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A Simulation-based Evaluation of the Benefits and Barriers to Interconnected Solar Home Systems in East Africa

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***Abstract*— This paper outlines the relative advantages and disadvantages of interconnecting Solar Home Systems (SHSs) to form micro-grids. Real world remote monitoring data from a number of SHSs operated by BBOXX in Rwanda is analyzed and it is shown that significant demand diversity and differing patterns of energy use exist in SHSs. Significant variation in daily demand, is demonstrated for identical SHSs from 0-10 Wh/day up to 110 Wh/day. Around 65% of generated energy is currently unused and could be utilised to connect new customers and increase the demand of existing customers if systems were interconnected.**

Keywords*— *Micro-grid, Interconnection, Solar Home System (SHS)

I. INTRODUCTION

With the spread of distributed renewable generation there are now more electricity prosumers (power producers and consumers) than ever, connected to distribution networks or as part of smaller standalone systems, such as minigrids or solar home systems (SHS).

Millions of small generators offer opportunities for a very different approach to power systems, discarding the traditional combination of centralized generation, high voltage transmission and distribution in favor of a more flexible approach. Bottom-up electrification involves connecting small generators, such as individual SHSs or minigrids, together as required, to allow a larger grid offering more secure and reliable energy supply to customers to evolve at a pace aligned with available investment and load growth. This allows investment in expensive transmission and generation infrastructure to be deferred or even eliminated altogether.

Significant potential for a bottom-up electrification was identified for Sub-Saharan Africa countries where growth of prosumers installations in the last years has been the highest. Existing SHSs and micro-grids typically give access to Tier 1 (lighting, phone charging) and Tier 2 (radios, small TVs) devices. As a result of interconnecting existing prosumers together, customers could share surplus of electricity in order to add devices with higher energy requirements.

II. BOTTOM-UP ELECTRIFICATION

This section presents some of the benefits and challenges associated with SHS interconnection for bottom-up electrification.

A. *Benefits of SHS interconection*

1) *Increased Diversity*

Diversity in the power system arises from a mismatch between supply or demand caused by differing demand and generation profiles. For a single SHS there is no benefit derived from diversity. The peak demand must be met by the panel and battery at all times to ensure constant operation. Systems are therefore specified to have large generation and storage capacities in order to satisfy this worst case peak load scenario.

Interconnecting solar home systems leads to benefits from diversity, particularly where significantly different load profiles exist across the interconnected SHS network. The load profile of domestic dwellings in a given community will tend to be similar, but similar loads can still result in improvements in diversity as demonstrated in section III of this paper. Schools, healthcare centre, small industry, agriculture and other loads have differing profiles, further increasing the demand diversity present if connected. By connecting a variety of loads to the system, each with different operating regimes, diversity can further increase. For example, an industrial application such as maize mill could utilize the excess solar energy available directly from the generation during the middle of the day, reducing the need for energy storage.

Smaller demand peaks require less generation to be despatched at peak times, reducing the need for backup generation (e.g. diesel generation) and battery storage. This can reduce capital costs and reduce the utilisation of batteries; reducing charge/discharge cycles and deep cycling of batteries, and so increasing their lifetime.

Shared storage assets can also be despatched in a co-ordinated manner, fully discharging one set of batteries before utilising others, reducing the total number of charge discharge cycles seen by each battery to improve lifetimes for some forms of battery technology such as Lead-acid

2) *Increase reliability and flexabiltiy*

In the case of a fault on the system, an interconnected network of distributed SHSs could revert to islanded operation, providing at least limited functionality for basic loads such as lighting. This could significantly increase the reliability of systems compared to a minigrid with centralized generation and storage. A minigrid connected to the national grid could similarly intentionally island itself in the case of a fault on the system.

The system could also be configured to exhibit reconfiguring or “self-healing” properties, re-routing power to avoid faults, similar to the way that the internet can route packets to ensure system performance [1], or quickly restore affected customers post-fault and so minimising disruption to supplies.

There is increasing interest in operating energy systems with the possibility of intentional islanding [2], even in countries with high electrification rates and established national grids as distributed generation and storage becomes more prevalent across every level of the grid. A bottom-up, interconnected SHS network could build in this functionality from inception, saving money and effort in the long term.

3) *Financial flexibility for individuals*

Many SHSs and minigrids rely on a pay as you go business model or microfinance to fund their operation. The risk of failure to pay is a significant barrier to the commercialization of this technology. An interconnected SHS network provides a platform across which peer to peer energy trading can occur, where prosumers can export surplus to other users willing to pay for this. This platform/market offers an opportunity for prosumers to generate income directly from the sale of their excess energy, or help them meet payments in difficult times by reducing their electricity demand (and focus on selling rather than consuming energy) rather than losing access altogether.

4) *Connect new customers with no generation*

The cost of a solar home system is dominated by the batteries and panel [3]. Individuals who cannot afford to invest in a full SHS (i.e. panels and battery storage) could instead connect directly to the network via a less expensive controller and converter; allowing them to purchase excess electricity from other connected systems without the need for significant capital outlay. The quality of service may not be as good as an SHS might provide, as there may be times when all systems of the network may be unwilling to export (sell) energy, but this first step may be an effective method to spread the cost and facilitate quicker and more cost effective electrification for those who cannot afford to purchase a complete SHS (while offering income generation opportunities for those willing to sell). This could potentially give rise to the situation where for some locations with a high density of interconnected SHSs, it may make sense for new customers not to buy a SHS at all and simply pay for a connection. This could also be used to connect new load centers without energy access to minigrids with excess energy. For example, small enterprises, with moderate to high demand, but with limited capital to invest an off-grid solution of their own, could utilize and benefit directly from this pooled energy resource and unlock business opportunities within local communities, while also providing income generating potential for prosumers in the sale of energy.

5) *Flexible investment*

Investment in the required technology to interconnect systems can be undertaken incrementally, targeting locations with basic electricity needs and where the greatest benefit may be delivered; such as those with varied demand or generation profiles located close together. Initially, access can be provided quickly and cost effectively with SHSs.

There is a documented trend in growth of energy consumption over time as human development increases [4]. As such, this bottom-up approach can offer a cost-effective method of ensuring the energy infrastructure evolves at a rate in accordance with growing demand. Phased interconnection of SHSs or microgrids can be implemented to gradually increase mini-grid capacity. Additional, centralized generation could then be added to the mini-grid, with grid-to-grid interconnected offering the potential to further increasing diversity of demand. Ultimately, this network of mini-grids could then be integrated into a national grid where appropriate.

These upgrades can be undertaken incrementally and can adapt to the changing consumption patterns and need of each community. Though not suitable in every situation, e.g. over large distances or between grids with low diversity, interconnection offers an additional path to grow and upgrade systems over time. In order to fully take advantage of the potential benefits offered by interconnection, a suitable planning methodology is required, involving detailed numerical modelling, real world experience and design tools.

B. Barriers to Interconnection of SHSs

1) *Standards and compatibility*

Well defined and widely adopted standards for voltage levels, connectors, communications protocols and many other factors are crucial to the adoption of interconnected SHS networks. It is desirable that two systems can be connected as quickly and easily as possible, with the minimum technical expertise required, to reduce costs and allow individuals and communities to have more agency in their own energy.

There are no internationally accepted standards for the application of Low Voltage Direct Current (LVDC) microgrids, although the IEEE Standards Association is developing a new standard for this [5].

2) *Distance and diversity*

The value of interconnection is dependent on a number of factors, but the most important are the distance between the interconnected systems and the level of diversity that exists between them.

$I^2 R$ losses between two systems are a function of separation distance. For a given conductor cross-sectional area, the resistance of a line grows linearly with distance. It is often desirable in such systems to use DC voltages less than 48VDC where possible to ensure touch safety, so resistive losses will be significant for longer distances.

Further investigation is required of the level of diversity and proximity of loads required to make an interconnected LVDC network an effective intervention.

3) *Commercialization*

In order to be widely utilized, the technology must not only present a positive socio-economic impact for consumers, but also be financially viable. There are a number of potential business models for interconnection, including PAYG with a centralized pool operated by the network owner, Peer to Peer selling with a transaction fee, microfinance or a flat rate subscription.

In order to ascertain the best approach, market research, pilot projects and detailed techno-economic modeling are required, with an understanding that there will most likely be a range of suitable solutions depending on the specific social, economic and geographical context.

III. FEASIBILITY STUDIES FOR BOTTOM-UP ELECTRIFICATION IN RWANDA

This section of the paper aims to identify potential for bottom-up electrification in Rwanda; a country currently experiencing a significant growth in off-grid systems. Presented data represent a village with a particularly high density of SHSs.

The statistics were produced based on data captured by a BBOXX Smart Solar remote monitoring system.

A. *Smart Solar Remote Monitoring System*

Most of the SHS distributors in Sub-Saharan Africa use remote monitoring systems to visualize consumption patterns associated with their customers. It also gives an opportunity to manage the customers' use of the SHS based on their payment plan.

Data exported from Smart Solar was crucial in illustrating demand diversities for BBOXX customers as well as enabling several simulations to be conducted to explore the potential of bottom-up electrification.

B. *Typical Energy Usage by BBOXX Customers and Business Model*

SHSs distributed by BBOXX aim to provide electricity for Tier 1 and Tier 2 customers. A standard PV module is rated at 50W. The battery used to meet demand at night or at the time of low solar irradiance is rated at 17Ah. The energy consumed by BBOXX customers varies depending on the number of appliances connected as well as the duration of operation. Basic appliances used by SHSs users together with their power ratings are illustrated in the Table 1.

TABLE 1: STANDARD ELECTRICAL DEVICES OFFERED BY 50W BBOXX SHS

Device	Quantity	Power Rating (W)
Light Bulb	3	1.1
Radio	1	0.75
Phone Charger	2	2-4
TV (Optional)	1	8

The operation time of each of these appliances depends on the individual needs of customers. Average generation capability for a single SHS located in Rwanda is around 200Wh/day which satisfies the basic demand of BBOXX customers. Despite this, SHSs users may still experience power shortages as a result of their disconnection due to exceeding contracted maximum daily energy consumption limits (typically set to around 50 Wh per day). Once this threshold is reached, the charge controller deactivates the SHS until the battery state of charge recovers back to the pre-disconnection threshold level. If the customers are willing pay to increase their daily electricity consumption (capacity) limit, they must first contact the SHS supplier who can offer a new tariff for this increased capacity limit.

C. *Statistics gathered from the Remote Monitoring*

This section of the paper illustrates results gathered from analysis of energy consumption patterns in a village located in the eastern part of Rwanda, where the estimated distances between SHSs users is approximately 30 meters.

The total number of installed SHSs in the case-study village is 117, however, for the studies performed, only

81 SHS customers were considered. Results presented are valid for a period between May and July 2017. Several parameters were considered while building these statistics, such as:

- Daily Energy Consumption - total energy that customers consume over 24 hours (Figure 1).
- Percentage of Energy Consumed directly from the PV Installation – rate of energy which is consumed by a customers and by-passes the battery (Figure 2).

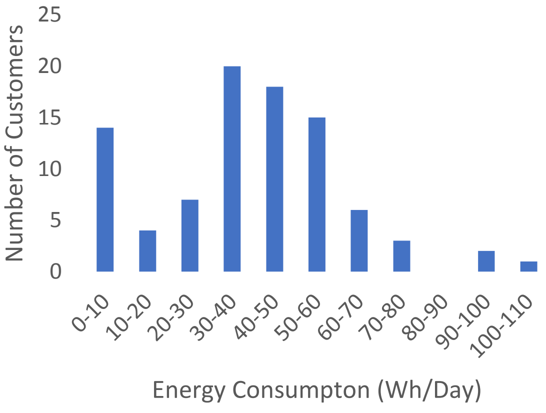

Figure 1: Daily Energy Consumption for Customers

Figure 1 presents significant diversity in demand between BBOXX customers varying from 0-10 Wh/day up to 110 Wh/day. For those with the lowest energy consumption, SHSs are typically used just for Tier 1 activities. According to the data gathered from the village, customers with the highest demand requirements consume between 90 – 110 Wh/day. Large variations in demand between BBOXX customers may result from the number of people living in a house as well as variations in the types of appliances connected to the SHS installation and their time and duration of usage.

The next set of statistics gathered illustrates the rate of electricity consumed which by-passes battery. This data is particularly important as it represents the balance between energy demand during day and night. For customers consuming most of their energy during the day, microgrids based on interconnected SHSs could bring additional benefits. They could make use of surplus stored electricity to feed Power Consumers (villagers without generation or storage capability) who are willing to consume energy for the most basic activities.

By introducing a local energy pool, the cost of energy would depend on the available supply capacity as well as demand. As a result, the highest cost of energy would typically occur in the evening, when available generation is at its lowest (or at zero), while the energy demand in the village is at its peak. Customers with a surplus of energy in the evening could now become active exporters with the potential to generate additional income. P2P energy trading between SHS customers could also result in introducing competition amongst prosumers (i.e. those with the capability to produce and consume power). Customers with high peak demand could reduce this in order to maximize revenues from selling electricity on the local energy pool. More evenly distributed demand profiles could also have a positive impact on the performance of the batteries and their longevity.

The diversity in energy consumption during day and night is illustrated in the Figure 2.

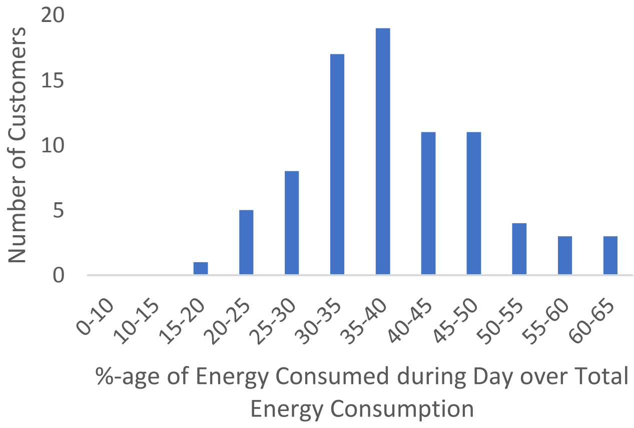

Figure 2: Percentage of Energy Consumed Directly from PV

According to statistics seen in the Figure 2 for the village, around 30-45% of overall energy is typically consumed during day.

Figure 2 shows that some SHS users consume significant portions of energy after sunset, when their energy supply relies purely on the battery. Significant imbalance between depth of discharge of the batteries may lead to variations in 'state of health' of energy storage devices between BBOXX customers. By introducing interconnected SHSs microgrids these variations could be mitigated. Villagers currently remaining with energy surplus could potentially share surplus electricity with those where there is evidence from remote monitoring data indicating overstressing of their batteries. As a result, the overall supply reliability could be improved as the loss of load probability due to battery failure is reduced.

Despite benefits resulting from sharing energy more evenly in an interconnected SHSs microgrids, peak power demand for individual customers could also be more evenly distributed. As a result, maximum peak demands could be reduced, improving the overall performance of the system.

Average demand across seven days for seven chosen village SHSs, as well as average power consumption per customers after interconnection are illustrated in Figure 3.

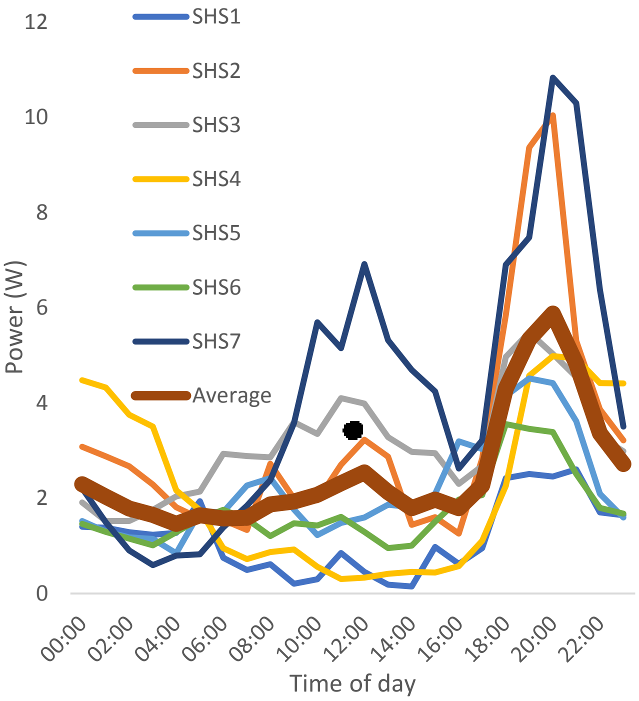

Figure 3: Demand Profiles for Seven Village SHSs

Figure 3 shows the maximum demand for a standalone SHS occurs for customer 'SHS 7' at around 11W. After interconnecting all customers in order to 'shave' the peak demand, maximum power consumption for 'SHS7' could potentially drop to around 6W.

Other benefits resulting from providing interconnection between SHS customers is a capability to add larger electrical appliances which are currently limited by the size of standalone SHS installation. According to analyzed profiles based on the 81 SHSs studied, around 65% of generated energy is currently unused. This unused energy could be offered for customers willing to add electrical devices such as fridges (estimated energy consumption 200 - 300 Wh / day), fans (estimated energy consumption 200 - 400 Wh/day), big TVs (estimated energy consumption 90 – 150 Wh/day).

The capacity which is currently unused could also be utilized by those customers that currently do not have access to electricity at all. They could potentially have a chance to buy energy from the local energy pool by purchasing a connection agreement, and without the need to invest in a full SHS system of their own although they would have no capability to earn revenue from the exporting of power. Only those with SHSs can export power and generate an income from selling energy. This ensures there is still a clear incentive for those with the financial capability to invest in an SHS as a means of income generation. Adding consumers equipped with the basic appliances, together with growing demand amongst prosumers could reduce system reliability. In order to estimate the impact of adding power importers to the microgrid it is required to find the rate of demand growth within the network of interconnected SHSs. Energy consumption data was extracted from the BBOXX Smart Solar Remote Monitoring System for a 3 months period and is illustrated in Table 2.

TABLE 2: AVERAGE ENERGY CONSUMPTION PER HOUSEHOLD

Month	Energy Consumption (Wh)
May	1624
June	1637
July	1656

The results presented in Table 2 indicate a slow rise in energy demand. It could be a result of the addition of more electrical appliances by consumers.

A function estimating the future energy demand, based on the analysis of past demand was generated. The demand growth trend was assumed to be linear, with an average growth extrapolated based on measurements listed in Table 2, when the total demand in the village has been growing by around 1% per month.

D. *Loss of Load Probability for Interconnected SHSs Minigrids*

This section illustrates the influence of adding consumers to the microgrid which could potentially be formed by interconnecting the SHSs in the village case-study under consideration. This part of the analysis does not consider any network constraints or losses while exchanging power within the system. It also ignores the efficiency of the batteries used by BBOXX customers.

Assuming that consumers connected to the network (without capability to generate or store energy) are those with the lowest energy requirements (i.e. Tier 1/2), the estimated demand for this group of customers is listed in Table 3.

TABLE 3: TYPICAL DEMAND TIER 1/2 IMPORTERS

Appliances	Power Rating (W)	Time (h)	Energy (Wh)
L. Bulb x 3	1.1	4	13.2
Charger	4	2	8
Radio	3.7	4	14.8
Total			36

Based on the demand listed in Figure 2, and statistics gathered from the village, relating to average demand and its daily variations, relationship between the number of consumers/prosumers and loss of load probability over time is illustrated in Figure 4.

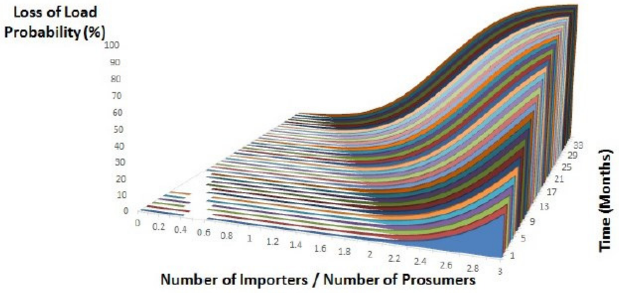

Figure 4: Loss of Load Probability after adding Importers to the Microgrid.

According to Figure 4, it is possible to add a significant number of customers with the lowest energy requirements in order to make use of unutilized energy. The loss of load probability slowly grows over the time for a high ratio of consumers to prosumers. Data illustrated in Figure 4 is based exclusively on average generation capability by the SHSs. In order to further improve the accuracy of the estimation, it is required to consider the stochastic nature of power generation on a daily basis as well as seasonal demand variation. Other aspects requiring consideration involve technical constraints, such as losses in the network as well as maximum power transfers between prosumers.

It is also important to distinguish between the generation and storage capabilities of the systems. Figure 4 considers a case where 100% of energy could be utilized. In a practical case, this could never be reach due to the storage limitations as well as efficiency of the batteries.

E. *After Diversity Peak Demand of Interconnected SHS Micro-grids*

An important metric when designing a power system is the peak demand. Generation, storage and conductors must be sized to ensure the optimal ratio of cost and reliability in the system.

Average peak demand per house was simulated for a year, using a Monte Carlo based model. Each house was modeled as having an hourly probability use for each load, derived from load data in Table 3. For each hour of the year, a random variable was drawn and compared to the chance of load for that hour to determine if each load was in use. The peak demand experienced in this year was then recorded. This process was repeated for each year 10,000 times and the peak demands averaged to give an average diversity adjusted peak demand.

The number of identical houses was then varied from 1 to 200, and the peak demand per household calculated.

Figure 5 shows the result of this simulation, with average peak demand for a single house equaling 11Wp (the total installed demand). The average peak demand falls quickly as more houses are connected to the system, demonstrating that even systems with identical demands and demand profiles exhibit benefits from diversity due to the stochastic nature of energy demand.

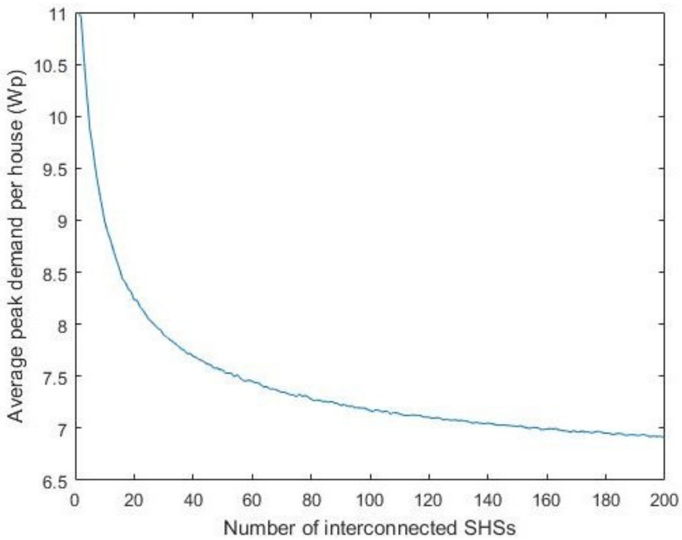

Figure 5. Average diversity adjusted demand per household for a micro-grid of interconnected SHSs

IV. CONCLUSION

Interconnection of SHSs has the potential to be an effective route to climb the energy access tiers for millions of consumers across the world. The benefits of this approach could be significant, with more reliable energy system, better utilization of assets and contextual and incremental investment.

We have shown that there is significant demand diversity within a real world community operating SHS. Connecting these systems using low cost, low voltage distribution networks offers an opportunity to connect new customers and facilitate demand growth for existing consumers.

Much work is still required analytically, in simulation and in real world case studies in order to prove the viability of this approach in a real implementation, but the data presented within this paper, demonstrates that this is an area meriting further investigation.

ACKNOWLEDGMENT

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