Analyzing sub-optimal rural microgrids and methods for improving the system capacity and demand factors

Filibaba microgrid case study examined

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Abstract*—Solar energy kiosks in developing countries are commonly designed with battery storage as daytime energy production does not coincide with an evening peak consumption. Curtailment of excess solar energy production can occur when current load and battery storage charging is not high enough during peak solar generation hours. Valuation of the options for coping with this phenomena, after a system is already built, is important for kiosk operators to continue to improve technical and economic performance. Furthermore, little real-world data is available to analyze the extent and impact of this issue, much less the available decisions for the manager of such systems when it occurs. This paper analyzes some of these phenomena and the decisions that kiosk operators can make to improve such performance. Furthermore it analyzes data-sets from a 1.8 kW solar-battery energy kiosk in rural Filibaba, Zambia to determine the level of lost energy production/curtailing that occurred in that system. Finally, potential strategies, including demand response strategies are proposed to both increase as well as shift consumption to daytime hours and ultimately increase the capacity factor of the system. Such strategies could potentially help reduce the lost production of almost 1.7MWh that was witnessed in 11 months of system usage. These strategies could also increase the revenue of the system by approx. US$810 annually. Such strategies include pricing incentives, manual demand response, and system re-design options. In the general context of operations of rural solar kiosks, this work advocates for the need to continuously improve operational as well as hardware strategy based on field-evidence.

Keywords*—rural microgrid systems; operational optimization; hardware optimization; solar systems; demand response

I. INTRODUCTION

Zambia is among twenty countries in the world with the lowest electrification rates, with an electrification rate of 19 percent [1], which drops to about three percent in the rural areas. However, providing electricity to remote rural communities can prove challenging. Hence, off-grid solutions, often powered by renewable resources, offer an alternative to grid extension. These small scale systems can be installed in a variety of architectures to provide modest electricity service to remote communities [2].

Designing small scale systems however is a challenge, especially in rural settings. One is not completely sure about the electricity needs of a community that has never had electricity before. Electricity access tier and expected financial capacity of a project are deeply tied to community needs. Microgrid sizing is a critical issue decided during the design of a project. A sub-optimally sized system can lead to two undesirable results: an under-sized system with lower availability than planned or, an over-sized system which is an economically inefficient investment. It is commonplace for practitioners to survey the community needs in order to estimate base load, peak load, and a daily load profile. Subsequent component sizing steps including inverters, batteries, charge controllers, wiring are dependent on the demand estimation. However the accuracy of the demand estimation is often erroneous and has been found to be as high as 728% of the actual consumption [3].

After installation, it is often a challenge, due to the high logistical costs, to adjust the design parameters if it is found to be sub-optimal. Relatively little practical documentation exist on the decision space after installation for such systems and the merits of the practical options available despite the clear value for these projects. Operators of such projects have an incentive to reconsider design parameters after operations are underway to ensure the maximum level of sustainability can be achieved.

In September of 2015, Kilowatts for Humanity (KWH), a Seattle, US based non-governmental organization (NGO) along with Lichi Community Solutions Ltd. (LCS), a Zambia based NGO installed an energy kiosk in Filibaba, near Chingola, Zambia. This work was funded by IEEE Smart Village. The Filibaba system was designed and installed keeping a number of parameters in mind, including a business-model based on an expected load of 20 Portable Battery Kits (PBKs) among other loads. The team conducted extensive pre-design data collection work in the form of surveys, a focus group meeting as well as a community meeting and based on that designed/sized the system and designed the business-model for the system [4].

This system was designed as a community based energy kiosk/micro-utility to be operated by LCS, with the revenue collected from the system to be invested in the community through job creation in the community. Based on the data collected during the pre-design data collection phase, the team designed and installed a 1.8kW solar panel system with a 2kW charge controller, a total energy storage capability of 10.56kWh and a 2kVA inverter supplying 230V AC, 50 Hz. Load included an envisioned load of 20 PBKs, along with mobile phone charging, security lighting, school/community center load and miscellaneous. However, the reality of operation, business-model and revenues turned out to be very different from what was designed despite all the pre-design data collection. This often happens in rural micro-utility settings where what is anticipated or actual reality during one part of the project does not hold true during another part of the project due to a number of reasons. Such issues could manifest in terms of sub-optimal hardware design or sub-optimal operational/business-model design and lead to either under or improper utilization of the systems installed and/or loss of revenue for the micro-utility.

The main contributions of this paper are, first, to describe in simplified terms some common hardware design or operational/business-model sub-optimal scenarios that can occur in rural micro-utility settings similar to Filibaba, (i.e. a system of solar panels and batteries), and that can lead to under or improper utilization of the rural micro-utility system installed and/or loss of revenue for the micro-utility. Second, the paper suggests several strategies through which rural micro-utilities could overcome such hardware or operational/business-model challenges. Third, this paper compares the Filibaba system and the system behavior that was envisioned to the actual system production and load of the Filibaba system and calculates the lost energy production. An analysis of anticipated original design and simulations versus actual performance suggests the sub-optimal operation is the result of unforeseen business model changes. Fourth, the paper presents some potential strategies that can be used to increase the load and hence capacity factor of the system and also potential demand response strategies that can be implemented in Filibaba for further improving the capacity factor of the system and improving the demand factor of the system as well.

The paper is arranged as follows. Section II describes common hardware design or operational/business-model sub-optimal scenarios that can occur in rural micro-utility settings similar to Filibaba and followed by typical design strategies and/or thumb rules used for mitigation. Section III briefly describes the system installed in Filibaba and how it was envisioned to be run. Section IV describes the reality that the team faced later, and calculates the lost energy production based on what was anticipated when the original system was designed and simulated. This section describes the unforeseen business model changes that later occurred. Section V finally applies some aspects discussed in section II but now describes some potential strategies that can be used in the Filibaba system specific to it, to increase its capacity factor and also potential demand response strategies that can be implemented for further improving the capacity factor and demand factor of the system.

II. COMMON DESIGN ISSUES THAT COULD OCCUR IN RURAL SOLAR BATTERY SYSTEMS

The Filibaba system is a typical small renewable system involving solar panels and battery system common in rural electrification scenarios. Decreasing PV module costs have made such systems the most economical in many contexts, but particularly when load centers are remote and dispersed. In these systems, energy storage in the form of batteries provide continued functioning when the solar resource is unavailable or during periods of low sunlight. Excess generation between peak production hours of noon-3pm charge the batteries while they are typically discharged during evening hours and early morning.

The Filibaba system was designed with six PV modules of 300W each for a total generation capacity of 1.8kW. The system also consists of a 2kW charge controller with maximum power point tracking (MPPT), four 12V, 220Ah absorbed glass mat (AGM) lead-acid batteries, and a 2kVA inverter supplying 230V AC at 50 Hz. The Filibaba system was designed optimally from a hardware standpoint to provide a high level of system reliability and equally expected to maximize the revenue potential from the available pre-design data. These assumptions are described in more detail in later sections. In this sense it can be noted that the intention was for the design to provide both technical optimization and economic optimization based on the business model deployed. Data monitoring after installation revealed that in practice, system operation did not fit with design assumptions, or in other words, the system *ex-post* could be considered sub-optimally designed.

This section will discuss some common scenarios that can occur in hardware and operations design that can cause such PV and battery based kiosk systems to become sub-optimal from either a hardware or operations design perspective. It also discusses some common design considerations and some thumb rules that can be used as mitigation strategies that micro-utilities can adopt to make the system more optimal and generate more revenues. Although there is general relevance for kiosk systems in developing countries, specific application to a particular system requires a full understanding of its context as it is done later in this paper for the Filibaba system.

A. Considerations for sizing of solar panels

Sizing/number of panels that need to be installed depends on a number of constraints, for example: budget constraints, availability of panels, ease of transportation of panels.

However, some general rules can also be kept in mind while deciding on the sizing/number of panels that should be installed. Such rules of thumb here are intended for practical use by kiosk operators with little data available for advanced system redesign. Solar panel sizing depends on the load expected on the system. Ideally, a past consumption data from a sample of customers from a target location can be used to predict future consumption of the whole population [5]. Other techniques can include probabilistic approaches to generating representative load profiles [6]. However, in cases where little past data is available, energy use field surveying continues to be the de-facto standard for making demand estimations.

Approaches include surveys, community meetings, and pre-feasibility analysis and are used to determine the scope and nature of load and load growth to expect. A system can be sized to serve expected whole or part load of the community as prescribed in an accompanying business model. Depending on the base and peak load value one decides to serve, a simple rule of thumb is to **multiply panel nameplate capacity by 5 to 6 times this peak load** to correspond with typical capacity factors of rural solar systems usually ranging between 15%-20%. This comes from the definition of capacity factor where capacity factor is a measure of how much energy is produced by a plant compared with its maximum output. It is measured as a percentage, generally by dividing the total energy produced during some period of time by the amount of energy the plant would have produced if it ran at full output during that time. Thus, given typically that capacity factors for rural solar systems range in the 15% - 20% range, this rule of thumb of multiplying the expected peak load by 5 to 6 times to come up with a panel name plate capacity can be used. For example, if a micro-utility operator wants the system to serve 500W of peak load, a 2.5kW–3kW panel capacity would be desirable.

If the micro-utility operator suspects that generation is insufficient for the load, checking panel nameplate capacity against observed load could provide an initial sense of the appropriate panel sizing. Conversely, if there is more panel capacity than needed for the load, increasing the load connected to the system would improve capacity factor closer to 15%-20% that is expected from a solar PV system. This situation is representative of the Filibaba system, where low load conditions has led to generation curtailment and underutilization of the system.

In solar systems wired to homes/businesses where the primary use of solar is for lighting load, a common phenomenon observed is that this lighting load does not coincide with the peak solar production. Generally, this occurs between noon and 3pm when one does not need lighting. The most common solution given for such scenarios is to charge battery systems during this period to 'shift' the usage to later hours. While this is technically feasible, important considerations are the expense of the batteries, lowered roundtrip efficiency, and battery ageing effects. Additionally, use of battery storage opens the possibility of under-sizing the storage, a hardware design issue, and introduction of a charging discharging cycle where the battery health must be sufficiently managed from cycle to cycle, an operations issue. With an under-sized battery system it is possible that batteries are charged earlier than desired during peak solar production hours, thus leading to generation curtailment during peak production hours.

In this case, the micro-utility operator can adopt the rule of thumb of **'using it when it is produced'** strategy, or in other words attempt to adjust load to better match the generation profile. This can be achieved by encouraging the community to use more energy during higher solar production hours for uses apart from lighting. For example, price based demand response strategies can be used to encourage electricity intensive businesses in the communities to increase their non-lighting load during peak solar production hours. This can be achieved for example by increasing prices of services during the evening or lowering prices of daytime services. PBKs can be introduced and customers encouraged to charge them during peak solar production hours.

For the Filibaba system for example, several strategies are being pursued. First, the project is exploring the introduction of new loads, corresponding to new lines of business, which operate primarily during the peak solar production hours. In this case, the community has identified the need for a barber shop. Secondly, lowered prices for cell phone charging (an existing line of business for the kiosk) at daytime hours can shift some load where it is practical for customers to change their behavior. Finally, reduced daytime pricing of PBK charging is hoped to improve capacity factor. Estimation of the effect of these strategies on generation curtailment as well as business performance are addressed in Section V.

There are other design considerations that can be taken into account for increasing the capacity factor of a solar panel based system. These considerations can include placement, desired level of reliability, and specific characteristics of the panel technology. However, this detail is out of the scope of this paper.

B. *Considerations for sizing system batteries*

Apart from load and budget constraints, sizing of batteries for a system depends on the array name plate capacity and expected solar production hours. These can be used to determine the annual peak daily energy production capacity of the solar panels. Such analysis can be done using solar resource analysis studies. Tools for the same are readily available to give this value based on solar panel technology, total solar panel name plate capacity, placement and tilt of the panels.

As a rule of thumb, **station battery capacity should be sized to at least 110% of this energy production capacity value**. This will ensure that the batteries will only charge up to about 90% of their total capacity under no load conditions even during the highest solar production day of year. This is because, batteries are recommended to be charged not beyond 90% of their capacity, and not discharged below 10% of their capacity (in fact discharging to a lesser degree like only up to 50% of battery capacity is usually recommended for increasing battery life). Based on this rule of thumb, for ratios of under 110%, (i.e. if battery capacity is lower than generation production) the operator should increase the battery capacity.

For the Filibaba system, this rule of thumb calculation matches the sizing based on peak daily energy production of the system occurring in the spring months of September to

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This work was performed as part of research efforts by the IEEE PES SIGHT/IEEE PES WG on Sustainable Energy Systems for Developing Communities

October of about 9.6kWh per day. This implies a battery capacity of 10.56 kWh, i.e. 110% of the peak daily energy production.

C. Considerations for sizing charge controllers

Charge controllers are typically used between a solar panel and a battery pack to prevent over charging of batteries. One can buy many different types and sizes of charge controllers depending on budget and needs of the project.

For sizing a charge controller, the capacity of solar panels is an important consideration. For example, in Filibaba, a 2kW charge controller was used since the total panel capacity is 1.8kW.

If a charge controller is undersized compared to the total capacity of the solar panels, depending on the final design of the system, it may result in solar curtailment during peak production hours (unless such solar is also directly used instead of only being sent to a battery), thus limiting the output of the system. If a load increase is anticipated in a system, and the micro-utility desires to increase the capacity of its solar panels, it is recommended the team revisit its charge controller size to ensure no under sizing occurs.

D. Considerations for sizing inverters

Inverter types, technologies and budget constraints heavily influence the choice and sizing of inverter. Inverters need to be sized considering both the surge power expected from the system and the continuous power expected from the system. Surge power is power expected to last only a few seconds or a few mins, like when a motor of an appliance connected to the inverter starts and a surge power is needed by the motor for starting. Surge power rating of the inverter should be greater than or equal to the sum of the surge powers needed by all appliances and loads connected to the inverter. Continuous power rating of the inverter should generally be greater than or equal to the continuous rating of all appliances connected to the inverter. However, in case of a solar PV and battery system in a rural area, where all the load on the system need not be wired to the system at all times, like cell phone charging etc. and some loads may even be directly DC rather than connected to the inverter, the inverter continuous power rating can also be based on the maximum power expected from the solar system. This will ensure that the inverter will be optimally sized to output even peak solar production if needed.

In case of Filibaba, since the maximum power expected from the panels cannot exceed 1.8kW, an inverter sized at 2kVA seems to be a good choice of size. However, a freezer load and 2 home loads are wired to this system. The inverter appears to be functioning sufficiently for all the surge power needed by the freezer and 2 homes. This could also be because the system is lightly loaded at the present moment. However, in future, before wiring anymore load directly to the inverter in Filibaba, it is recommended that the surge rating as well as continuous rating of all load is calculated to ensure the inverter is never loaded beyond its capacity, both for surge as well as for continuous power.

III. CURRENT FILIBABA SYSTEM AND DESIGNED LOAD MODEL

Pre-installation data collection at Filibaba was conducted prior to system design. This included surveys of about 80 homes in the community and a focus group meeting. A larger community group meeting of over 230 households was also conducted and fed into some initial assumptions of the expected load as well as needs of the community. Some good insights were found from all this data gathering. First, households in the community expressed a willingness to pay roughly double their current spend on energy if they could have access to high quality electricity. Second, the current system design would be insufficient to power the entire community; as a result those without access wondered when the system could be scaled to everyone. Third, the community expected a major benefit due to closer access to cell phone charging, whereas previously they would have to travel long distances. Finally, the community expressed interest in achieving higher tiers of electricity access, namely, TVs, radios and other appliances [4].

A. Background of the Filibaba Village

Filibaba is a rural farming community located in the Copperbelt Province of Zambia. The community is one of 9 zones in the Ipafu ward of Chingola, which has a total city population of 5,517 people, including around 1,148 households. The Filibaba community is currently populated at approximately 1,200 people, encompassing 200 households and 300 farms, 6 churches, and a community school. A sizable population live in the city but visit the Filibaba community solely to tend to their farms. Although the community is accessible to vehicles, the area has dusty, gravel roads and no formal mode of public transport and remains relatively remote.

Fig. 1. Map showing the Chingola area of Zambia, where Filibaba is located

The Filibaba population has an estimated 75%-80% literacy level. School facilities here are inadequate in the area. The existing community school in Filibaba lacks many educational materials such as books, desks, a chalkboard, and writing utensils, or more advanced tools such as computers. Furthermore, the community school has neither teachers nor staff members to manage the building.

B. Current system

Based on the data collected prior to installation, KWH designed and installed a 1.8kW solar panel with six panels rated at 300W, a 2kW charge controller with MPPT, four 12V, 220Ah AGM lead-acid batteries in series, giving a total energy storage capability of 10.56kWh and a 2kVA inverter supplying

230V AC, 50 Hz. The daily output from the PV panels was calculated at 0.35kW as a continuous average based on HOMER simulation results. Expected capacity factor was 19.5% with an average daily production of 8.41kWh. Peak generation was during the spring months of September and October and was expected to be 0.4kW while the lowest production was during December to February at 0.3kW [4].

Fig. 2. The energy kiosk serves as the central hub for the Filibaba community where people can charge phones and purchase groceries, supplies, and talk time

C. Expected Load Model

The baseline load was based on a daily recharge schedule of ten 17Ah PBKs and ten 7Ah PBKs, along with mobile phone charging, security lighting, school/community center load and other miscellaneous small loads. It was also assumed that a 17Ah PBK requires approximately 330Wh to fully recharge including losses, while assuming proportionally the 7Ah battery requires 136Wh per recharge. It was conservatively assumed that the PBKs require a full charge when returned to the kiosk and that six PBKs will arrive at 8:00am when the kiosk opens, six at 9:00am and four at 10:00am, thus resulting in a distinctive peaked load pattern. It was also estimated that the kiosk will recharge 35 mobile phones per day at 9Wh per charge, and the phones will be charged between 8:00am to 6:00pm during the day. The system was also designed with four 16W compact florescent lights, which would be drawing power for 14 hours for security lighting purposes. The 100W wired connection to the school/community center was planned for six hours every evening after the energy kiosk closes. Lastly it was assumed that the system would see 10W continuous miscellaneous load thus bringing the total nominal load to 5.9kWh per day [4].

As briefly stated before, based on the pre-design data collection, 79% of the community stated they were willing to pay more than US$8 per month for access to electricity or more than twice their current average energy expenditure[4].

IV. CURRENT ELECTRICAL AND ECONOMIC PERFORMANCE

Despite the pre-design data collection work and due diligence, the energy consumption differed from expected/ modeled consumption. Both security lighting and mobile charging were reasonably similar to the original model. However the school and community center lighting load could not be satisfied due to location change of the energy kiosk. In addition, the PBK distributer failed to deliver the required PBKs, reducing a major potential load for the kiosk. Therefore, it became immediately apparent to the operator that the system would likely be underutilized without these two critical loads. Hence, within 3 months of the kiosk becoming operational, KWH and LCS sought to respond to a community desire for chilled drinks by installing a freezer. The freezer was operated by a person of the community and has thus resulted in job creation within the community.

Economically, by March 2016, the energy kiosk sales, which was made up of chilled drinks sales, mobile phone charging, the wiring of two nearby homes, and the church, amounted to an average monthly income of US$22. The freezer makes an average monthly income of US$5 selling on an average 2 crates of drinks a week. Cell phone charging at the kiosk generates roughly US$7 per month in revenue. The two wired homes provide US$6 and US$5 respectively per month. The difference in rates is due to the difference in consumption in the two homes where the homes are charged for energy in blocks of 1.5kWh. Following their electrification, these homes started charging people's cell phones which cut into kiosk sales, thus causing a loss of revenue at the kiosk of about US$4 per month. The electrical loads at the two homes are each 5 CFL lights, a TV, a Radio and cell phone charging load. In March of 2016, a church was connected to the kiosk and the church generates a revenue of US$3 a month for the electricity provided.

The upper plot of Figure 3 shows the hourly average production for each month for the solar panels for the period of October 2015 to August 2016. The lower plot shows the average hourly load per month connected through the inverter.

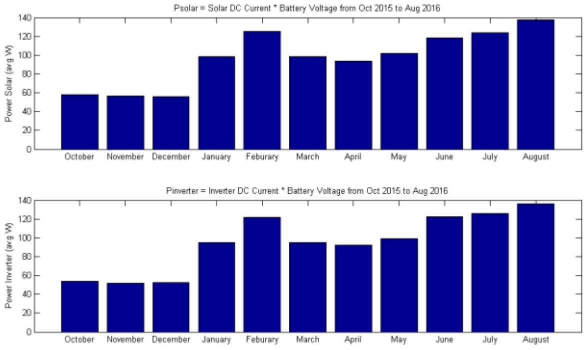

Fig. 3. Hourly Avg. Solar Production per month

As can be seen from the plots, the average production of the panels and inverter was about 0.06kW per hour in October 2015. As demand grew (from connecting the freezer and two homes), the average production of the panels and inverter increased to about 0.14kW per hour in August 2016. As stated above, the average daily production based on simulation results was expected to go up to about 0.4kW hourly average in September and October, go down to about 0.3kW hourly average from December to February and for the rest of the year average at about 0.35kW hourly for the system, giving a capacity factor for the system of about 19.5%. Thus while the average production (or utilization) has gone up from 0.06 kW per hour average to 0.14 kW per hour average, the system can still be considered under loaded and hence underutilized.

A. Motivation for this work

As also stated above, it can be clearly seen that despite the freezer load, cell phone charging load, church load, and the load of the two homes coming on, the installed energy kiosk system is clearly underutilized and the capacity factor less than half of what was expected. Compared to the expected loading, we can see that the system would have been optimally sized. With the actual loading and performance known, the charge controller is more than adequate for the peak production of all the panels. The battery pack is adequately sized so it will charge up to about 90% of its capacity daily even during high production months of spring and even when no load is connected to the system on any given day. The inverter is also adequately sized so that during peak solar production, the full instantaneous power from the system can be supplied. Hence, from a basic design perspective we can conclude that the issue with the Filibaba system is not one of hardware design, but that of operations and/or business model design/issues.

The average hourly load curve of the Filibaba system for months of June, July and August 2016 is shown in Figure 4 below. Typically batteries are charged early in the day with the remaining generation curtailed by the charge controller.

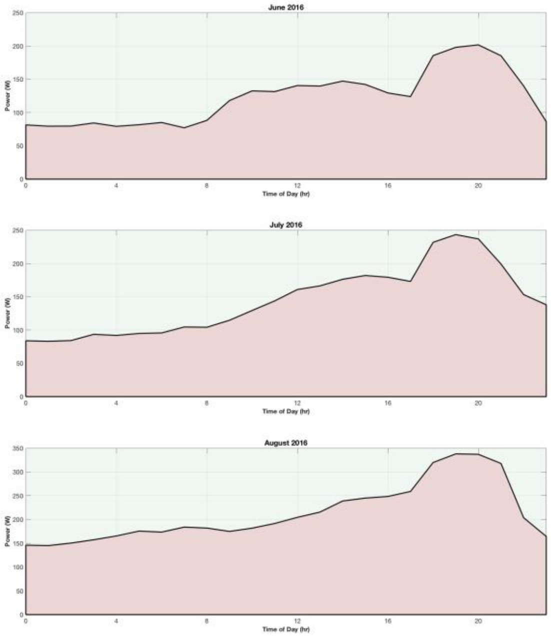

Fig. 4. Hourly Avg. load connected to the system

It can be seen from the plots that peak solar production (between 12:00 and 15:00) does not correspond with peak load (between 17:00 and 21:00). Hence most of the solar during peak production hours has to be dumped into the battery or curtailed once the battery is fully charged. Thus, significant solar production from the Filibaba system is getting curtailed during the day, during most of the peak solar production hours, lowering the capacity factor of the system. This situation seems particularly ironic as many families in Filibaba continue to live without power.

As stated above, from the simulations it was determined that the hourly average production of the panels would be 0.4kW in September and October, 0.3kW from December to February and can be taken as 0.35kW the rest of the year. Hence, the total anticipated production of the system from October to August of a year was

Total simulated production from October 2015 to August 2016 was 0.8MWh as calculated below:

(No of days in October)*0.4*24 + (No of days in December, January and February)*0.3*24 + (No of days from October 2015-August2015)*0.35*24

Thus we see that total lost production due to the underload in the system was = ~(2.5MWh – 0.8MWh) = ~1.7MWh. This corresponds to roughly 32% of full utilization.

The total load in kWh of the two homes connected to the Filibaba system between March 2016 and August 2016 was 203.36kWh, giving a monthly load per home of 17kWh per month.

Potential revenue not generated was significant. If we assume additional households could be connected, then revenue from roughly 100 household months of operation (1.7MWh/17kWh per home) was lost in the 11 months of operation of the kiosk. At US$5.5 average revenue per home this is equivalent to US$550 in extra revenue from October 2015 to August 2016 for the Filibaba system. This corresponds to approximately 9 homes served continuously by the system.

V. POTENTIAL STRATEGIES FOR IMPROVING THE CAPACITY AND DEMAND FACTORS OF THE FILIBABA SYSTEM

An initial strategy Filibaba could adopt is to connect new households to the system i.e. connect 5 homes to the system and monitor this load for a year to make sure the system can provide sufficient reliable power to the new homes, church, freezer and security lighting. 5 homes are recommend against the maximum of 9, as the calculation misses the fact that energy produced by solar does not coincide with the load, hence the first expected limitation is on the battery storage. Additionally, load from the existing home connection, freezer and church started only recently, during the first quarter of 2016, hence further monitoring for load growth is needed. New home loads connected in Filibaba can conservatively be expected to be very similar to the loads of the two homes. The plot below shows the average hourly load of the two homes connected to the Filibaba system during August 2016

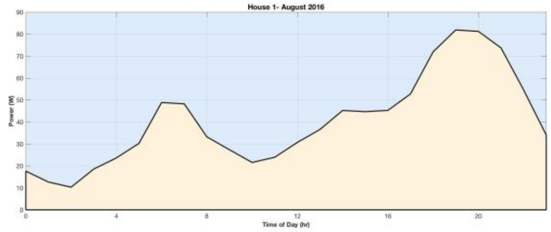

Fig. 5. House 1 August 2016 Avg. Hourly Load

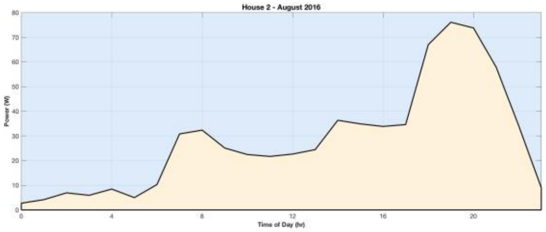

Fig. 6. House 2 August 2016 Avg. Hourly Load

As can be seen from the average hourly load plots of the system, House 1 on an average had a small morning peak between 6am to 7am, and then an evening peak between 6pm to 9pm during Aug 2016. House 2 also seems to have had an average morning peak in Aug 2016 but between 7am to 8am and an evening peak between 5pm-9pm. Neither of the two peaks (morning and evening) in the two homes however coincides with the expected peak of the Filibaba system, which is expected to be between noon and 3pm. Thus, even with more homes connected, it should be expected that a degree of solar curtailment during peak production hours will occur, unless mitigated by some other method (demand response strategies).

Also, while the total load of the Filibaba system shows only one distinct peak during in the average daily load pattern, the two homes clearly show two distinct peaks in their average daily load patterns. Thus it is important to be conservative and only connect 5 homes initially to the Filibaba system. Further connection of homes should follow a more detailed study of load growth patterns as the system becomes better utilized. This will give very good insight into the pattern of home load growth in Filibaba. It follows that adding 5 wired home connections will increase the revenue by US$330 annually.

Demand response strategies can be utilized through procurement and distribution of 10 7Ah PBKs. A rental model can be followed for the PBKs with a monthly rental value. As mentioned before, these PBKs need about 136Wh per charge. Hence limiting about 3 PBKs to charge from 12:00 to 13:00, 4 from 13:00 to 14:00and about 3 PBKs to charge from 14:00 to 15:00 will help with reducing some of the solar curtailment losses in the system that can occur between 12:00to 15:00. This can be done by allocating the specified hour to the PBK renter in which they can come to the energy kiosk to charge their PBKs. Further, as an incentive to the PBK renters for coming at the exact time for charging, the rental of these PBKs can be made as low as US$4/month for unlimited charge cycles, as long as these charge cycles are in the allotted hour. Thus, LCS can provide some kind of Tier 1 access to electricity for about another 10 homes in the community. Rental income from these 10 PBKs can be expected to be US$40 a month.

A point to note is that this is income from energy that would otherwise have been curtailed due to the load not being perfectly coincident with the solar production. While it may be that all this energy could get stored in the battery pack connected to the kiosk, without proper study of the new home loads, we cannot make any conclusions and hence PBKs are an appropriate interim solution.

Some members in the community have wanted to start a barber shop near the energy kiosk. We further recommend LCS open this barber shop but limit hours to 12pm-3pm. This will help with access to a barber shop in the community. It will also help utilize some of the energy that will otherwise get curtailed during the peak hours of production. The revenue implications of the barber shop is unclear at this time as development of a business plan is needed.

As also discussed, revenue from cell phone charging has reduced from US$7 to about US$3 a month following the wiring of the two homes. With the connection of new homes, further competition can be expected for cell phone charging. While this can be seen as a loss of revenue for LCS, adoption of a flat energy tariff, rather than the current blocked tariff that has discrete steps, will make LCS neutral towards this competition.

Overall, by connecting new homes and new PBK based rental revenue, the anticipated revenue increase for LCS is US$330 + US$480 = ~US$810 annually. This is a substantial revenue increase and does not include the extra barber shop revenue.

VI. CONCLUSIONS AND NEXT STEPS

Despite the extensive pre-design data gathering work at Filbaba including surveys, a focus group and community meeting, and strong local partner (LCS) engagement, actual implementation realities were significantly different from design expectations. As a result of this mismatch, the system was calculated to be 32% utilized even after initial steps to add load to the system. Additionally, it was observed that the system regularly experienced generation curtailment during peak generation hours while there was a large non-coincident load peak in the evening hours. Keeping all the pre-design data in mind and with the help of sound design and simulations, a technically and business process wise well designed 1.8 kW solar system was initially installed in Filibaba. However, due to unforeseen circumstances, sufficient load could not be connected to the Filibaba system, thus leading to its underutilization or sub-optimal functioning. Approximately 1.7MWh of solar production was curtailed in 11 months of system usage due to this underutilization.

This paper provided several design rules of thumb and design considerations that micro utilities could quickly check for when they suspect their systems are not optimal once the reality of operation is known. Specific analysis of the Filibaba system found the business model and operations as the current challenge rather than any design issue. This stemmed from several critical loads that were not realized after installation.

Several strategies were proposed for LCS to increase the capacity factor and improve the demand factor of the system. Implementation of strategies such as connecting new homes and renting/leasing out portable battery kits is anticipated to increase the revenue from the system by about US$810 annually.

Further measurement of the results of such strategies is needed after these strategies are enacted. Continuous operational and hardware improvement to the Filibaba system based on data collected from the system should be an annual exercise to better utilize of the Filibaba system and hence increase revenues for micro-utilities like LCS, provide more electricity to the community and support more job creation within the community.

ACKNOWLEDGMENT

The authors would like to thank Lichi Community Solutions, Zambia for all the “on the ground” information of the system operation, Kilo Watts for Humanity, Seattle, USA for all the knowledge on initial system design considerations and for the data that they are collecting from the system, that provided the basis for analysis in this paper, IEEE PES SIGHT/IEEE PES Working Group on Sustainable Energy Systems for Developing Communities for their support and guidance in the undertaking of this study and IEEE Smart Village for all the initial support and funding for the Filibaba system.

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