricity to the 1.3 billion people without electricity access. However, both electrification methods have inherent merits and drawbacks. SHS are usually owned (or rented) and operated by a single customer. Note: because the use of solar home systems i.e. (small PV systems with battery backup) is not strictly limited to households, they can also provide energy to small business, education facility, health clinics, etc.; we will refer to the users of solar home systems as customers. Single ownership of a SHS reduces any conflicts that may arise over ownership of the system. It also removes disputes that may arise over allocation of energy and power capacity. SHS also remove the need for distribution networks. Depending on the distance between customers, electricity distribution can be expensive. Moreover, customers and non-customers may expect compensation for the right to run aboveground or belowground wires across their property.

In this paper we limit our discussion to isolated solar PV microgrids with battery storage. A primary advantage of microgrids is that a) generation capacity (e.g. kWh of PV generation on a given day) b) inverter capacity (e.g. kW of inverter rating), c) usable battery storage capacity (in fraction of installed kWh capacity, taking into account depth of discharge concerns), are all three shared amongst several customers. Over the course of a day, individual customers have temporal variation in instantaneous power demand. Moreover, individual customers use different amounts of energy on different days. Using microgrids might enable the hardware to be sized only to the aggregated instantaneous peak power and aggregated energy consumption, as compared to each individual consumer's peak power and energy demands. A cost saving method that can be used is to sacrifice some reliability in exchange for savings on batteries. A sizing strategy based on this was proposed by Lee, Soto, and Modi. [1] where systems are designed to fall a certain percentage short of the total demand is used in our analysis.

The demand data used in the paper is taken from SharedSolar systems in western rural Uganda. SharedSolar systems are solar microgrids with 1.4 kWp that provide electricity to between 1 and 13 customers. There are nine total systems in this cluster, and two of those systems (Site A and Site B) were chosen for analysis because they are representative of systems with relatively many varied customers.

Previous analysis comparing SHS to a solar microgrid has been completed by Chaurey and Kandpal [2] Aulich, Raptis, and Schmid [3], Palit [4], and Dakkak, Hirata, Muhida, and Kawasaki[5]. Chaurey and Kandpal [2] performed a detailed economic analysis for systems of various sizes and found that at low customer numbers (~<150-250) SHS were the cheaper option. Aulich concluded that solar microgrids had advantages in lower storage needs and ability to adjust to changing customer demands, but these advantages must be compared to the additional costs associated with a microgrid. They also postulated that these same reasons were why developed countries developed centralized grids over time [3] Dakkak, Hirata, Muhida, and Kawasaki. did an interesting analysis where they compared four individual SHS and then

978-1-4799-7193-0/14/$31.00 ©2014 IEEE

did an analysis if the four systems were connected and had common shared batteries. Their analysis showed that a microgrid of this sort would offer some savings but probably not as much as a microgrid that shares all of the electric components [5].

These analyses are very helpful in understanding the behavior and dynamics of these two systems; however, for these assessments it was assumed that all customers will behave exactly the same as each other and that their demand will be the same every day. Thus, they assume there will be very little grid diversity. We have long term measured data that shows in some cases demand diversity can actually be quite high (especially when people have to pay per kWh). If the peak demand of different customers occurs on different days, you can cut down on battery needs. Taking advantage of demand diversity is what really what makes microgrids preferable under the circumstances we have seen.

Our analysis takes advantage of the data that has been collected at SharedSolar sites in western Uganda, and thus gives a better comparison for the costs associated with SHS systems and microgrids than previous work.

The analysis conducted in this article relies on energy consumption data from two communities in western Uganda. Each community was recently provided with dependable electricity for the first time through the use of PV/battery microgrids. The systems were intended as a pilot and were installed with capacity in excess of expected peak power and daily energy demand. Over-installation of capacity was permitted so that insight into consumer usage behavior could be gained, and lessons learned could be used in future installations. Energy consumption data is available because the microgrids operate as a utility and customers are metered at sub-minute resolution. Customers purchase electricity on a prepaid basis either through SMS message, or by paying a local vendor. The start date for the data used in this study was approximately one year after each site was commissioned.

In this paper, we use HOMER energy system simulation software to optimally size microgrids that would meet the aggregated consumer demand from each microgrid. We then use HOMER models to optimally size SHS systems for each customer given its historical demand data. We then review the simulation results and conduct additional analysis to assess the relative advantages of microgrids and SHS from both the micro-utility and consumer perspectives. In our analysis, we assume that both the microgrid and solar home systems will be operated by an energy service company, ESCO, in a manner similar to the pilot communities. We also assume that electricity will be provided to customers on a metered energy use basis.

We do not take into consideration social and behavioral aspects that would also influence the choice of options. For example, an individual SHS might be much easier to manage by the owner of the system, and eliminates the transaction costs and security risks or other risks associated with sharing a system or having an external agent or utility operate a microgrid. On the other hand, a microgrid might be more desirable for a customer than a SHS since the former allows a service-based contract with a provider and hence removes upfront financial barriers of the maintenance risk. Palit noted that access to credit/capital is a key stumbling block for both types of systems, and it must be addressed [4]. Credit is more of a stumbling block for SHS than microgrids because they are usually purchased individually and not as part of a group like a solar microgrid might be. It would be easier to access capital as a group rather than individuals. Maintenance is a significant concern that Pode addressed saying that for a group of SHS installations in Guatemala 45% were no longer functioning after five years [6]. This is due to lack of support from installers and lack of understanding from customers about the systems.

The analysis will help inform the economics of providing access to electricity, an objective that has emerged to be an important global goal, as it one of the three specific targets of the UN SE4ALL initiative.

A. *Characteristics of communities in case study*

Demographic considerations

Microgrid A (Site A)

- 10 customers installed within a settlement of 15 households
- The local has not yet emerged to be a hub for any commercial activity (not on a main road).

Microgrid B (Site B)

- 8 customers installed
- This site is part of a larger community in the vicinity that is partially electrified through the use of this and other similar small microgrids.
- The site is a commercial hub. There is a weekly market day at the location.

B. *Cluster wide demand*

The two microgrids analyzed in this article were selected because of differences in their energy consumption characteristics. Table 1 provides an overview of the energy consumption characteristics of the two micro grids. The units of all parameters, except for the first row in the table number of days, are Wh/day.

TABLE 1. ENERGY CONSUMPTION PROPERTIES OF THE CLUSTERS A AND B

	Site A	Site B
Mean Daily Energy Use (Wh)	954	1660
STD of Daily Energy Use (Wh)	479	422
Max Daily Energy Use (Wh)	2741	2658
75% Quartile of Daily Energy Use (Wh)	1226	1935
Median Daily Energy Use (Wh)	911	1692
25% Quartile of Daily Energy Use (Wh)	640	1430
Min Daily Energy Use (Wh)	0	244

Table 1 illustrates that the average daily energy consumption of Site B is significantly greater, 74.0 percent, than the average daily energy consumption of Site A. Despite the large difference in the mean daily energy consumption, the relative standard deviation of Site A, 0.502, is much greater than that of Site B, 0.254. This implies that the demand factor of Site A will be lower than that of Site B. A lower demand factor will result in a higher cost per kWh to generate electricity for Site A. As seen in (1), the demand factor of a microgrid is the maximum instantaneous power demand of the entire grid divided by the sum of all customers' time independent peak power.

$$\text{Demand Factor} = \frac{\text{max power demand of shared system}}{\text{combined max power demand of individual systems}} \quad (1$$

C. *Individual customer demand*

In order to better summarize the customers served by each microgrid, we sort customers into three basic groups. We classify low energy consumption customers as those who use less than 150 Wh per day. This level of energy consumption would be commensurate with compact florescent lighting (CFL), and cell phone charging. Low power electronics, such as radios or hair clippers, may also be used in the consumption group. The second consumption group, medium energy consumption customers, includes customers that use between 150 Wh and 500 Wh per day. These customers have appliances such as cathode ray tube (CRT) televisions, multiple speaker stereo systems, computers, and soldering irons. The third consumption group, high energy consumption customers, uses more than 500 Wh of energy per day. High energy consumption customers have similar appliances to those in the medium energy consumption group; however these customers may use more appliances concurrently or they may use appliance for more time during each day. Note that these distinctions amongst consumption groups from the daily Wh levels shown above are relative, and in absolute terms one to order of magnitude lower than the consumption levels of customers in the United States.

Even with these low absolute consumptions levels, many of the customers use their appliances sparingly. On most days total energy consumption is very low; however, on a smaller percentage of days energy consumption is much higher. Mean daily energy consumption do not provide a good picture of a customer's usage characteristics, nor does it give us an idea of the higher levels of energy consumption that a solar home system would have to be designed for. As a result, we decided to assign customer to an energy usage type according to the third quartile of its energy demand. In summary, a customer's energy consumption characteristics can be placed into one of the following groups:

- Low energy customers: third quartile of daily energy consumption ≤ 150 Wh
- Medium energy customers: 150Wh < third quartile of daily energy consumption ≤ 500 Wh
- High energy customers: 500 < third quartile of daily energy consumption

According to the aforementioned criteria, Table 2 provides a summary of the customers on Site A and Site B.

In addition, Figure 1 and Figure 2 contain boxplots of daily energy demand for individual customers connected to Site A and Site B, respectively.

Within these figures, the centerlines of the boxes represent the median daily energy consumption. The upper and lower edges of the boxes represent the upper and lower quartiles of the data. The upper and lower whiskers represent data falling just within 1.5 IQR of the upper and lower upper and lower quartiles. Outliers are marker with a cross.

From these figures as well as Table 2, we see that a majority of Site A customers use electricity for lighting and cell phone charging only; whereas, a majority of customers in Site B use electricity to power something other than lights and cell phones.

TABLE 2: ENERGY CONSUMPTION CATEGORIES FOR CUSTOMERS CONNECTED TO EACH MICROGRID

	Site A	Site B
Low energy	6	3
Medium energy	4	3
High energy	0	2

Figure 1: Boxplot of daily energy consumption of each customer connected to Site A

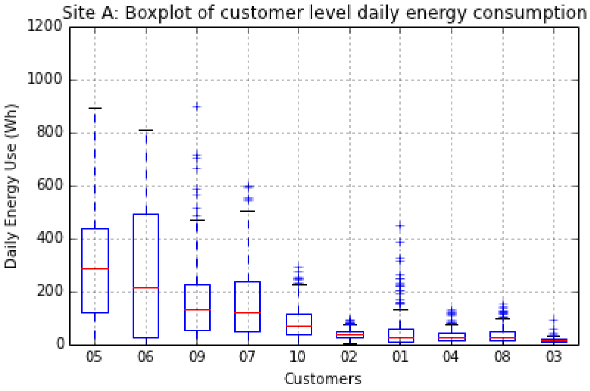
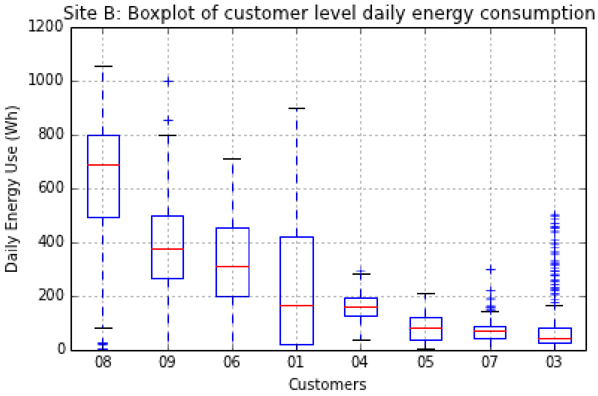


Figure 2: Boxplot of daily energy consumption of each customer connected to Site B



D. *Methods*

In order to compare the technical and economic performance of microgrids and solar home systems for each microgrid, we used HOMER energy simulation and optimization software. Using the optimization software we determined the optimally sized solar home system for each customer given its historical energy demand data. Then, for each microgrid, we summed the hourly energy demand of all customers and calculated the optimally sized microgrid given the aggregated demand. The optimal solution for a microgrid or a SHS is the combination of PV, battery, and inverter capacity that has the lowest net present cost, NPC, while still having a system reliability that falls within an acceptable range.

In our analysis, we wanted to quantify the effect of system reliability on the cost of energy for both SHS and microgrids. System reliability refers to its ability to meet demand during periods of low solar availability or high demand. The metric we use to quantify system reliability is unmet load percentage, which is equal to the total energy supplied to customers of the course of a year divided by the total energy demanded for that year. We optimally size both microgrids and SHS while specifying maximum allowable unmet loads of 0.0, 0.1, 0.2, 0.3, 0.4, 0.5, 1.0, 1.5, 2.0, 5.0, 7.0, and 10.0 percent. This enables us to view how the performance of a system changes depending on the grid reliability. When sizing microgrids for a cluster of customers the maximum allowable unmet load percentage is computed for the community in aggregate. When sizing solar home systems, maximum unmet load must be achieved for each individual customer.

In our analysis, the project life of all solar home systems and microgrids was specified to be 20 years. The nominal value of all costs is fixed with respect to time. However, an annual discount rate of six percent is used to compute the net present costs of all future expenditures.

We are interested in the relative difference in the cost of energy between solar home systems and microgrid. As a result, we focused on estimating cost parameters that vary significantly between solar home systems and microgrids. These parameters include installed photovoltaic capacity, battery capacity, charge controllers, and inverters. We elect to not include the cost of component enclosures, PV racking, internal home wiring, operations and maintenance costs, or customer metering. These costs are highly variable and are not directly influenced by the microgrid versus solar home decision. They are dependent on site specific parameters such as geographic remoteness, weather conditions of the local environment, local supply chains, and availability of trained solar technicians.

E. Input Parameters

Battery costs dominate the cost for both systems; however, the costs of other components are considered for a more complete analysis.

1. PV Modules

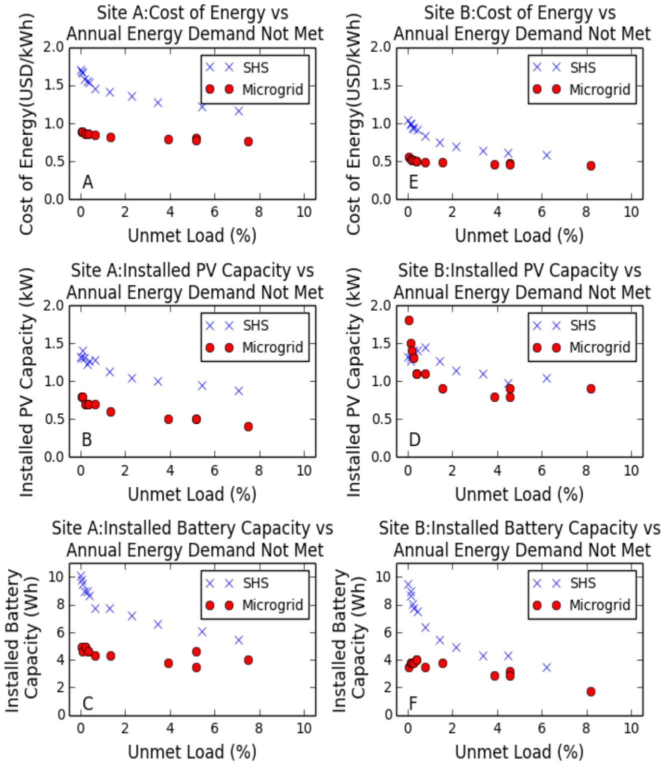
When sizing the PV modules for SHS, panels with discrete step sizes of 20 W are selected. For microgrids, panels with a step size of 100 W are selected. The cost per installed PV capacity is 1 USD/ W. We model the PV modules as lasting the entire project life without needing replacement.

The microgrids being modeled within this paper are located in southwestern Uganda at the approximate coordinates of 0° 36' south, 30° 39' east. In order to maximize annually available solar radiation, while allowing for rain and dirt runoff, the panels for both the microgrids and solar home systems face due north and are tilted at an angle of 5°. A ground reflectance of 0.20 and a PV derating factor of 0.85 were selected.

2. Battery System

Our simulations use absorbent glass mat (AGM) sealed deep-cycle lead-acid battery. The batteries have nominal energy content 0.288 kWh. We specified the round trip efficiency of the batteries to be 80 percent, and a lifetime throughput 103 kWh (or 368 kWh of throughput per kWh of nameplate capacity). We also specify that the batteries must be held above a minimum state of charge of 40 percent. For the solar home systems, the search space is in discrete steps of one battery. The capital cost of the batteries is 0.1875 USD per Wh installed.

Figure 3: Cost, installed PV capacity, and installed battery capacity



3. Balance of System Components

The charge controller within the system was modelled to have 94% efficiency. In addition, the cost of the charge controller was assumed to be 0.30 USD/W of capacity and the charge controller is capacity the same as the PV panel. The inverter is assigned a cost of 0.60 USD/W and an efficiency of efficiency of 90 percent. Both the electronics are assigned a design life of 15 years. In addition to the proceeding text, all microgrid input parameters are summarized in Table 3.

II. RESULTS

The primary result of our analysis is that, before distribution costs, for a given grid reliability i.e. (unmet load) the microgrid option is more cost effective than using solar home systems. The cost savings of microgrids when compared to SHS is illustrated in Figure 3, subplots A and D.

Another important finding is that the cost advantage of microgrids is driven primarily by shared storage. Figure 4 shows the Net Present Cost, NPC, of PV and battery for SHS and microgrid for both Site A and Site B. In Figure 4, we see that at high reliabilities, for Site A and Site B the NPC of microgrid batteries is much less than the aggregate NPC of SHS batteries. For Site A with high reliability (unmet load less than 0.1 percent), the NPC of microgrid batteries is 2530 USD, whereas the NPC of batteries using SHS is 4764 USD. For Site B at the same reliability, the NPC of microgrid batteries is 1782 USD, whereas the NPC of SHS batteries is 4491 USD.

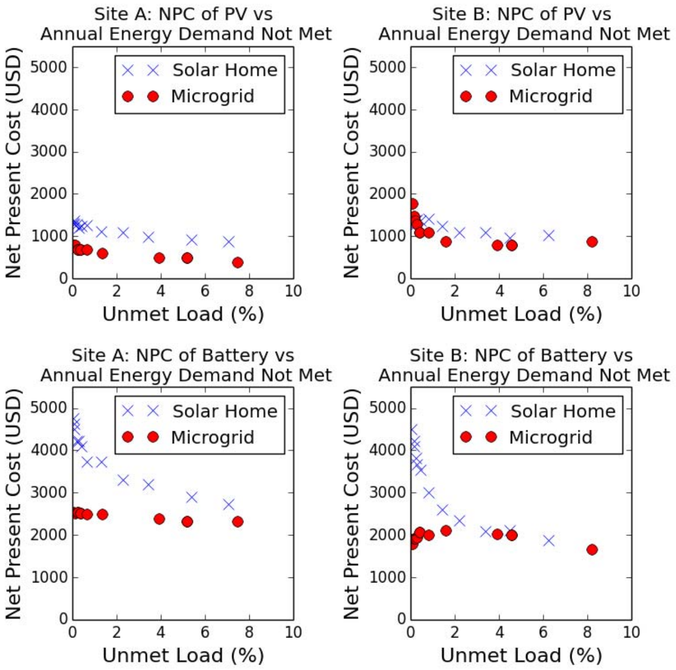
Conversely, Figure 4 illustrates that the NPC of PV for the microgrid and SHS options are relatively similar (compared to battery costs). For Site A with high reliability (unmet load less than 0.1 percent) the NPC of microgrid PV is 788 USD, which is only a modest decrease from the NPC of SHS PV, 1300 USD. For Site B with the same reliability, the NPC of microgrid PV is 1773 USD, which is actually slightly greater than the NPC of PV using SHS, 1301 USD. In Site B, the small increase in microgrid PV capacity compared to SHS PV capacity is most likely due to the discrete step sizes in PV and battery selection, and the sensitivity of these parameters when cost optimizing for a specified grid reliability.

Another result of our analysis is that as the desired reliability of a system is increased, the advantage of microgrid shared storage is also increased, Figure 3, subplots C and F indicate that when using microgrids, less additional battery capacity is needed in order to improve reliability levels. For Site A, to improve reliability from a unmet load of 7.49 percent to 0.04 percent, battery capacity only had to be increased from 4.0 kWh to 4.9 kWh. A similar result occurs for the other microgrid. For Site B, to improve reliability from a unmet load of 8.19 percent to 0.06 percent, battery capacity is increased from 1.7 kWh to 3.5 kWh.

Figure 3, subplots C and F indicate that with the SHS option, required storage capacity is greatly dependent upon the desired grid reliability, as defined by unmet load.

For Site A, in order to improve reliability from a unmet load of 7.06 percent to 0.02 percent, aggregate SHS battery capacity had to be increased from 5.5 kWh to 10.1 kWh. Similarly, for Site B to improve reliability from a unmet load of 6.22 percent to a unmet load of 0.03 percent aggregate SHS battery capacity had to be increased 3.5 kWh to 9.5 kWh.

Figure 4: NPC of PV and Battery for both Site A and Site B



III. DISCUSSION

A. Distribution Costs

Although our results illustrate, that for our sample communities, the use of microgrids over SHS results in a significant decrease in the required amount of battery storage, this does not mean that microgrids will always be preferable to SHS. Distribution costs are a major cost that was not included in our analysis. When choosing between microgrid and SHS electrification, an ESCO will have to determine whether or not the costs savings in reducing battery capacity will be outweighed by distribution costs.

Distribution costs were overlooked because they are dependent on many factors and are difficult to generalize. Our experience has shown that factors such as inter-household distance, cost of wire, and the cost of labor can vary significantly depending on location. Depending on the climate, locally available materials, and risk of unauthorized and unmetered electricity connections, an ESCO will decide whether to use above or below ground wiring. The decision to use above or below ground wiring will influence distribution costs.

B. Limitations to System Sizing

In our analysis, PV and batteries were sized according to a household's, or a community's, particular energy demands. However, in practice, exact sizing of PV and batteries in order to perfectly match a community's energy will not be practical. When deploying rural energy solutions at scale, an ESCO would need to have a limited number of SHS and/or microgrid options sized to serve a wide range of community/household types. Limiting the number of designs will help to minimize the costs associated with design and manufacturing.

Another primary challenge in selecting and sizing an electrification strategy is the need to estimate future usage. Due to the relatively small number of customers, the demand is often unpredictable and can vary greatly based on local events or purchases of relatively high energy usage items. In our systems deployed in Uganda, we have seen significant overall growth in energy usage for many of the systems since they were installed, but we don't know what that demand might look like in 5 or 10 years. For now, the system sizes that we have chosen seem to be sufficient, but we don't know if the demand has peaked or if it will continue to grow. Some systems were seen as better candidates for increased demand than others, and an example of this is a site that has only one customer, a school. If a few relatively high power appliances were added to this system, it could cause the system to overdraw on the available energy and reduce reliability. The point being that every system is different and not every system is expected to see growth uniformly. Electricity demand inherently has a lot of randomness and it is impossible to preemptively account for all the randomness in a system.

Regardless of this, we designed our system to be oversized and therefore 100% reliable, and as of right now we have achieved that. If the demand increases in the future, we do have the option to either add more batteries or PV panels as a system might require it. This process would obviously take some time though and reliability would suffer during the period where the demand didn't meet the supply. For a utility managed SHS, this process would mostly be the same, but the cost for one customer to add more capacity would be a lot compared to spreading it across many customers.

IV. CONCLUSION

Our analysis using real time data has shown that the cost of a solar micro grid is almost always less than a set of SHS over almost all desired reliabilities. This is primarily due to shared storage giving significant cost savings. As noted in the discussion, this doesn't mean that a microgrid is always favorable over SHS, but adding the distribution costs for a particular location for both SHS and microgrids to the costs calculated in the paper will provide a very good estimate for the cost of each system.

V. ACKNOWLEDGMENTS

We are grateful to the Millennium Village Project Uganda, especially Emmanual Toko and Innocent Niwamanya. We would also like to thank the people of the Sustainable Engineering Lab at Columbia University for their efforts. In particular, we would like to thank Chris Natali for his work in managing and archiving SharedSolar data, Rajesh Menon for writing the SharedSolar metering software, and Denis Papathanasiou for his help in all things programming.

APPENDIX A: CONVERTING CUSTOMER DATA INTO HOMER READABLE FORM

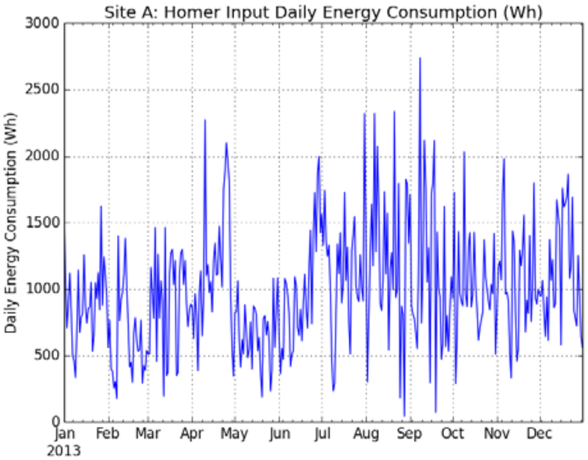
Microgrid optimizations were conducted using HOMER (Hybrid Optimization Model for Electric Renewables) Software. Within HOMER, simulations are conducted over one year of data that begins on January 1st and ends on December 31st and does not include leap year. In order to use historical energy demand data as a model input, HOMER requires a yearlong hourly, or daily, data set without any gaps. Below we discuss how we used the demand data available to us to create model inputs.

A. Site A

For Site A, we had one year of demand data.

- The data went from September 1, 2012 to August 31, 2013
- 910 hours without data
- 14 complete days without data
- To make the data HOMER readable, all missing data was replaced with data from the corresponding hour one week in the future. For one instance where data was missing from that day as well, the data from one week prior was used.
- The data set was shifted so that the first data point occurs on January 1st.

Figure 5: Site A demand data inputted to homer



B. Site B

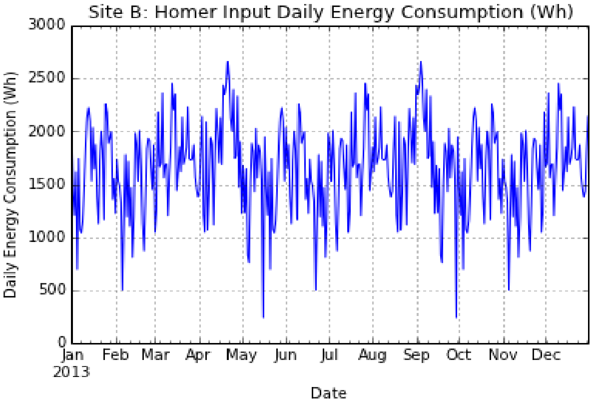
For Site B, we had less than one year of demand data.

- The data went from January 1, 2013 to September 31, 2013. However, there was a large gap in data from April 10, 2013 to August 1, 2013
- There is 136 days of total data
- There is 2754 hours of total data

To make the data HOMER readable,

- All days without any data points were completely removed.
- Remaining hours without data had NA replaced with zero.
- Resulting data set is then appended to itself until a 8760 hour data set is constructed.

Figure 6: Site B demand data inputted to homer



C. *Optimization Model Input Parameters*

The parameters shown in Table 3 were common to both SHS and the solar microgrid.

TABLE 3: COMMON PARAMETERS FOR SHS AND MICROGRID INPUTTED TO HOMER

	Parameter	Value
Financing Parameters	Annual interest rate	6%
	Project lifetime	20
PV	Design life	21 years
	Derating factor	0.85
	Slope	5° above horizontal
	Coordinates	0° 36’ south, 30° 39’ east
	Azimuth	180° W of S
	Ground reflectance	0.2
	Capital cost	1
Battery	Number of batteries to consider	[1, 2, 3, …]
	Battery type	Absorbent glass mat (AGM) sealed deep-cycle lead-acid battery
	Nominal capacity per battery	0.288 kWh
	Capital cost	0.1875 USD/Wh
	Replacement cost	0.1875 USD/Wh
	Round trip efficiency	85%
	Min state of charge	40%
	Float life	5 years
	Lifetime throughput per battery	103 kWh
Charge Controller	Efficiency	94%
	Cost	0.30 USD/W
Inverter	Sizes to consider	[100, 200, 300, ...] Wh
	Capital cost	0.6 USD/W
	Replacement cost	0.6 USD/W
	Lifetime	15 years
	Efficiency	90%

A design life of 21 years was chosen because the industry standard design life for PV panels is 20 years, and we didn’t want the HOMER model to replace the PV modules in the last year of operation.

The only parameter that was different was the capacity of the PV to consider. For the SHS, smaller modules were considered because in a real life situation they would be the ones that people would be likely to consider. For SHS, we considered capacities of [20, 40, 60 Wh,…], and for the microgrid we considered increments of [100, 200, 300 Wh,…].

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