A Prepaid Architecture for Solar Electricity Delivery In Rural Areas

ABSTRACT

This paper demonstrates a model for electricity distribution in a rural context with the potential to lower both installation and operating costs below what a conventional grid extension would offer. The microutility in this paper provides power on a pre-paid basis similar to the way cellular phone air-time is sold. This system uses SMS messages sent over the GSM networks for communication allowing installation in any place within reach of a GSM tower. Several of these individual microutilities are monitored and administered via a central server. These microutilities are currently installed and providing power to approximately 90 households in Mali.

1. INTRODUCTION

Modern electricity services are almost absent from rural areas of developing countries. Some 1.4 billion people lack access to electricity with 85% of them living in rural areas.[4] Rural customers gain access to energy services by purchasing kerosene and drycell batteries and by paying for battery charging services. Survey data in the Millennium Villages show that these expenditures are a significant fraction of household spending.[3] Despite this evidence of spending on energy services, grid extension has not occurred in many areas. Even modest levels of electricity bring the benefits of clean lighting and communication through cellphones.[5] Higher levels of electricity allow for mechanized power and can directly increase incomes in rural areas.[9]

One barrier to the extension of the existing grid to rural areas is cost. Grid extension costs can exceed $2000 USD per household, prohibitively high even for many governments in developing nations.[12] Moreover, grid extension requires that capital be allocated in large lump sums to pay for the installation of the expensive, high voltage power lines in remote areas that are necessary prior to individual connections. Even if capital costs are raised and grid extensions constructed, reading meters and collecting tariffs in remote locations pose significant logistical problems, driving up operating and maintenance costs for power customers.

Lacking grid connections, customers turn to costly alternatives for power: batteries, kerosene, solar panels and travel to grid connected locations are relied upon for services that would be more efficiently (and usually cleanly) delivered via a grid connection. Such substitutions are often at a much higher price per unit of service than grid connections in the same country.[10, 6, 16] Chemical energy sources such as kerosene, candles, and dry cell batteries are often used for lighting. Kerosene, a very common lighting fuel, carries the drawbacks of heat, soot, and fire risk. While single-use chemical fuel is used for lighting, rechargeable batteries are often used to power communication and entertainment devices such as cellphones and televisions. Since electrical energy production does not exist in most remote areas, the devices themselves, or large rechargeable batteries, are instead carried to stores that offer charging services. Such recharging of cellphones and lead-acid batteries carry small purchase costs, but the cost per unit of electricity is much higher than that of electricity provided via a grid connection. Wealthy consumers in some markets are able to purchase solar home systems that provide modest amounts of convenient power but these require a large initial investment. In Kenya, investment in individual solar home systems has been considerable, but such systems are primarily owned by the wealthy.[8] Solar home system users in Bangladesh report that the costs of financing associated with solar home systems are a hardship.[11] At a lower price, solar lanterns with rechargeable batteries are available and can provide light and cellphone charging but cannot provide power for television or other common demands.

In an environment in which the most common affordable energy sources have significant drawbacks and household electricity generation services remain out of reach for most consumers, an opportunity for a new service model arose. By combining distributed generation with cellular communication, we demonstrate that a modular microutility can deliver power to remote locales using a robust prepaid collection system. This effort is builds on previous work in prepaid electricity and GSM-based communication in rural areas. Prepaid metering for grid electricity has been successfully demonstrated in South Africa and proven as a viable business model.[15] We also build on previous work using SMS to gather data from remote areas.[1, 7] Also related are efforts to build autonomous metering systems using GSM and SMS.[13] Researchers have demonstrated a system for gathering of solar panel electricity production and battery health over SMS networks.[14] Simpa Networks is also providing a solar home system that can be paid for in installments.[2]

Distributed solar generation, though costly, can be deployed gradually, without the large lump expenditures required for grid extension. By using the telecommunications networks that have been established in many rural areas of developing countries, these systems can operate with remote supervision and administration. With customer billing and monitoring of the system done remotely using wireless communications protocols such as SMS, the travel costs to the site can be reduced by eliminating routine visits and restricting travel to necessary maintenance visits. If manufactured at a cost-effective scale, this architecture could make for an attractive business proposition for a utility, which could deploy the systems as an alternative in areas where grid extension is prohibitively expensive. The concept is similar to that of a power-purchase agreement whereby an outside investor provides the capital to pay for solar generation, while the power is consumed by a private party that pays solely for the electricity. By focusing on an approach that aggregates several households together, we hope to circumvent the difficulties of end-user finance by creating an investment opportunity for an enterprise. The selling of excess power from cellular towers is a similar idea to this where the capital for energy generation is paid by a cellular communications provider and the electricity services are sold to consumers. Meanwhile, this architecture allows for the construction of a rich data set on power consumption following the introduction of near-grid-quality power to previously unelectrified sites. Such data is of use to researchers and business people seeking an understanding of energy purchasing patterns in rural, unelectrified areas.

2. ARCHITECTURE

This section describes how the system allows for the generation, metering, distribution, and switching of photovoltaic-generated electricity for consumption by households. As implemented, the system allows power to be sold to consumers on a pre-paid basis. Each generation and metering system provides power to a small network of up to 20 homes. Payment and monitoring takes place via local cellular networks, with commerce functions performed by a central server that allows for the remote administration of multiple generation and metering systems. Figure 1 shows a schematic of multiple systems delivering power networked to a central server.

2.1 Generation, Metering, and Distribution

Power is generated and distributed locally from a small central facility placed near a group of 10 to 20 customers. This facility consists of a weatherproof structure to protect the electronics, solar panels, batteries, a power conditioning unit (PCU), and three custom cabinets containing metering and communications electronics. Figure 2 shows the power flow and voltage levels between the generation and metering components and the households. The DC components of the system are 48V and power is delivered to consumers at 230 VAC.

The central facility is approximately two meters by two meters by three meters tall with solar panels mounted on the roof. Electricity generation is provided by an eight-panel array of 175 W monocrystalline panels, yielding 1.4 peak kW (Sharp NT-R5E3E 24 V 175 Wp). The array power is received by the power conditioning unit inside the structure, which carries out the functions of battery charging and con-

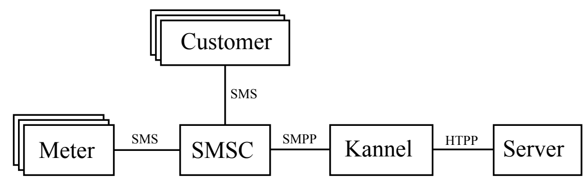

Figure 1: Diagram of a network of meters and customers administered by a central server. Multiple meters communicate via SMS messages that are relayed through a short message service center (SMSC). These messages are received by a server running the Kannel gateway software that relays the messages in HTTP format to a server. Customer messages also communicate through SMS and the SMSC before messages are sent to the server.

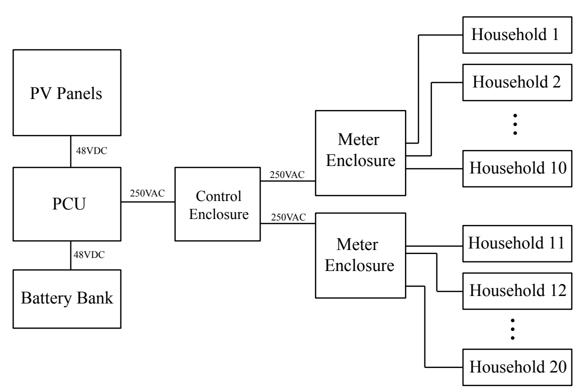

Figure 2: Power Generation and distribution. Power is generated by an array of photovoltaic panels. Output of these panels is used to charge a bank of batteries. An inverter is powered by the batteries and power is distributed through busbars and meters before distribution to the households.

version to AC power. The PCU (PPS Enviro Power, Single Phase SOLA ECO Inverter) contains a battery charger, inverter, maximum power point tracker, generator input, and an RS-232 interface for data collection. The inverter supplies power to the system and the customers at 230 V and 50 Hz. Power produced while the sun is shining is stored in a bank of valve regulated lead acid (VRLA) (HBL T Series Tubular Gel VRLA 48 V 360 Ah) batteries. This battery bank provides power to the inverter during the nighttime hours. The output from the inverter is fed into the first of the three custom cabinets. The first cabinet is the control enclosure which contains communications hardware and a plug computer. As shown in Figure 3, power enters this control enclosure, where it is measured in order to monitor the total power consumption of the system. The AC power is then distributed from the central control enclosure to each of the two metering enclosures. Inside the two metering enclosures, the power is distributed by bus bars and is individually metered before being sent to households. Each metering enclosure is capable of distributing metered power to up to 10 households, which are individually wired to a meter in a star topology where each house has an individual wire running to the generation site. Each connected household is provided with two energy-efficient light bulbs (5 W Philips LED), switches, and a plug outlet for appliances. Power to each of up to 20 households flows through a commercial metering product (Smart Circuit SC20, EED) that communicates via an ethernet interface. This device measures consumed power and switches the power supply on and off. Each metering enclosure has 10 SC20 devices on an ethernet switch, which is connected to another ethernet switch in the control enclosure. A Linux plug computer, (SheevaPlug) which is connected to the switch, runs a custom Python software application to monitor loads, switch circuits and communicate with a central server. The plug computer polls each of the 20 meters as well as the main meter for power consumption data. Information on each household's balance of remaining credit is stored on the computer. As power is consumed, credit is subtracted from each account according to the per-kilowatt-hour price of electricity. The custom metering software allows for the electricity tariff to change based on the time of day, the instantaneous power drawn, or the overall daily energy demanded.

This software also controls communication between the local system and the remote server. The system communicates with a central server via SMS messages sent over the GSM network. At hourly intervals, the computer sends the accumulated daily consumption of each household to a central server for storage in a central database for later data retrieval. The meter also listens for messages from the central server over the GSM network. These messages include commands to add credit to an account or to turn a circuit on or off.

2.2 Communication

The proposed architecture allows multiple installation sites to be monitored and administered from a central server. The central server communicates with customer cellphones and the local meters using HTTP and SMS messaging over the GSM network. For communication to occur between either the customer and the server or between the meter and the server, a gateway is needed between the GSM network and the internet. The gateway can either be provided by the

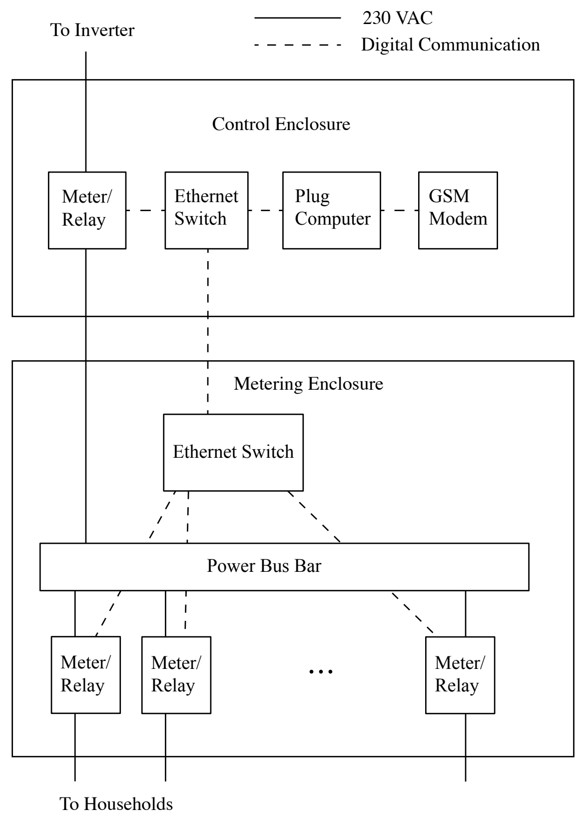

Figure 3: Schematic of the power and information flow in the metering hardware cabinets. Power flows from the inverter to a main metering circuit. The power is then distributed by bus bar to up to 20 individual metering and switching circuits. Information is collected from each of these metering and switching circuits via an ethernet network and is aggregated on a plug computer. The plug computer controls the accounting and communication functions and communicates with the central server by a GSM modem.

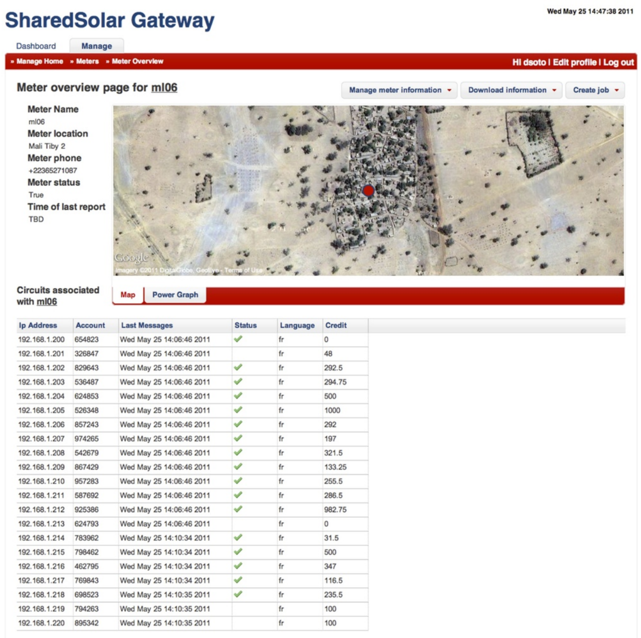

Figure 4: Screen shot of the administration interface. This web application allows the administrator to view the information collected from the installed systems. Information on the household electricity consumption and credit purchases can be viewed.

local telecommunications operator or by employing custom software in conjunction with a modem. In Mali, we initially used the latter to relay messages from SMS directly to HTTP before contracting with the local telecom operator to create a service that converts SMS messages to Short message peer-to-peer (SMPP) messages. The local telecommunications operator can provide a system that is more reliable than our custom solution by housing it in a location with more robust power and communications. A custom server running the Kannel package forwards these SMPP messages from the local telecom to our central server over HTTP. This system's server uses a Python-based Web application and a PostgreSQL database to store information received from customers and meters on their power consumption. The server also has a web interface (Figure 4) that allows for the configuration of consumers' circuits and a visualization of their electricity consumption.

2.3 Transaction and Reporting Descriptions

The system uses the functions described (generation, metering, switching, and communication) to create a pre-paid microutility that builds on the successful and locally familiar model of pre-paid cellular phone air time. To purchase power, the customer buys a scratch-card from a local vendor. Scratch cards (Figure 6) are available locally in amounts as low as \$1 USD and as high as \$4 USD. The cards contain instructions on how to recharge the buyer's account and a concealed authorization code. The customer enters the revealed code into his mobile phone and sends it by SMS to the central gateway server for validation. Once validated, the gateway server sends a message to the local meter instructing it to add the scratch card's credit amount to the customer's account. The meter sends an acknowledgment back to the gateway that credit has been added, and the gateway in turn notifies the customer by SMS that the transaction has been successful. The consumer can then access electricity until her credit is exhausted, at which time the household meter automatically turns off its relay.

As energy is consumed, the plug computer reduces the consumer's credit accordingly. When the credit level reaches a low setpoint, a message is sent to the gateway server, which in turn sends a message to the consumer warning that her account is low and should be refilled soon. Customers are also able to interact with their accounts to inquire about their balance via SMS. The customer sends a text message to the server, which responds back with a message containing her credit balance. She can also send a message to the gateway requesting that the household's connection be turned on or off. This allows the customer to protect against unauthorized power use during an absence.

The system is programmed to collect and store information about customer electricity consumption on the central server. Hourly, a message is sent from the central server to the gateway containing information on each household's accumulated daily energy usage. The meter can also send data regarding photovoltaic energy production and battery voltage. To guard against depleting the batteries, the meter can shut off a consumer circuit that is using more electricity than the system is designed for. The meter software can turn off electricity to the household if the consumer's power or daily energy is over an agreed maximum. The meter also listens for incoming SMS messages from the gateway, which are often diagnostic requests.

3. DISCUSSION

At the time of this writing, we have five systems installed in Mali serving about 90 households with pre-paid electricity. One of these systems is near a city and four of the systems are in the Tiby Millennium Village. This area is well suited for the system since it has a plentiful solar resource and though remote, has dense settlement patterns that allow for short wire distribution lengths.

3.1 Installation

The installation process began with an assessment of a potential site for suitability followed by planning and installation. Consumers were approached about their willingness to pay a connection fee and a service fee for electricity. Those customers who agreed to these fees made an initial deposit and were connected. The connection fee of \$60 USD covers a wire from the central meter location to the home, the internal wiring in the home, and two 5 watt LED light bulbs and a power outlet. Each customer has a unique wire running from the central meter location to the home that is their property and responsibility. Wires were primarily run underground in these installations. The soft soil made digging trenches for installation more cost-effective than installing utility poles. Customers were also provided with a card with their account number. They were instructed to save this account number since it would be used for electricity purchase transactions.

3.2 Consumer Training

Figure 5: Photo of local training session. Sessions were held to train users on the use of mobile phones and scratch cards to purchase electricity.

Although consumers are familiar with mobile phone technology and the purchasing of mobile phone airtime, we conducted trainings (Figure 5) to instruct consumers on account management. These trainings were conducted to be sure that customers knew how to purchase credit and inquire into their account using their mobile phones. Training sessions were conducted in Bambara, the local language, with the help of translators. At the training sessions, customers were provided with scratch cards (Figure 6) that contained a numeric authorization code and instructions for sending the code to the central server for validation. To purchase credit, the scratch card instructed customers to send a short alphabetic command code, followed by their assigned account number, followed by the authorization code. This scheme was modeled after the purchase of cellphone airtime. During training, customers reported that the combination of numbers and letters was cumbersome to enter and that our instruction cards were verbose and difficult to understand. We also discovered that not all villagers in Mali were as comfortable with SMS messaging as we initially assumed. Anecdotally, we noticed a higher level of familiarity with SMS among some of the younger members. In response to these reports, we modified the format of our SMS messages to adhere more closely to the messages used by cellphone providers for recharge and eliminated letters from the message formats. The most familiar message format is the USSD protocol used by cellphone providers for users to manage their accounts. Unfortunately, the USSD protocol used by the providers was not available to us so we could not create a system that was identical to the existing systems that the villagers had experience with. In order to purchase credit or inquire about the balance on a customers account, an SMS message must be sent. During this training period we observed that while most people owned cellphones, they often did not carry a balance of usable air-time on their phones. This validated our choice to provide a toll-free number for SMS messaging.

3.3 Electricity Consumption

Using the data collected on our server, we can examine the electricity consumption patterns of the households par-

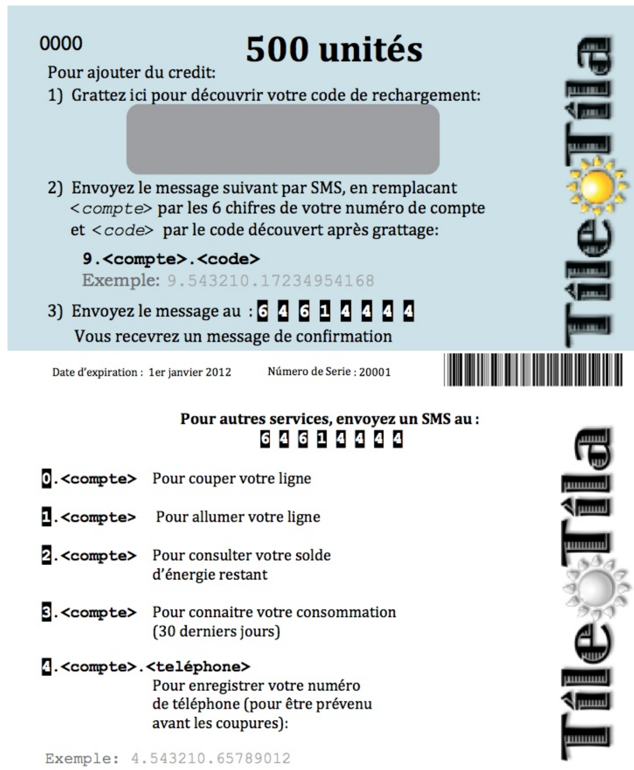

Figure 6: Scratch cards. Cards contain a concealed code as well as instructions on the use of the account.

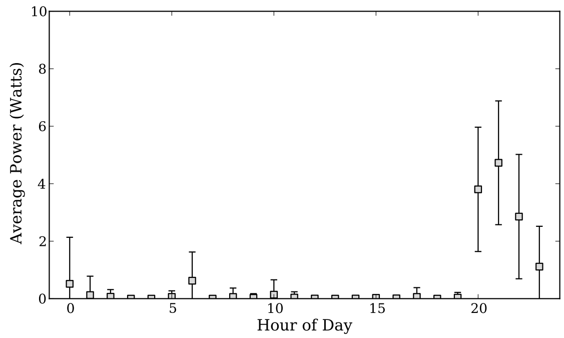

Figure 7: Hourly power use averaged over one month of data. Each datapoint is the average power consumed for that hour over a time period of one month. Error bars indicate the standard deviation for the data set.

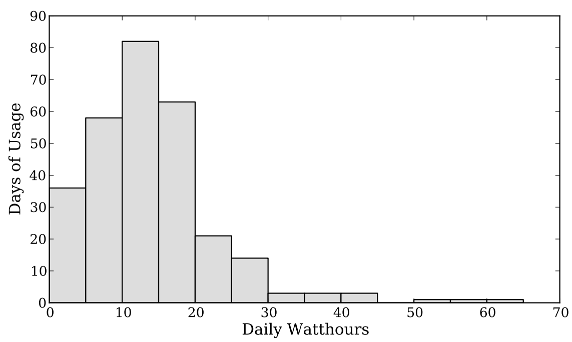

Figure 8: Histogram of daily consumption. The watthour consumption of households in increments of 5 watthours in plotted on the x-axis. The y-axis is the number of days of where this level of consumption is observed.

ticipating in the project. We start by looking at a typical consumption pattern for households. Figure 7 shows the averaged hourly power readings over a period of one month. Most of the load is at night with a wattage level that is consistent with the use of the 5 watt LED light bulb that we provide. There is also a small amount of early morning lighting load before sunrise. During the day however, there is almost no electricity consumption. This pattern necessitates battery storage of the photovoltaic energy generated.

To get a sense of the daily consumption levels in our Mali pilot sites, we plot a histogram (Figure 8) of the daily energy consumed with the frequency being the number of days that power was observed in any household. This data is for one meter in one village, Tiby II, in the Tiby cluster in Mali with 17 households connected.

The histogram shows that the most frequent daily usage is in the range of 10–15 watt-hours. This is equivalent to 2–3 hours of use of the 5 watt LED light bulbs installed with the system. The households that display usage above this level usually own an appliance such as a television or radio.

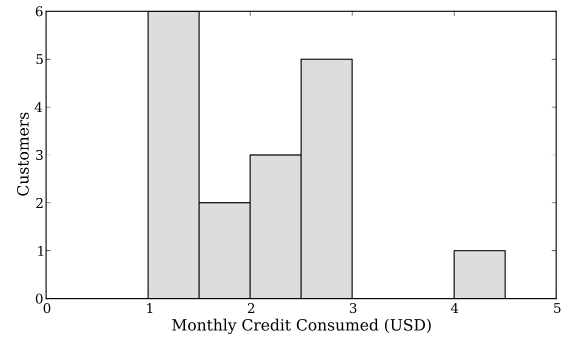

Figure 9: Histogram of monetary amount consumed per household over one month period.

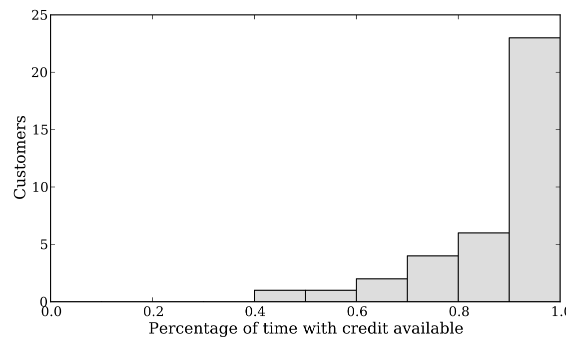

Figure 10: Histogram of percentage of time customers have a positive non-zero balance of available credit in their accounts. The majority of customers have electricity available in their homes over 90% of the time.

Figure 9 shows the number of customers consuming a given amount of credit monthly. The exchange rate is approximately 500 XCFA to $1 USD. The most frequent expenditure is from $1 USD to $1.5 USD.

This architecture for power delivery uses a prepaid model. Customers must maintain a non-zero amount of credit in their accounts in order to use electricity. The histogram in Figure 10 plots the number of customer households that have a given percentage of time with credit available. Over half of the consumers maintain non-zero amounts of credit over 90% of the time.

To understand if only consumers with higher expenditures on electricity are able to maintain non-zero balances consistently, we plot the fraction of time with credit available against the expenditure per household in Figure 11. This plot shows that some customers with both high and low expenditures are able to keep credit available most of the time. However, those customers with credit available for lower fractions of time had lower monthly expenditures.

3.4 Challenges

We have identified several areas needing further work in order to have a robust and economically viable system. Prob-

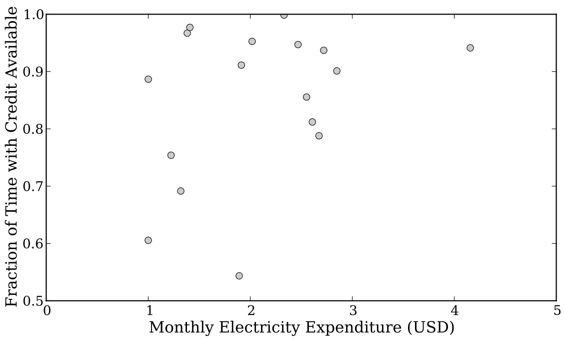

Figure 11: Scatterplot. Each point represents a household. The percentage of time that the account has available credit is plotted on the y-axis while the monthly monetary value of electricity consumed in USD is plotted on the x-axis.

lems with communication can prevent consumers from replenishing their accounts causing an interruption of service and frustration. Also, excessive power consumption by the meter and communication electronics diverts electricity from consumers and requires extra generation costs.

These systems are intended to run uninterrupted and unattended in remote locations. Communication uptime is very important. We have observed problems with communications reliability and latency. Problems with network reliability have prompted us to explore other means for information flow in the presence of intermittent connectivity. We are considering both queueing information until the network becomes available as well as using physical information movement such as flash drives.

Another challenge is reducing the cost of wires for power distribution. We use a star topology for power distribution where each household has an uninterrupted line to the meter. The main reason for this choice was clearly define the boundaries of ownership between the utility and the consumer. In the current model of the system, the consumer pays for and owns the wiring leading from the central production shed. Any tampering of the wire will result in lost power for the consumer rather than lost revenue for the utility. This reduces the risk of one common type of fraud and uses social pressure as a deterrent. One disadvantage to this approach is the potentially higher cost of distribution. A bus distribution scheme would in most cases lower the total length of cable needed. However, long sections of aboveground and accessible utility-owned cable are vulnerable to unauthorized splicing.

The electricity consumed by the metering system must be minimized to reduce capital expenditures on solar panels and battery storage. We have chosen commercially available components for integration into these systems. The metering components are designed for developed markets and cannot measure loads below 2.0 W and they consume 1.5 W–2.5 W. These specifications are acceptable in markets where the loads are usually on the order of 100 W but are not well suited for the more modest energy consumption in these rural areas. An undetected 0.5 W vampire load of a cellphone charger can consume 12 Wh in a day, equivalent to over 2 hours of LED lighting. If this load is not measured, there is no possibility of collecting revenue. The consumption of the meters themselves also creates power expenditure that harms the economic viability of the system.

4. FUTURE WORK

Our work so far has been concerned with the provision of solar electricity with low operating costs and robust revenue collection. However, the framework we have constructed allows for a much richer set of features. A demand response system using text messages and discounts would be straightforward to implement within this framework by incorporating logic at the meter or central server that could monitor the energy generation, send demand response requests to customers, and credit accounts accordingly. In this pilot study, solar electricity is the good that is being metered and delivered by our system. It is also possible to adapt this to architecture to the provision of other generation technologies like hydropower or diesel generation. Application to other easily metered and valuable goods like purified water is also possible. Such a clean water kiosk could enable carefully measured amounts of water to be provided in an automated fashion. The open software tools we have developed can also be adopted for remote monitoring. This work could be adapted to create server storage of weather stations, agricultural monitoring, or other measurements where GSM coverage exists. To address the problems of power consumption by the meter, we are developing custom electronics that have lower power consumption and are capable of measuring loads below 1 watt.

5. CONCLUSION

We have designed and deployed a system that allows for the deployment of microutilities in remote areas. These microutilities can be monitored and administered by a central server. Approximately 90 households in Mali are purchasing solar-generated electricity using this prepaid business model. Since communication takes place over the GSM networks via SMS messages, these microutilities can be deployed anywhere that GSM coverage exists.

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