SIMbaLink: Towards a Sustainable and Feasible Solar Rural Electrification System

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***Abstract*—Rural areas lack sustainable electrification solutions. Although solar solutions hold promise, they are fundamentally constrained by high maintenance costs (due to low user densities, equipment failure, poor handling) and a complete lack of accountability. In this paper, we describe our experiences deploying more than 5,000 Solar Home Systems in Ethiopia and the sustainability problems we faced. Towards developing a decentralized and sustainable solar solution, we have designed SIMbaLink, an extremely low-cost real-time solar monitoring system that significantly reduces both the maintenance costs and the time to repair. By explicitly exposing the real-time status of a solar system to all parties concerned, SIMbaLink addresses the lack of accountability and trust concerns. SIMbaLink can be easily integrated with existing solar systems and can reduce equipment failure rates through early detection of system malfunctions.**

I. Introduction

The International Energy Agency estimates that 1.6 billion people worldwide do not have access to electricity [1]. Basic electrical lighting brings safety, opportunity, and hope. A business with reliable electricity can operate for four extra hours per day; a student can study longer; classrooms operating at night can provide adult education to communities. Access to light can elevate a household's income from mere subsistence by providing opportunities for education and entrepreneurship. For the majority of the developing world the setting sun still necessitates the harmful and unsustainable burning of wood, dung, or kerosene to provide even a dim light. In Sub-Saharan Africa (SSA), less than 10% of the rural population have access to electricity [2].

Grid-based electrification is not viable in developing regions with low population density and purchasing power. Connecting to the grid is cost-prohibitive in remote and sparsely-populated areas [3]. As a result, renewable energy technologies have become increasingly prominent in rural electrification initiatives. Developing countries currently consume 40% of the world's total renewable energy capacity, and 2.5 million households utilize solar lighting systems [4]. However, SSA has a highly under-capitalized potential for wind, solar, and bio-diesel power. The primary barriers in the region are price distortions created by weak regulations, inefficient distribution infrastructure, and high operational costs.

In this paper, we investigate SIMbaLink's potential to make solar a sustainable and decentralized rural electrification solution. Since 2006, we have been working with Stiftung Solarenergie (also referred to as Solar Energy Foundation or SEF) to deploy more than 5,000 Solar Home Systems (SHS) across different rural regions in Ethiopia. Our experiences have shown that one of the fundamental roadblocks to sustainable and scalable solar electrification has been high maintenance costs induced by several factors: high equipment failure rates, poor maintenance/rough usage practices, high fixed maintenance costs due to travel, low user densities in sparsely populated areas, and a severe lack of accountability in the system. This remains a serious impediment to the sustainability and profitability of solar businesses. Routine maintenance is critical for solar systems to function for their expected 20-year life span.

SIMbaLink's key function is to make solar sustainable by reducing operational costs while extending the life span of the SHS and reducing the initial cost to the rural homeowner. The SIMbaLink module is an add-on device to a standard SHS that enables a solar business to remotely monitor their installed systems. The module interprets states from the solar panel and the charge of the battery in order to diagnose the health of the SHS. The data is transmitted over GSM networks to a regional technician, allowing early detection of problems and reducing the number of in-person maintenance visits. Constant communication between the solar provider and the homeowner increases accountability and transparency between parties. The solar provider is ensured of receiving full re-payment of loans in return for providing proven reliable systems. The homeowner now has an increased incentive to employ proper usage practices, thereby extending the life span of their SHS.

SIMbaLink also creates the potential for solar cooperatives and entrepreneur-driven solar mini-grids that leverage the aggregate purchasing power of the rural population. Clustered households, forming a cooperative, can share the initial cost of a higher capacity solar PV system and meter each household's usage through the SIMbaLink module – a model that prevents abuse and enforces fair use. An entrepreneur in a densely populated region can invest in a solar PV system and create a micro-market for solar power, with customers paying to charge lamps and mobile devices. Both solar cooperatives and entrepreneur-driven solar mini-grids increase access to solar electrification solutions to even the poorest households in the region.

Based on our cost analysis, we find that the introduction of the SIMbaLink module reduces routine maintenance cost by a factor of 11, and the cost of equipment replacement by a factor of 4 (5 for social entrepreneurs), by reducing required maintenance visits and rates of equipment failure through daily remote monitoring.

In the rest of this paper, we describe the design and operation of the basic unit of solar power in rural areas – the Solar Home System (SHS) – and outline the primary problems with its installation and maintenance based on our experiences in the field. Next, we discuss in detail how SIMbaLink operates as a solution to the problems previously outlined. We then provide a detailed cost analysis of the impact of SIMbaLink on solar rural electrification and discuss its future implications.

II. Rural Solar Electrification Strategies

Sub-Saharan Africa receives an average of 6kWh per square meter a day in solar radiation and has 325 days of strong sunlight a year [5]. By 2007, more then 500,000 solar home systems were installed in the region. More than half of these are installed in Kenya and South Africa [4]. Solar initiatives are currently undertaken by nonprofit organizations and solar companies through two main strategies. The more established strategy is project-based and involves organizations competing for funding from development institutions and/or local governments for a solar initiative that usually involves the donation of residential SHSs or larger systems for schools, clinics, and other public buildings. The Solar Electric Light Fund (SELF) is a nonprofit organization that has achieved considerable success with this approach. SELF operates in more than 20 countries worldwide and has been involved in several large-scale solar initiatives that range from SHS installation to solar-powered irrigation. However, the use of donor funding to finance the capital and installation costs of an SHS creates limited or no accountability for the household or public building. Also, short-term project initiatives do not create the infrastructure needed to support the long-term maintenance needs of the installed systems.

A second strategy utilizes the micro-finance model to establish the infrastructure for a sustainable solar market in rural developing areas. In the micro-finance model, a household pays for their SHS in micro-payments over a predetermined period of time. Their ownership and investment in the system creates an incentive for the homeowner to properly maintain and use their system. This also encourages the growth of entrepreneurship by allowing homeowners to make a return on their investment. The systems are maintained by a local trained technician employed by a solar business or nonprofit. Stiftung Solarenergie (Solar Energy Foundation, hereafter SEF), a German nonprofit organization, has installed 5,000 SHSs in Ethiopia based on this strategy. In addition to their work in Ethiopia, SEF has expanded to the Philippines and Kenya, where they have established relationships with micro-finance institutions. SEF also sells products to customers in Nigeria and Senegal. The success of SEF's approach is also seen in Tanzania, where Zara Solar Ltd., a solar company started by a local entrepreneur, sells SHSs to rural Tanzanians. In 2010, Zara Solar and its sister company, Mona-Mwanza Electrical & Electronics, had sold more than 3,600 solar PV systems [6].

III. Solar Home Systems

Solar rural electrification systems can be designed in various configurations, tailored to a variety of energy needs and situations. The most basic of these configurations is a stand-alone solar home system (SHS). The SHS model has several advantages over other solar electrification strategies. First, an SHS is small scale, which makes it significantly easier to install for both the customer and the provider. Second, a stand-alone SHS requires less maintenance than large-scale PV installations. Third, the SHS is modular and affordable for poor rural households, as increased capacity can be added to the system after initial installation.

A typical SHS consists of photovoltaic (PV) panels, a battery, a charge controller, and several loads (appliances). The battery stores energy collected by the panels, the charge controller prevents the battery from being overcharged, and the loads (typically some combination of two or more LED lamps, a small radio, and a mobile phone) draw power from the system. The solar home systems sold by the Solar Energy Foundation (SEF) follow this basic model and include a 10-watt PV panel, 4 LED lamps, and a sealed box containing both the battery and charge controller with an outlet for mobile-phone charging. In addition to these stand-alone home systems, SEF has successfully deployed several portable lighting solutions with small 1.5-, 2-, and 5-watt PV modules that connect to one or more LED lamps with a battery encased in the body of the lamp.

A. Deployment in Ethiopia

In the past five years, SEF has deployed more than 5,000 solar systems throughout several rural regions in Ethiopia and has experienced a wide range of maintenance and reliability problems that have affected the functioning of the deployed SHSs.

The majority of SEFs systems were purchased by the homeowners through a micro-finance loan agreement, with payments collected annually for 3 to 5 years. 2,700 of the SHS owners have already successfully paid off their SHS loans. The cost of the system includes installation and yearly maintenance over the duration of loan period. During the annual maintenance visits, the technician provides customer-relations services, such as the dissemination of information about new products and services, along with routine maintenance. At present, the routine maintenance procedure consists of checking the condition of the PV panels and battery, as well as checking the cable connections between all components in the system. The technician might also clean the panels, reposition them if necessary, and remind the homeowner to do the same on a more regular basis if the condition of the panels shows that the homeowner is not performing either of these basic maintenance tasks. They also check the status of the battery, replace it if necessary, and query the homeowner about the household's daily energy use and alert them if they are inadvertently misusing the system. These maintenance visits occur annually because ongoing system monitoring and battery replacement is not only critical to the functioning of the SHS but also secures the value of the investment for the customer by ensuring the SHS's functionality.

B. Deployment Problems

The importance of after-sale product maintenance to the long-term sustainability of the solar market cannot be overstated. In rural areas where in-person maintenance is too costly to be deployed adequately, remote, automated monitoring, such as the solution proposed by SIMbaLink, becomes the key to laying the groundwork for an infrastructure of after-sale maintenance. Preventing equipment failure improves customer satisfaction and ensures the full payback of a loan. [7]

We experience five types of deployment challenges:

1) Equipment Failure: The battery is the most frequent point of failure in an SHS. Under ideal usage conditions, a typical SHS battery would need to be replaced every 3 to 4 years. Based on our field experience, inadvertent misuse by the SHS owner causes the battery to fail much earlier, shortening battery life by as much as 75% in some cases. Misuse occurs when a load, such as an LED lamp, is left to run continuously. This will over-drain the battery and prevent it from returning to a fully-charged state between charge cycles. Another common case of misuse is the connection of devices that are not intended for the system. Constant monitoring of a battery's state of charge can tell the system to stop outputting voltage when it reaches a level that is potentially damaging to the battery [8]. The climate in many parts of SSA can be extremely hot, dry, and dusty, which can affect the productivity of the panel and create additional wear and tear to the equipment.

2) Fixed Cost of Maintenance Visit: The majority of our installed SHSs are located in sparsely populated and remote areas that have limited accessibility due to bad roads and other factors. The geographical distance between houses in sparsely populated areas increases the cost of maintenance visits by increasing a technician's travel time, work hours, and fuel costs. For example, SEF bought additional vehicles at a cost of $30,000 each and individual motorcycles for rural staff at $2,000. In addition, a technician is unable to determine what components of an SHS need to be fixed or if the SHS needs any repair at all until they have reached the SHS owner's house. This lack of information increases the number of unnecessary maintenance visits and increases the overall cost of operations for the solar business.

3) Time to Repair: In our experience, a non-functional SHS has already been broken for several months by the time a technician arrives at a site. The delay between system failure and a technician's visit creates a tension in customer relations and leaves the SHS owner unsatisfied with their experience with solar power. It is currently not feasible for a technician to diagnose the original cause of a problem. However, the situation could be improved by an increased frequency of maintenance visits, but the additional operational costs would be unsustainable for the solar provider and increase the cost for the homeowner. To address this issue, we tested a possible solution using RFID tags that stored battery-use information daily. Although this solution did allow the technician to diagnose the problem accurately, the tags still had to be collected in person, which did not solve the problem of time delay. In addition, the RFID tags increased the overall cost of the SHS by $70. To reduce the time until the system is repaired, we require a monitoring system that records and transmits system diagnostics daily.

4) Lack of Accountability: Lack of accountability occurs at two levels: (a) between the homeowner and energy provider; (b) amongst a community of homeowners sharing power. In the first case, when equipment failure occurs, the question remains as to which party (homeowner or provider) is accountable. This situation is exacerbated by the typically lengthy delays between the time of system failure to system repair, which is often necessitated by the provider's need to limit annual maintenance visits to an area in order to reduce overall maintenance costs. The second type of accountability problem occurs amongst users in a shared-SHS setting, wherein the fundamental problem is one of trust. When a battery is completely drained in a shared SHS due to excessive usage, the user who is the primary cause may remain unknown; this creates a basic lack of trust that may become irreparable with time. In a specific case that occurred in rural Ethiopia, three families shared the cost of a PV system purchased on loan, and within a year they had stopped payment on the loan due to a dispute over the use of the battery. To improve both forms of accountability, we require a monitoring system in place to constantly measure the effectiveness of an SHS and the individual usage of each user in shared settings.

IV. Sustainable Solar Home Systems

Based on our experiences in the field, the difficulty of achieving low-cost and timely maintenance has been one of the most significant roadblocks to building sustainable SHSs. We believe that the most efficient SHS maintenance model relies on near real-time remote monitoring that allows the provider to constantly monitor the health of an SHS. This approach provides several benefits while also directly addressing the four primary deployment problems we have faced. First, in order to maximize the life cycle of an SHS, continuous monitoring of the system is essential for detecting early signs of equipment malfunction, thereby reducing the chances of equipment failure. Second, remote monitoring eliminates the need for unnecessary maintenance visits and allows technicians to address problems in a timely manner. This, in turn, significantly reduces fixed maintenance costs and time to repair. Through constant monitoring and feedback and the active involvement of both the SHS owner and maintenance provider, SIMbaLink aims to make rural solar energy reliable, efficient, transparent, and more easy to maintain.

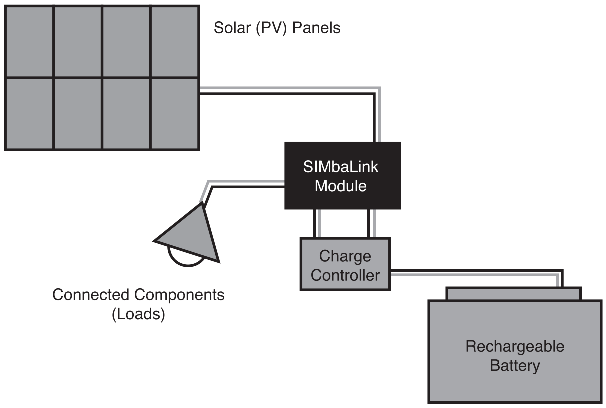

Fig. 1. A diagram of the integration of SIMbaLink with the other components of a solar home system.

A. Prototype Design

The SIMbaLink prototype intercepts connections between the battery, solar panel, and charge controller in order to take readings from each component. The prototype consists of a voltage divider circuit, a GSM module, and a microcontroller. The voltage divider circuit reads the voltage from the battery, panel, and load and scales it to under a 5V threshold, which is the capacity of our microcontroller, the Arduino. The microcontroller reads the voltage through its analog inputs and converts them into a text message that is sent every 20 minutes by the GSM module. We are currently incorporating the SMSAppStore in order to be able to encode a full day of readings into one SMS message. The important system readings that we gather are the panel voltage, battery voltage, battery amperage, load voltage, and load amperage. Based on an algorithmic analysis of this logged data, SIMbaMain is able to determine if the SHS is functioning properly and diagnose the overall health of the system.

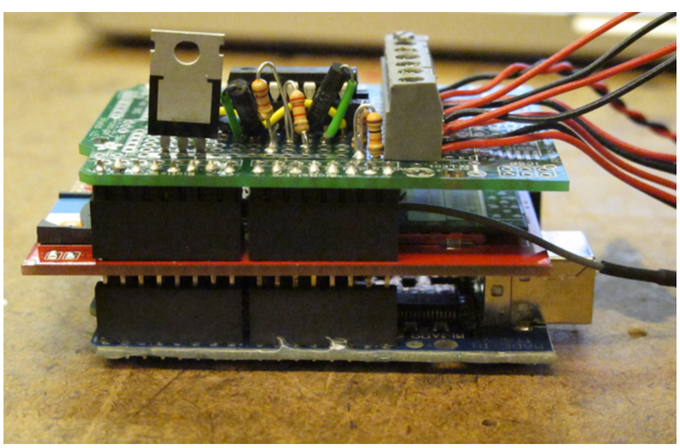

Fig. 2. SIMbaLink's current prototype

1) Voltage Divider Circuits: The voltage divider circuit intercepts the panel, battery, and load outputs from the charge controller. A 10,000 Ohm and a 2,200 Ohm resistor are tied in series from an input voltage to ground. The circuit then taps in between these resistors to provide a voltage that is effectively 18% of the original component's output, in order to make it readable by the SIMbaLink module. The Arduino microcontroller runs at 5V, which is much lower than the voltage output from an SHS. As a result, we use these circuits to safely bring all readings under a 5V threshold by scaling voltages between 0-27.75V into a 0-5V range.

2) GSM Module: The SIMbaLink prototype currently uses the SM5100B as its GSM module. It requires a SIM card and has all the functionality of a mobile phone, stripped of a battery, screen, keypad, earpiece, and microphone. We programmed the module using the (C/C++-based) Arduino language. In the next prototype we will incorporate the SM5100Bs chip into a single printed circuit board in order to cut costs.

3) Microcontroller: Our microcontroller is currently the Arduino Duemillanove board. In addition to producing microcontroller hardware and the free open-source software to run it, Arduino is an open-source community with a strong supply of libraries that make it robust yet simple to program. The SIMbaLink module uses the Arduino's 6 analog inputs to read the voltages pulled by the voltage divider circuit. Our software converts the 8-bit (values between 0-1023) readings into actual values after they are sent to the server.

B. Data Transmission

The SIMbaLink module takes readings on a time schedule as determined by the SIMbalink software. In August of 2010 we will begin using SMSAppStore [9] for our data transmission. SMSAppStore supports a semantic compression engine that leverages the structured nature of the information being transmitted and is designed to support database-centric applications that express and operate upon information in structured formats. SMSAppStore opens up the 140 bytes available in an SMS at the bit level, making 1120 bits available to be sent. Once the data from SIMbaLink is compressed, it is pushed onto the 1120-bit stream that is the content of the SMS message. The SMS message is sent only when the stream has been completely filled, providing the most information in the fewest messages and reducing costs by minimizing the number of SMS messages that need to be sent. SMSAppStore also allows SIMbaLink to do a period of intense data readings, for instances when a more thorough analysis is needed. Currently we are able to send more than 25 sets of readings in a single SMS message.

The SMS message is received by a USB 3G Mobile Broadband Modem connected to a computer with Internet connectivity. The computer also runs the open source WAP and SMS Gateway software, Kannel, in order to continuously check for incoming messages. When an SMS message is received, our server-side SMSAppStore script retrieves the content of the message, decodes the message, then sends the readings to another script that uploads the data to our database. When the data reaches the database, it is analyzed by our

SIMbaMain software in order to diagnose the health of the SHS.

Fig. 3. A test deployment on the roof of 319 Scholes, a building in Brooklyn. Deployment from June to July 2010

C. Data Analysis

Figure 3 illustrates one of our test deployments of four 32W SHSs. We ran the systems under various conditions in order to test the performance of our first prototype. The SHSs are each comprised of a 32W solar panel, a 20Ah lithium-polymer battery, and a EPRC-ST solar charge controller. The interaction between the panel, charge controller, and battery are important to an understanding of the health and functionality of an SHS. Solar panels are rated by watts output per hour under peak conditions and should be paired with a corresponding battery of sufficient size to power devices between charge cycles without being drained too severely or prevented from returning to a fully-charged state on a daily basis. Consequently, a history of battery health, particularly when compared with other identical systems, can allow us to extrapolate overall system health, as well as changes in usage patterns.

1) Battery Misuse: Figure 4 shows the output voltage of a battery charged during our test deployment. The healthy battery shows voltage levels between 12V and around 14V. (The load was turned on at 5:30pm). SIMbaMain analyzes the battery's highest state of charge over its entire life cycle and issues a warning when peak levels diminish. A misused battery would show a declining average highest state of charge over time [10]. The software also monitors an SHS's battery levels from midnight to dusk, in order to check if it is being over-drained, which is an indicator of misuse (keeping a light on all night, for example). If a reading taken at midnight returns the battery's state of charge to be 11.5V, the system sends an alert text message to the server and shuts itself off, as 11.5V is too low a state-of-charge for the battery. The module may determine that the likely cause of the low reading was atypical and may prevent devices from drawing from the battery until it is fully charged again.

2) Panel Failure: Solar panels require constant cleaning to maximize their utility and life cycle. Productive capacity drops when dust or film accumulates on their surface. Concentrated areas, sustained over a period of time, can lead to failure of an entire segment of a panel. Every panel has a rating factor which indicates its expected readings under healthy conditions. A constant read of the expected value is a strong sign that the panel is functioning well, whereas a sudden dip or a consistently low reading during daytime is a sign of a potential problem. The underlying causes for a dip in the power output of a panel can be one of several: an unclean panel, a faulty battery, poor climate conditions, improper panel orientation. In such a situation, SIMbaLink can send a text message to

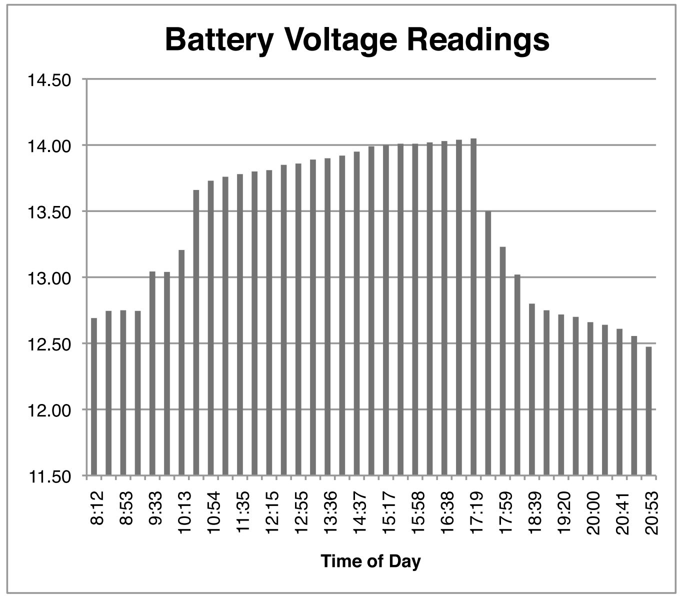

Fig. 4. These are sample voltage readings that were gathered from our test deployment in Figure 3. Voltages were measured on June 26.

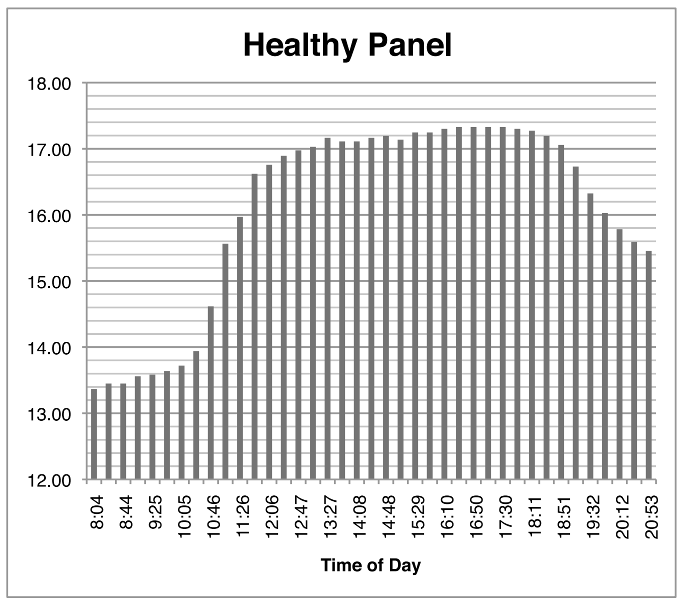

Fig. 5. These are sample voltage readings that were gathered from our test deployment in Figure 3. Voltages were measured on June 30.

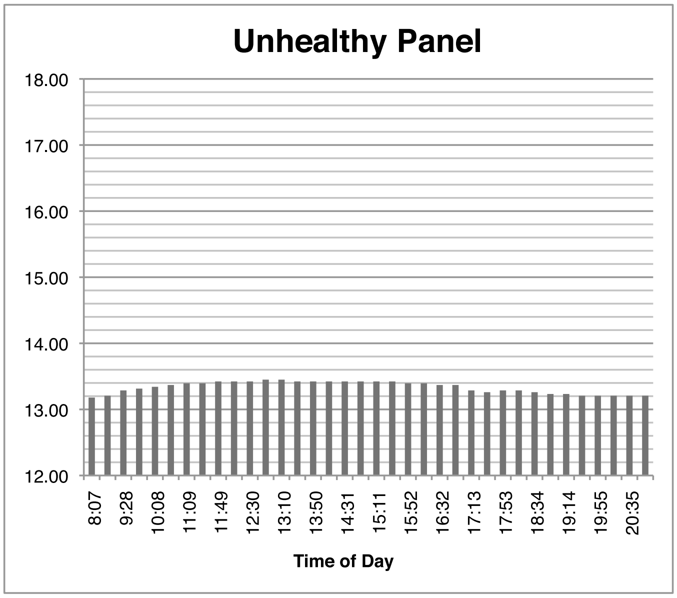

Fig. 6. These are sample voltage readings that were gathered from our test deployment in Figure 3. We covered 50% of the panel with reflective material to simulate panel failure. Voltages were measured on June 30.

the owner to alert them of the problem and instruct them to clean the panel and check the panel's orientation. If the problem persists, the system can alert a technician, who may then schedule an in-person maintenance visit.

Figure 5 and Figure 6 compare the voltage readings from a healthy panel to a panel that has stimulated failure. Both sets of readings were taken on the same day, which was sunny and slightly overcast. In order to fully diagnose panel failure, our software compares a panel's readings to local weather conditions and monitors the system for three days after warning signals occur before maintenance action is taken.

3) Charge Controller Failure: Charge controllers vary from system to system, but they all regulate current from the panel to the battery until it is fully charged. At that point they either cut power completely or transmit the minimum energy needed to keep the battery topped off. If the SIMbaMain software is not receiving expected readings from the SIMbaLink module, such as erratic, higher, or lower voltage and/or amperage, then the possibility of charge controller failure is addressed by a maintenance visit.

4) SIMbaLink Module Failure: The SIMbaLink module will be encased to withstand harsh climatic conditions and is currently in a state of minimal sensitivity to wear and tear. However, failure is always a possibility. During our test deployment, we ran two modules that had blown their current-sensing resistors. The readings from the broken modules ranged between erratic figures to 0, clearly showing that the module was not reading accurately. In this case the SIMbaMain software would issue an immediate warning for a technician to visit the site and replace the broken components. The points of failure in the SIMbaLink module are the resistors and connections, all of which are the least costly components to repair.

D. User Interface

The SIMbaMain website an easily accessible platform that contains in-depth information regarding each individual SHS, from daily diagnostic readings to system location, homeowner, and loan-payment information. The website displays an easy-to-read bar graph, updated daily, that shows the system's readings by date and time and also provides a broader view over weeks, months, and years. Each SHS is tagged according to its most recent data readings (under an appropriate label, such as ”Healthy,” ”On Alert,” ”Maintenance Required,” or ”System Failure”), and a technician signing in to view the SHSs that he or she is responsible for is immediately alerted to any system that has had a major change in status. All SHSs are routinely classified as ”On Watch,” requiring the technician to sign off on a system's recent status before it can be removed from this ”On Watch” list. This guarantees that each system's data is regularly reviewed and problems are properly tracked.

The technician is also able to send an SMS directly to an SHS in order to increase the frequency of data gatherings or to run an intensive 24-hour diagnostic on that system. The software also groups SHSs geographically, so that technicians can plan maintenance visits in a way that maximizes time, materials needed, and operational costs. There are also other benefits to visualizing the data in a geographical way. For example, if several homes in the same area are taxing their systems, the technician can organize an educational seminar for the homeowners.

E. Limitations

1) Availability of GSM: Since 2003, Africa has become the fastest growing mobile market in the world. Mobile penetration ranges from 62% to 3% across the continent. Only Ethiopia, Somalia, Burundi, Djibouti, the Central African Republic, and Eritrea have less then 10% penetration [11]. This growth is projected to increase [12] due to heavy private investment, the subsidization of mobile phones, and the exercise of aggregate purchasing power in poor rural communities. The presence of GSM networks provides a unique opportunity to reach the rural consumers that were previously inaccessible without high operational costs. For solar companies and nonprofits operating in the region, remote access to their customers would drastically cut the costs of their operations and, as a result, reduce the price of solar home systems for the consumer.

2) Cost of SMS: Sending an SMS over the GSM network is currently the best option for retrieving data in rural areas. The cost of transmitting the data is reduced to the cost of sending a single SMS, which was $0.04 in 2008 in Tanzania and $0.05 in Kenya [13].

3) Cost of Module: The SIMbaLink module currently costs $154.50. This is due to small-scale production and the additional cost of buying off-the-shelf modules and microcontrollers. However we can significantly reduce that cost by producing on a larger scale and printing our own boards. We have estimated our costs based on an order exceeding 1000

TABLE I
COST ANALYSIS OF SIMBALINK MODULE

Components - Prototyping	**Cost in USD**
Arduino	30
Cellular Shield w/ SM5100B	100
Female Headers and Terminals	6
Protoshield w/ Male Headers, Resistors, and Hookup Wire	10
Three .1Ohm 5W resistors	7.5
TIP120	1
SIM Card	25
Total	179.5

Components - Production	**Projected Cost in USD**
Microcontroller components	5
ATmega Chip	3
Printed Circuit	2
Mounts and Miscellaneous Hardware	5
GSM Module and Antenna	20
SIM Card	15
Total	50

units. In this scenario, the estimated cost of our module would be \$50, with the potential to decrease as the GSM module and SIM card decrease in cost. We hope to bring down the cost of our module to below \$30 by the time we begin full deployment.

V. COST ANALYSIS

We conducted our cost analysis by calculating current and projected component costs. Estimated costs are based on our deployment experiences; future projected costs, since they are not publicly available, are based on real estimates of projected solar price reductions. Table II shows the current and projected cost breakdown of the ST-20, which is our most popular SHS, along with the cost breakdown for a solar cooperative and a social entrepreneur. The charge controller and battery are the highest-cost components in the system. Reducing their failure rate is critical to lowering overall maintenance costs for any given system. The miscellaneous costs include small parts and one-time travel and shipping costs for installation.

To calibrate maintenance costs, we need information about expected failure rates of components. Table III shows the expected equipment failure rates for the components of the ST-20. Each component has a different failure rate based on industrial life cycles and our experience in the field. The PV panel has an expected life cycle of 20 years, but without routine maintenance the panel may fail after 10 years. The battery has an expected life cycle of 4 years, but this is reduced to a range of 1 to 2 years based on varying levels of misuse. The charge controller lasts between 5 and 7 years, depending on the level of misuse. The failure of miscellaneous hardware ranges from 2 to 10 years based on ruggedness and the possibility of tampering by homeowners or vermin (it is common for rats to chew cable wires). Based on our calculations, the highest rate of equipment failure occurs with the battery and is most often the result of battery misuse. The reduction of this failure rate is critical to lowering the overall cost of the SHS. [14]

Projected system failure rates determine the required number of visits to an installed system by a trained technician. Our current time to repair is once a year; however, this number is insufficient. Routine maintenance by a trained technician is required, at minimum, once a month if the system cannot be monitored daily. Table IV shows our breakdown of maintenance costs for different capacity systems. In order to simplify our analysis, the labor, transport, and additional costs of maintenance visits per SHS remain fixed at \$40, which is a level based on our deployment experience. The costs of maintenance do vary, however, according to the size of the system and the complexity of the required repair. The cost of replacing failed batteries and/or charge controllers and entire systems adds the highest cost to maintenance. The equipment costs for a stand-alone ST-20 system are based on our previous breakdown of component costs, but the costs for the solar-cooperative and social-entrepreneurship model have increased to accommodate the increased capacity of the system. For example, a solar cooperative requiring a 80W capacity system, increases the system cost to \$650.

A. Analysis

Case 1 - Solar Home System: We first analyze the cost reduction that SIMbaLink provides for a stand-alone SHS. Table V shows the maintenance cost breakdown of an SHS with and without SIMbaLink. We find that the introduction of the SIMbaLink module to an SHS would reduce the cost of maintenance per household by a factor of 11 for routine maintenance and a factor of 4 for battery and/or charge controller replacement. Daily remote monitoring reduces the number of required visits to the site from 12 to 1 and reduces the potential for equipment failure.

Case 2 - Solar Cooperative: The same analysis can be extended to the case of a solar cooperative before and after the introduction of SIMbaLink. Table VI shows that the introduction of the SIMbaLink module to a solar cooperative shared between 4 homes will reduce the cost of maintenance

TABLE II
CURRENT AND PROJECTED COST OF SHS COMPONENTS (IN USD)

Component	**Stand-Alone ST-20 (20W)**	**Solar Cooperative (80W)**	**(Social Entrepreneur (200W)**
PV Panel	57	300	600
Charge Controller	100	100	100
Battery	105	210	420
Miscellaneous Cost	123	160	180
Current Non-SIMbaLink Cost	385	850	1400
Projected Non-SIMbaLink Cost	220	485	798
Projected Cost of SIMbaLink Module	50	50	50
Projected Cost of SIMbaLink Components (SIM card, Software, etc)	30	30	30
Current SIMbaLink Cost	465	930	1480
Projected SIMbaLink Cost	300	565	878

TABLE III
EXPECTED EQUIPMENT FAILURE (IN YEARS)

SHS Component	**Normal Usage**	**Misuse**
Battery	4	1
Charge Controller	7	5
PV Panel	20	10
Connections and Miscellaneous Hardware	10	2

TABLE IV
BREAKDOWN OF MAINTENANCE COSTS PER VISIT (IN USD)

Maintenance Costs	**Stand-Alone ST-20 (20W)**	**Solar Cooperative (80W)**	**Social Entrepreneur (200W)**
Labor	20	20	20
Transport	10	10	10
Additional Expenses (Accommodation, etc)	10	10	10
Total Fixed Cost	40	40	40
Minor Equipment Replacement	10	10	30
Replacement of Battery/ Charge Controller	105	210	420

TABLE V
MAINTENANCE COST FOR SINGLE SHS BEFORE AND AFTER INTRODUCTION OF SIMBALINK

Single SHS	**Routine Maintenance**	**Equipment Replacement**
Households	1	1
Frequency of Required Visits	12	1
Cost of Equipment Failure (in USD)	10	105
Fixed Maintenance Cost (in USD)	40	40
Total Cost per Visit per Year (in USD)	600	145
With SIMbaLink		
Frequency of Required Visits	1	0.25
Cost of Equipment Failure (in USD)	10	105
Fixed Maintenance Cost (in USD)	45	45
Total Cost per Visit per Year (in USD)	55	37.5

TABLE VI
MAINTENANCE COST FOR SOLAR COOPERATIVE BEFORE AND AFTER INTRODUCTION OF SIMBALINK

Solar Cooperative	**Routine Maintenance**	**Equipment Replacement**
Households	4	4
Frequency of Required Visits	12	1
Cost of Equipment Failure (in USD)	10	210
Fixed Maintenance Cost (in USD)	40	40
Total Cost per Visit per Year (in USD)	600	250
Total Cost per Visit per Household per Year (in USD)	150	62.50
With SIMbaLink		
Frequency of Required Visits	1	0.25
Cost of Equipment Failure (in USD)	10	210
Fixed Maintenance Cost (in USD)	45	45
Total Cost per Visit per Year (in USD)	55	63.75
Total Cost per Visit per Household per Year (in USD)	13.75	15.94

per household by a factor of 11 for routine maintenance and a factor of 4 for battery and/or charge controller replacement.

Case 3 - Social Solar Entrepreneurship: For the case of a social solar entrepreneur, before and after the introduction of SIMbaLink, Table VII illustrates the key cost estimates. Similar to the single SHS case, the introduction of the SIMbaLink module would reduce the cost of maintenance per household by a factor of 11 for routine maintenance and a factor of 5 for battery and/or charge controller replacement.

VI. Beyond Solar Home Systems

Based on the cost analysis, a household with an ST-20 SHS will pay an initial cost of $385. However, this cost-structure model is not sustainable in poor rural areas, especially those that are densely populated and could benefit from the exercise of aggregate purchasing power. By increasing the efficiency and life expectancy of the SHS and reducing overall maintenance cost, the SIMbaLink module allows new strategies for rural electrification to be modified to suit the needs of different settlement patterns. Our vision for the future of rural electrification rests on *solar cooperatives*, where larger panels are shared across three or four homes, and *decentralized complex systems*, where households/entrepreneurs can invest in a larger SHS and sell electricity to nearby households through a metering system. Both of these solutions enable the provision of pay-per-use small-scale and local solar electricity that serves even the poorest households. If access to just one node of electricity can increase household or individual income and productivity hours, then this benefit will multiply within the community and lead to further socioeconomic progress.

A. Solar Cooperative

Within the solar cooperative, the cost of a higher capacity SHS can be spread across several households. The installation and maintenance of the photovoltaic (hereafter PV) system would be undertaken by a solar initiative, such as SEF, whereas the loan would be provided by a micro-finance institution. The system is modular, so the cooperative can choose to increase capacity at any time, and individual households can buy more products, such as energy-efficient entertainment systems or refrigerators, over time. An 80W PV system satisfies the initial demand of 4 households with small loads, such as lights and mobile phone charging. Such a system is estimated to cost $850, with a recurring maintenance cost of $13.75 per household per year. The capital and recurring maintenance costs are distributed amongst the participants. Using the SIMbaLink module, the cooperative can meter the energy usage of each household and divide loan payments accordingly.

In order to pull energy from the charge controller, the user sends a text message to the module, which identifies the outlet/load they need to use. The module, after accessing the user's mobile bank account, activates the outlet and begins charging a fee per kilo-Watt of use. A percentage of the payment is deposited in a shared mobile bank account to save for the cooperative's future purchases, such as increased capacity and replacement batteries, while a fixed amount is collected by the lender to repay the loan. This solution works for households in areas that have an existing grid but cannot afford a connection to it, or are connected but experience frequent black-outs, as well as households in clustered but remote settlements.

B. Small-Scale Solar Social Entrepreneur

Another possibility for the future of rural electrification is the small-scale solar social entrepreneur. In this scenario, a high-capacity PV system purchased by an entrepreneur is financed through micro-payments and maintained by a solar provider such as SEF. This solution works best in a clustered settlement wherein nearby households without access to their own solar system can pay the entrepreneur to charge their portable lamps and other solar products.

This solution also benefits the poorest households by serving as the first step to their electrification. A household that cannot afford an entire PV system can invest in a more cost-effective and modular solution, such as SEF's newest product, the ST-2, which is a portable LED lamp with mobile charging capabilities and an integrated battery. The ST-2 is currently sold for $42, but would be about $9 less if it was bought without a panel and charged at an entrepreneur's micro-business. A 200W PV system could satisfy the energy demands of 15 rural households. It is estimated to cost around $1400 currently and can power several portable solar product with 6V, 4.5Ah batteries. These solar products individually demand 0.027 kWh to fully charge and provide at least 6 hours of bright light, which is suitable for the smallest unit of electrical need.

Using the SIMbaLink module, the entrepreneur monitors the energy drawn by the customer's solar product and charges the customer's mobile banking account on a per-kWh basis. The entrepreneur can then use the payments to repay their own loan and expand their micro-business. The data gathered by the SIMbaLink module is shared via the SIMbaMain software with the technician (an employee or independent worker), the lender, and the entrepreneur. Using this information, the technician can provide rapid and sustainable customer service as the entrepreneur's business grows. As a result, the recurring operational costs for the PV system are estimated to be reduced to only $4.67 per user per year, which increases the entrepreneurs opportunity for further investment. In addition, the micro-finance institution or other lender can monitor the entrepreneur's business strategy and use their performance as a reference for future loan applications.

C. SIMbaLink Improves Accountability

SIMbaLink addresses both granularities of accountability problems in prior SHS systems, which is critical to successful deployments and long-term sustainability [15]. By collecting a systems health status information and explicitly exposing it to all the parties involved, SIMbaLink creates information transparency between the homeowner and the solar provider. This is especially useful in the case of the battery, which is the key point of failure in an SHS. By constantly recording data

TABLE VII
MAINTENANCE COST FOR SOCIAL SOLAR ENTREPRENEUR BEFORE AND AFTER INTRODUCTION OF SIMBALINK

Solar Entrepreneur	**Routine Maintenance**	**Equipment Replacement**
Households	15	15
Frequency of Required Visits	12	1
Cost of Equipment Failure (in USD)	30	420
Fixed Maintenance Cost (in USD)	40	40
Total Cost per Visit per Year (in USD)	840	460
Total Cost per Visit per Household per Year (in USD)	56	38.34
With SIMbaLink		
Frequency of Required Visits	1	0.25
Cost of Equipment Failure (in USD)	30	420
Fixed Maintenance Cost (in USD)	45	45
Total Cost per Visit per Year (in USD)	75	120
Total Cost per Visit per Household per Year (in USD)	5	8

about the health of the battery, the SIMbaLink system gives the homeowner the assurance that if a battery is defective and fails after just a few months of use, there will be data to back up their claim that the battery failed even though they used it properly. For the solar company, the system provides assurance that if the homeowner misuses a battery and shortens its life, the data will also reflect this, and the company would be able to charge the homeowner for the new battery.

At the solar cooperative level, where a single SHS is shared across multiple users, each user has access to the same information, which can enhance better trust amongst shared users. This transparency creates an incentive for fair use of the system and responsible maintenance by the cooperative and the solar provider. The members of the cooperative can meter each household's usage and divide the loan payments accordingly. The solar provider can isolate which household misused their equipment without penalizing the rest of the cooperative. This incentive is critical to the success of a shared solar grid future in rural Sub-Saharan Africa, as SEF has learned from its work in Ethiopia.

VII. CONCLUSION

Our objective is to incubate a solar market that the rural poor can sustain independently in the long-term. Solar power is an abundant, locally available, and sustainable resource that can increase household and community income. The potential to increase productivity and improve the way of life in developing rural areas through solar electrification is dependent upon the creation of an accessible and transparent market for the transfer of unused power. Although a lot of progress has been made in both reducing the cost of solar technologies and creating distribution networks to supply the growing demand for power in the developing world, the bottom line must be reduced further. SIMbaLink has the potential to further reduce the operating and maintenance costs for solar cooperatives and shared solar grids, which would extend the reach of solar rural electrification to even the most remote homes. Although we do not present progress on the shared solar paradigm, we have expounded on the necessary tools to ensure a successful implementation, deployment, and evaluation.

REFERENCES

[1] R. Priddle, "Energy and poverty: Iea reveals a vicious and unsustainable circle," IEA Press Release, August 2002.

[2] L. Parshall, D. Pillai, S. Mohan, A. Sanoh, and V. Modi, "National electricity planning in settings with low pre-existing grid coverage: Development of a spatial model and case study of kenya," *Energy Policy*, vol. 37, no. 6, pp. 2395–2410, 2009.

[3] U. Deichmann, C. Meisner, S. Murray, and D. Wheeler, "The economics of renewable energy expansion in rural sub-saharan africa," The World Bank, Policy Research Working Paper WPS 5193, January 2010.

[4] E. Martinot, "Renewables 2007 global status report," REN21, Tech. Rep., 2007.

[5] D. J. Grimshaw and S. Lewis, "Solar power for the poor: facts and figures," http://www.scidev.net/en/features/solar-power-for-the-poor-facts-and-figures-1.html, March 2010.

[6] "Providing affordable solar systems in northern tanzania," Ashden Awards for Sustainability, 2007. [Online]. Available: http://www.ashdenawards.org/files/reports/Zara_2007_Technical_report.pdf

[7] "Rural electrification with photovoltaics," Stiftung Solarenergie, 2009.

[8] "Pv battery: Photovoltaic system component." [Online]. Available: http://www.solardirect.com/pv/batteries/batteries.htm

[9] P. Lu, J. Chen, F. Kazi, M. Tierney, and L. Subramanian, "Smsappstore: Sms-based applications made easy," NYU Technical Report, 2010.

[10] J. Stevens and G. Corey, "A study of lead-acid battery efficiency near top-of-charge and the impact on pv system design," 25 IEEE Photovoltaic Specialists Conference, 1996.

[11] A. Gillwald and C. Stork, "Towards evidence-based ict policy and regulation: Ict access and usage in africa," Vol 1 Policy Paper 2. Johannesburg: Research ICT Africa, May 2009.

[12] "African mobile factbook," Blycroft Publishing, 2008.

[13] "Mobileactive.org mobile data: Kenya and tanzania." [Online]. Available: http://www.mobileactive.org/mobiledata

[14] F. Nieuwenhout, J. Martens *et al.*, "Life-cycle analysis and optimization of solar home systems," August 2001.

[15] E. Martinot, A. Cabraal, and S. Mathur, "World bank/gef solar home system projects: experiences and lessons learned 1993 - 2000," Renewable and Sustainable Energy Review, 2000.