IMPLEMENTING GRIDSHARE TECHNOLOGY IN RURAL BHUTAN: ANALYZING EFFECTS ON ELECTRICAL BROWNOUTS AND ASSESSING COMMUNITY ACCEPTANCE

by

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ABSTRACT

IMPLEMENTING GRIDSHARE TECHNOLOGY IN RURAL BHUTAN: ANALYZING EFFECTS ON ELECTRICAL BROWNOUTS AND ASSESSING COMMUNITY ACCEPTANCE

Margaret Harper

This thesis evaluates the effectiveness of the pilot installation of GridShares, demand-side management devices designed to reduce the severity of brownouts on isolated, power-limited mini-grids. The low voltages associated with brownouts cause lights to dim and resistance heating appliances, such as rice cookers and water boilers, to function poorly. GridShare devices and the accompanying education program were designed by a team consisting of the author and fellow undergraduate and graduate students from Humboldt State University. In coordination with partner organizations, the team built and installed 90 GridShares in all households and businesses connected to a 40 kW village micro-hydroelectric system in Rukubji, Bhutan in July 2011. Prior to the installation, residents of Rukubji faced routine brownouts due to the use of high-wattage appliances to cook breakfast and dinner. Through a combination of education, indication and enforcement, the GridShare limited this peak demand while still enabling the use of these large appliances when excess energy was available. After the GridShare installation, the village experienced severe brownouts on 92% fewer days than in the prior year. Though the installation did not eliminate the brownout problem entirely, in

household surveys, residents stated that the GridShares made the grid more predictable and provided information necessary for residents to make informed decisions regarding their electricity use. Additional data from electricity billing records, individual household data loggers and GridShare serial data provide further insight into the functioning of the system. Following the one-year pilot test agreement, the community of Rukubji decided by consensus to keep the GridShares installed, and the Bhutan Power Corporation continues to support the effort. This pilot project indicates that user-interactive demand-side management strategies, such as the GridShare, are effective at reducing brownouts on mini-grids.

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Along with the BPC and Bhutan DoE engineers and electricians, local translators Phub Dorji, Kinley, Deki Choeden and Sonam Tobgay Tshering enabled cross-cultural communication. Lastly, I would like to sincerely thank the residents of Rukubji, Bumiloo, Sangdo and Tsenpokto, particularly Phub Gyeltsen and Wangmo, our hosts in Rukubji, for graciously welcoming us into their homes, providing us with practical feedback and keeping us full of butter tea.

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LIST OF ACRONYMS

A – Amp (unit of electrical current)
AC – Alternating Current
BEA – Bhutan Electricity Authority
BPC – Bhutan Power Corporation
Bhutan DoE – Bhutan Department of Energy
CFL – Compact Fluorescent Lamp
CI – Confidence Interval
DC – Direct Current
DILC – Distributed Intelligent Load Controller
DOE – Department of Energy
DSM – Demand-Side Management
EPA – United States Environmental Protection Agency
ESMAP – Energy Sector Management Assistance Program
GNH – Gross National Happiness
GNP – Gross National Product
GW – Gigawatt (1000 MW)
GWh – Gigawatt-hour (1000 MWh)
HSU – Humboldt State University
Hz – Hertz (unit of frequency)
ITDG – Intermediate Technology Development Group
kW – Kilowatt (1000 W)
kWh – Kilowatt-hour (1000 Wh)
LED – Light Emitting Diode
LPG – Liquid Petroleum Gas
MCB – Miniature Circuit Breaker
MW – Megawatt (1000 kW)
MWh – Megawatt-hour (1000 kWh)
Nu – Ngultrum (Bhutanese currency)
P3 – People, Prosperity and the Planet Student Design Competition
PTC – Positive Temperature Coefficient (a type of thermistor)
PV – Photovoltaic
PVC – Poly-vinyl Chloride
RESU – Renewable Energy Student Union (club at HSU)
RGoB – Royal Government of Bhutan
TV – Television
US$ -- United States Dollar (US currency)
V – Volt (unit of electrical potential or voltage)
W – Watt (unit of power)
Wh – Watt-hour (unit of energy)

CHAPTER 1. INTRODUCTION

This thesis provides a program assessment of the pilot installation of GridShares in Rukubji, Bhutan. Rukubji receives its electricity from a small, isolated micro-hydroelectric system and is therefore limited in the amount of power it can use at any one time. When the system was first installed in 1986, ample power was available, but as the population of the village increased and people acquired more appliances, the system could no longer meet the peak demand. By 2010, the village faced daily brownouts when everyone plugged in their large appliances, such as rice cookers and water boilers, to cook breakfast and dinner. These brownouts, or periods of low voltage, caused lights to dim or flicker and rice cookers to function poorly. One way to improve this situation is through demand-side management: encouraging residents to shift the time that they use large appliances to spread out the load. Over the past three years, our team of engineering students and advisors developed a low-cost "GridShare" device to encourage electricity consumers to shift their use of high-powered appliances to periods of low demand.

This section, Chapter 1, provides an overview of the GridShare technology our team developed to address brownouts on isolated mini-grids. Following this introduction, Chapter 2 offers a literature review that covers mini-grids, along with their issues and other load management strategies, as well as some background information on Bhutan and micro-hydroelectric generation. Chapter 3 describes the pilot installation in Rukubji, while Chapter 4 details the methods of evaluation, including the analysis of electrical data, survey results, utility billing data and data collected directly from the GridShares. Chapter 5 provides a discussion of the results of these analyses and provides evidence for the conclusions of the study, which are presented in Chapter 6.

The assessment found that the GridShare installation in Rukubji was successful at reducing the occurrence of severe brownouts in the village. Though the program did not completely eliminate the brownout problem, the GridShares made the grid more predictable and provided information necessary for residents to plan, discuss and make informed decisions regarding their power use. Residents were able to more reliably cook their rice and make use of their limited electricity supply. Residents decided by consensus to keep the GridShares installed, and our project partners, the Bhutan Power Corporation (BPC), agreed to continue to monitor and maintain the GridShare installation. A summary of the project and initial assessment can be found in a recent article written by our team: Quetchenbach et al. (2013).[1]

1.1. GridShare Development and the EPA P3 Design Contest

The development of the GridShare began when Karma P. Dorji, a graduate student in the Energy, Environment and Society program at Humboldt State University (HSU), drew attention to the problem of brownouts on mini-grids in the findings of his thesis which provided case studies of micro-hydroelectric mini-grids in Bhutan (Dorji

[1] Some material presented in this thesis is drawn from Quetchenbach, et al. (2013), but in all cases that similar text is included, I had drafted and played a large role in revising the original text.

2007). Dorji noted that brownouts often occurred during periods of meal preparation and suggested the concept of shifting the time of use of rice cookers to address this problem. Dr. Chris Greacen, an expert in village scale micro-hydroelectric, had also identified similar problems on mini-grids in Thailand (Greacen 2004). In conversation with Dr. Arne Jacobson, Dr. Greacen proposed the design of a device that would indicate voltage level and limit electricity consumption during brownouts. With this concept in mind, in 2008, a team of students from the Renewable Energy Student Union (RESU), mentored by Dr. Arne Jacobson, applied for support through the U.S. EPA's People, Prosperity and the Planet (P3) student design competition.

After securing the initial Phase I design grant of US$ 10,000 from the P3 competition, RESU students developed a prototype of the GridShare circuit. I was peripherally involved in this work and fully joined the team in the winter of 2009 to help plan and write the grant proposal for the second round of P3 funding, as well as file the application for approval by HSU's Institutional Review Board.[2] In the spring of 2010, RESU members presented the GridShare prototype and our Phase II grant proposal at the P3 Expo in Washington, D.C. and competed against teams from universities across the nation. After a successful presentation, we were awarded US$ 75,000 to refine the GridShare and implement a pilot project in a village in Bhutan. In preparation for the P3 competition, Chhimi Dorji, an HSU graduate student from Bhutan, coordinated with the

[2] The surveys and overall research plan have been approved and renewed by the HSU Institutional Review Board (Human Subjects log number 09-58).

Bhutan Department of Energy (DoE) and the BPC to identify an appropriate pilot village. Dorji, along with BPC representatives, visited the village of Rukubji in January of 2010 to establish initial contact and determine interest in the project.

After being awarded the P3 grant, we immediately started work on the project by traveling to Rukubji in June of 2010 to gather additional information and solidify partnerships that would enable us successfully conduct the pilot project. The information gathered allowed our circuit team to appropriately redesign the GridShare, while the rest of our team worked to develop educational materials and plan for the manufacture and shipping of the GridShares to Bhutan. Details on the GridShare design process can be found in Tom Quetchenbach's Master's thesis (Quetchenbach 2011). In the summer of 2011, the team installed 90 GridShares in the village of Rukubji, Bhutan. To evaluate the pilot project, we conducted surveys before and after the installation, collected electrical data for a year before and after, received utility billing data from the BPC and collected data directly from the GridShare units (Figure 1).

Figure 1. The three main methods of evaluation of the GridShare project included electrical data logging, household surveys and community meetings. On the right is the final community meeting when the community decided by consensus to keep the GridShares installed (Photo credits: Meg Harper and Sonam Tobgay Tshering).

1.2. GridShare Technology and the Three-Prong Approach: Education, Indication and Enforcement

The GridShare device consists of two primary components: a circuit board and an LED box. The LED box is mounted inside each residence, near the cooking appliances, while the circuit board and enclosure (hereafter referred to as the GridShare) are mounted outside near the household's electrical service entrance (Figure 2). A 20 amp circuit breaker is mounted in line with the GridShare and the utility meter, both to protect the GridShare from power surges and to provide an added safety measure for households with potentially inadequate wiring and circuit protection.

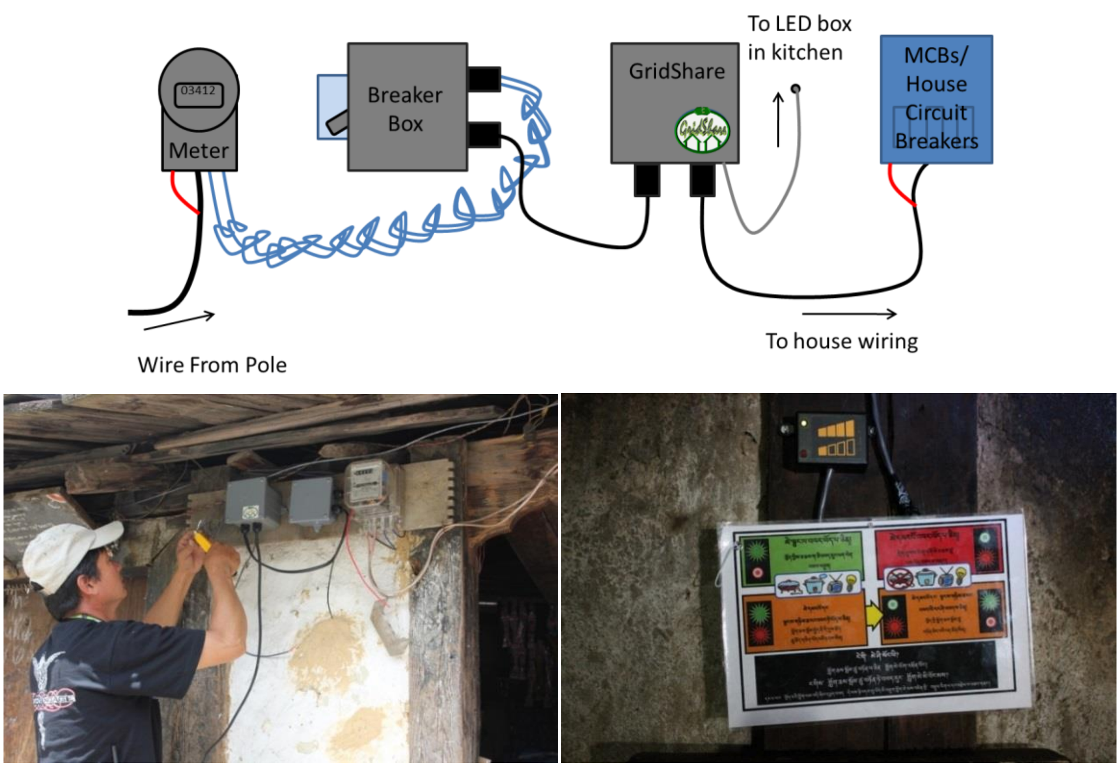

Figure 2. Installation diagram for GridShares (top). BPC electrician, Sangay Phuentsho, installs a GridShare and breaker box (bottom left). LED box with instructional sign installed below (bottom right) (Photo credits: Dr. Arne Jacobson).

The LED box is the point of user interaction where green and red LEDs communicate the state of the grid (Figure 2). If the system voltage is normal, the green LED lights up and the resident can use any appliance.[3] If the system voltage falls below a threshold, the GridShare enters brownout mode. In brownout mode, users are restricted to only using smaller electrical loads, such as lighting, a small TV or a rice cooker on warm mode. If users attempt to plug in a larger load, such as a rice cooker, when the red light is on, power to their house will be cut until the appliance is unplugged.[4] If however, when the brownout starts, a high wattage appliance is in use, the GridShare instead enters timer mode. Both the red and green lights illuminate, and the user is allowed to continue using large appliances for a preset time. The combination of the enforcement in brownout mode and this allowance in timer mode guarantees that users who begin cooking while the green light is on will be able to finish cooking and that the grid voltage will remain above an acceptable voltage to ensure that their rice cooks well. As soon as these users are finished cooking, presumably, load on the system will be reduced and the voltage on the grid will again rise to allow new users to plug in.

Both the LED indication and the enforcement mechanism are controlled by the GridShare circuit. The circuit is designed to measure the voltage and frequency of the

[3] Note that some appliances, such as electric space heaters and domestic water heaters, are not permitted for use on the mini-grid in Rukubji by village agreement due to the limited size of the micro-hydro system. These appliances are still not permitted with the GridShare installation in place.

[4] For reference, small loads, like lights and TVs might use between 11 W - 100 W, while large loads like rice cookers and water boilers are rated to use between 400 W and 2000 W depending on the size of the device. In warm mode, rice cookers and water boilers we tested used less than 100 W.

grid as well as the current drawn by the individual household.[5] Using these inputs, a programmable microcontroller directs the action of the LED lights and the relay used to temporarily cut power to a household.

Thanks to the microcontroller, all set points and time delays on the GridShare are programmable. Set points used in the installation in Rukubji assumed a nominal voltage of 230 V and an allowable load during brownouts of 400 W at the nominal voltage. The GridShares enter brownout mode when the voltage drops below 200 V and exit brownout mode when the voltage stays above 208 V for a random number of consecutive readings, which can result in a wait of up to six minutes. The timer mode is set to allow users to continue using appliances for one hour after the grid voltage initially drops. In cases where the GridShare is in brownout mode and a user plugs in a large appliance, the GridShare will disconnect the relay to cut off power to the household for 30 seconds, and then reconnect the relay for 10 seconds to measure the current draw. If the current has been reduced below the allowable threshold, power will remain supplied to the

[5] Due to the circuitry of the GridShare, the measurement of current is dependent on the frequency of the grid, or the frequency at which the sine wave of the AC electricity oscillates, measured in Hz. To compensate for this dependence, the GridShare measures the frequency and adjusts the value of the current measurement in the software. Lowered frequency can also be a symptom of a brownout; however, many mini-grids, including the one in Rukubji, use load controllers to regulate the frequency. In our field observations, we noted that during many brownouts, the frequency was maintained at the nominal 50 Hz, while during some severe brownouts, the frequency dropped as low as 35 Hz (Quetchenbach 2011).

household. Otherwise, the relay will again disconnect and continue this cycle until the load is removed or the grid voltage rises above 208 V.

Details on the GridShare function and specifications can be found in Tom Quetchenbach's thesis and in a recent article written by our team (Quetchenbach 2011; Quetchenbach et al. 2013).

The above description of the GridShare device covers the indication and enforcement aspects of our three-pronged approach. For either of these strategies to be effective, the installation must be paired with the third prong: education. Our education program was aimed at electricity consumers in the village and focused on discussing why brownouts occur and explaining the purpose and function of the GridShares. We also encouraged brainstorming on how best to interact with the GridShares and in what ways residents could shift their loads to avoid using large appliances during peak periods. We incorporated these educational goals into community meetings, in-home visits during and after the installation and activities with the local school children (Figure 3).

Figure 3. Meg Harper and Nathan Chase lead local school children in an interactive game focused on load sharing (left) (Photo credit: Chhimi Dorji). BPC electrician Phuentsho uses a brochure to discuss the function of the GridShare with Rukubji residents during an in-home visit (right) (Photo credit: Dr. Arne Jacobson).

Additionally, to best deliver our message, we created colorful brochures and visual aids, examples of which are included in Appendix A. Although education alone could potentially have a dramatic impact on electricity use in the village, to ensure that residents have the tools necessary to make decisions and the discipline not to take advantage of the common pool resource, indication and enforcement are also required. As was seen in Rukubji, over time, this education, indication and enforcement structure results in a more reliable electrical service.

CHAPTER 2. BACKGROUND AND LITERATURE REVIEW

This section provides an overview of mini-grids and the limitations of these isolated systems in terms of service quality. Alternative demand-side management (DSM) methods of addressing these service quality issues on mini-grids are then presented. Following this background on mini-grids, this section presents a brief introduction to the country of Bhutan, including aspects of its culture, governance, language and energy management. Additionally, a brief description of run-of-the-river micro-hydroelectric systems in Bhutan provides a technical background for the project.

2.1. Mini-grids

Mini-grids are often employed by governments, development organizations, utilities, private entities and communities to provide electricity to villages that are isolated from the main grid (ESMAP 2000; Terrado, Cabraal, and Mukherjee 2008; Martinot et al. 2002; GVEP 2011; World Bank 2007; Modi et al. 2005). While mini-grids are inconsistently defined in terms of generation capacity, number of generators and grid voltage, they are generally described as low-voltage village-scale distribution systems in which any single small generator (or combination of small generation sources, in the case of hybrid mini-grids) provides for a substantial portion of the load (Lopes et al. 2012; World Bank 2007; ESMAP 2000). Though no strict definitions exist, in practice, mini-grids range in size from less than 1 kW to several hundred kW of installed generation capacity (World Bank 2007; ESMAP 2000). When isolated from the main grid, mini-grids can also be referred to as dispersed generation (Carley 2009). The terms mini-grid and micro-grid are often used interchangeably; however, in most recent literature, it appears more common to refer to isolated grids in developing countries as mini-grids, while micro-grids are often associated with distributed, or grid-intertied, generation in more industrialized countries.[6]

Mini-grids often offer a more economical option for rural electrification than grid extension and can provide better utility in terms of commercial and industrial uses than individualized solar home systems (ESMAP 2000; Flavin and Aeck 2005; Kirubi et al. 2009; Rolland and Glania 2011). In cases where utility-scale grid connection is impractical, mini-grids are recommended for rural electrification when a village exceeds a minimum threshold of houses, can demand a minimum load, and when houses are located on traversable terrain, in a fairly concentrated arrangement (Palit and Chaurey 2011).[7] Mini-grids can range in size from systems designed to provide only minimal

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[6] Current trends appear to be using the terms "distributed generation" and "micro-grids" for localized generation and associated grids which are interconnected with the main grid. As utilities discuss the increasing integration of renewable generation, distributed generation is often touted as an ideal way to include small, localized generation, while simultaneously offering voltage support and back-up power to the local micro-grid. Despite observed trends, some documents do refer to isolated mini-grids as micro-grids or distributed generation, and to grid-connected micro-grids as mini-grids.

[7] For example, Palit and Chaurey (2011) cite that in India, under the Village Energy Security Program (VESP), the minimum threshold is 100 households, whereas other estimates suggest a minimum of 50 customers should be connected to make a mini-grid a viable option over stand-alone systems. Additionally, mini-grids are not recommended for villages where houses are widely dispersed; a guideline of no less than four customer connections per kilometer of distribution line is suggested. Of course, these guidelines have underlying assumptions about the expected load of each household; if

lighting loads, to larger systems enabling the use of domestic appliances and industrial machines (Rolland and Glania 2011; ESMAP 2000).

In addition to providing electricity to isolated rural communities, mini-grids also provide opportunities to use local renewable energy resources. Martinot and colleagues (2002) estimate that worldwide over 50 million households and 60,000 small enterprises are served by village-scale micro-hydro systems and 10,000 households are served by photovoltaic (PV), wind or hybrid PV/wind/diesel mini-grids. Biomass gasifiers, often powered with waste products, offer yet another common and cost-effective method of providing renewable electricity for isolated mini-grids (Palit and Chaurey 2011; Martinot et al. 2002; World Bank 2007). By incorporating renewable generation, mini-grids not only provide the benefits associated with rural electrification, but can also reduce greenhouse gas emissions associated with electricity production.

2.1.1. Limited Generation and Brownouts on Mini-grids

A common feature of all mini-grids is that, due to their isolated nature, generation is limited. Most electrical grids are large interconnected networks, that allow for "power wheeling," or sharing spinning reserve throughout the grid to balance supply and demand and thus maintain a stable voltage and frequency (Lopes et al. 2012).[8] Without this

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households had smaller or larger loads, the number of households required to establish a viable system would change.

[8] Though larger grids are better equipped to balance supply and demand, at a certain threshold, these grids can become overloaded as well. Palit and Chaurey (2011) note that in 2010, India and Bangladesh saw peak power deficits greater than 10% and 27%, respectively. These deficits caused voltage dips as low as

ability to balance supply and demand, peak loads, or periods of high electricity demand, can exceed the power generation capacity of a mini-grid and cause brownouts (ESMAP 2000; Greacen 2004; Dorji 2007; Dorji, Urmee, and Jennings 2012). During a brownout the voltage and frequency of the system drop, causing lights to dim and appliances to not work properly.

While there is no widely accepted voltage or frequency threshold that defines a brownout, most grids have standard operating ranges; operating below the minimum voltage and frequency may result in brownout conditions. In reference to Bhutan's main grid, the Grid Code Regulation states that normal transmission is maintained between 49.5 Hz to 50.5 Hz, with voltages that range between ± 5% of the nominal voltage (i.e. 219 V - 242 V on a 230 V nominal grid) (BEA 2008). The Code further states that the grid is considered in an emergency state if the frequency drops below 49 Hz and the voltage is outside the range of ± 10% of the nominal voltage (i.e. 207 V – 253 V). The country's Distribution Code promises voltages within the range of ±6% of the nominal voltage (i.e. 216 V – 244 V) and states that the distribution licensee is liable to compensate customers 100 Nu (US$ 1.82) for each week that voltage varies outside this range (BEA 2006). Though isolated mini-grids are not held to such strict standards, and no standards are publically available for mini-grids in Bhutan, a European standard exists (European Standard EN–50160, 1994) that requires non-interconnected power systems to

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110 V on a 230 V nominal system and were managed with load-shedding between 14 to 18 hours per day. Similarly, Nepal saw deficits greater than 20% and implemented load-shedding for up to 16 hours per day.

operate within the ranges of 230 V ± 10% (i.e. 207–253 V) during 95% of a week and 230 V–15% +10% (i.e. 195.5–253 V) during 100% of a week for voltage and 50 Hz ± 2% during 95% of a week and 50 Hz ± 15% during 100% of a week for frequency (Lopes et al. 2012).

The occurrence of brownouts on rural mini-grids is documented in several sources. In a review of 59 mini-grids in Thailand, Greacen (2004) found that on 48 of the mini-grids, respondents complained of low voltages. Similarly, Dorji (2007) reported that brownouts regularly occurred on the micro-hydroelectric mini-grid in Ura, Bhutan, primarily due to the common use of rice cookers. Low voltages can also result in equipment failure; in the study, villagers suggested that the low voltages had resulted in broken televisions, refrigerators, and lights, while Greacen suggests that continued low voltages can increase the likelihood of generator failure (Greacen 2004). Low voltages can further impact the functioning of resistance heating appliances, such as rice cookers and water boilers; a 10 % decrease in the voltage results in approximately a 20 % decrease in heat output (ESMAP 2000).

In addition to limited power generation, constrained or nonexistent energy storage presents a further restriction for users of rural mini-grids. While micro-hydroelectric mini-grids typically provide excess power during off-peak times, mini-grids with intermittent renewable energy sources, such as wind and solar, energy storage is requisite and often provided in the form of battery banks. This communal storage is limited and can be exhausted, potentially by a single user, if consumption is not regulated. Mini-grids that rely on diesel generators for at least a portion of their generation are further restricted due to recurring fuel costs. These limitations – peak power output, available energy supply, and recurring fuel costs – underpin the need to employ DSM to reduce load or distribute load over time to preserve mini-grid reliability and ensure that electricity is equitably shared among the mini-grid users.

2.2. Methods for Addressing Load Management on Mini-grids[9]

As mini-grids differ substantially in generation type, size, and financial support, appropriate strategies and technologies for DSM vary. One difference that will appear as a recurring theme throughout this report is the distinction between mini-grids that are primarily power-limited versus those that are also energy-limited. Demand management on power-limited grids, such as many micro-hydro grids, will mainly concern the equitable distribution and total demand for power at any one time. Power-limited grids typically produce a relatively constant supply of electricity and do not include battery banks or other methods of energy storage. These grids are therefore vulnerable to high peak power demand, but total energy consumption over time is inconsequential. However, energy-limited grids, such as those relying on intermittent generation like wind and solar, do require energy storage, and therefore do require regulation of daily energy consumption. For example, batteries enable electricity generated with solar panels

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[9] Much of the material in this section is published in a similar format in Harper (2013). Additionally, this section of the literature review describes specific companies, products, and services. These are presented for informative purposes only and should not be interpreted as endorsements. Much of the information gathered about these companies, products, and their associated case studies was self-reported by the manufacturers on websites, news releases and through personal communication.

during the day to be stored for use at night. Power demand throughout the day and night might never exceed the limits of the system, but the stored energy in the batteries could still be rapidly drained or inequitably allocated among users if energy consumption over time is not regulated.

As noted in Table 1, this review first provides examples of DSM strategies, or ways of encouraging load management without current limiting or metering technology. Next, the review covers technologies that are designed to aid load management on mini-grids. Some of these technologies are designed specifically for DSM, while others, such as prepaid meters, have been found to aid load management as an auxiliary function.

Table 1. List of DSM Strategies and DSM Technologies discussed in this review.

DSM Strategies	**DSM Technologies**
Efficient appliances and lights	Current limiters
Commercial load scheduling	Distributed Intelligent Load Controllers
Restricting residential use	Conventional meters
Price incentives	Prepaid meters
Community involvement, consumer education, and village committees	Advanced metering systems with centralized communication

2.2.1. DSM Strategies

The DSM strategies discussed below include introducing more efficient appliances and light bulbs, scheduling the “business hours” of commercial loads, restricting use of high power appliances, applying tiered pricing in electricity rates, educating consumers about their mini-grid, and creating village committees and agreements to enact any of the above strategies. To the extent possible, each strategy is described in terms of its purpose and its relevance to the different types of mini-grids. Projects or case studies that demonstrate or assess the effectiveness of each strategy are briefly described as well.

Use of Efficient Appliances and Lights

One of the most straight-forward DSM practices is the use of efficient light bulbs and appliances to reduce peak demand and encourage energy conservation. The Mini-Grid Design Manual recommends that in cases where customers cannot afford the additional cost of more efficient lighting, the mini-grid owner should cover the capital cost of the more efficient bulbs to take advantage of their benefits over time (ESMAP 2000). The same may be true for energy-efficient appliances (Rolland and Glania 2011). Regardless of who puts forth the initial capital, investments in energy efficiency at the start of a project can result in long-term cost savings for customers and can enable a reduction in the initial generation capacity of the mini-grid or allow the mini-grid to serve more users and productive purposes for a greater number of hours.[10] Further, investments in energy efficiency on an existing project can help to accommodate load growth without investing in additional capacity.

[10] While energy efficiency measures can reduce energy consumption, associated cost savings for the consumer will depend on the electricity tariff.

Influenced by low up-front costs, mini-grid customers will often use incandescent bulbs (Rolland and Glania 2011). Due to their high wattage, widespread use of incandescent light bulbs limits the total number of customers that can be served, displaces the availability of power and energy for other productive uses, and reduces the number of hours that service can be provided. Fluorescent tube lights and CFL bulbs can provide light output equivalent to that of incandescent bulbs with a quarter of the energy, while recently developed LED bulbs do the same with even less energy (DOE 2012).[11] The benefits of installing efficient lighting are widely recognized in central grid environments and have been core elements of DSM programs in utility Integrated Resource Planning processes for decades (Hirst, Goldman, and Hopkins 1991). More recently, studies have documented the effect of these measures on mini-grids as well. In their analysis of a biomass gasifier mini-grid in Dissoli village, India, Kumar and Banerjee (2010) recommended replacing sixty-one 100 W incandescent lights with 14 W CFL lights. They estimated this change would provide capacity for an electric flour mill and eliminate the need for a separate diesel generator that was currently powering the mill. In a study of a diesel mini-grid in Nicaragua, researchers found that by allowing residents

[11] Although CFLs use up to 75% less energy than incandescent bulbs, each bulb contains mercury, which is a health and environmental toxin (U.S. EPA 2010). While each bulb contains a relatively small amount of mercury (4 mg on average), proper recycling or disposal systems for these bulbs are uncommon in many countries, making the use of the bulbs less favorable. If the installation of CFLs is considered, consumers should be advised as to how to limit their exposure to mercury when cleaning up and disposing of broken or old bulbs.

to trade in two of their incandescent bulbs for two 15 W CFL bulbs, they were able to reduce overall load by 17% (Casillas and Kammen 2011).

With government support and market interest, industries are continuing to improve appliance efficiency, including that of appliances commonly found on mini-grids such as fans, TVs, and refrigerators. Though efficient appliances are becoming more available in many markets, there is often still a discrepancy between the most efficient technology available internationally and that available locally (Chunekar et al. 2011; Singh et al. 2011; Singh, Sant, and Chenekar 2012). For example, in India in 2011, even with an effective standards and labeling program instituted by the Bureau of Energy Efficiency (BEE), the most energy-efficient ceiling fan available used 51 W, while “super-efficient” fans with similar capacities were identified internationally that operated with 35 W (Chunekar et al. 2011). The BEE hopes to narrow this discrepancy with a new Super Efficient Equipment Program (SEEP). The SEEP program is a national program that would provide upstream incentives directly to manufacturers to encourage the development of super-efficient appliances while simultaneously lowering the cost of the appliances to the consumer (Singh, Sant, and Chenekar 2012). While energy efficiency is a chief concern, the SEEP program also prioritizes the performance, durability, and cost of appliances to ensure that they will meet the needs of the market. As India and other countries begin to institute similar policies, the market availability of super-efficient appliances for use on both the utility grid and mini-grids can be expected to increase. Additionally, thanks to the development of solar home systems, several energy-efficient appliances, such as refrigerators and TVs, have been developed for use on DC mini-grids.

To complement the use of efficient appliances, groups such as the Intermediate Technology Development Group (ITDG) have designed low-power "heat storage cookers" for mini-grids with restricted power but excess energy production throughout the day (Holland et al. 2002).[12] These cookers run at a low power for several hours to store heat in pebbles; the stored heat can then be extracted with a fan for short periods of high-intensity cooking. Other efficient appliances include low wattage water heaters that run overnight and super-insulated low wattage rice cookers. Despite their functionality, these cookers were typically too expensive for residential mini-grid customers because of their low production rate and limited market size (Holland et al. 2002; Pandey 2012, pers. comm.). However, some commercial customers, such as local hotels, were able to afford and successfully use the low wattage water heaters, in conjunction with solar and LPG systems, to reduce their use of both electricity and wood (Pandey 2012, pers. comm.).

Commercial Load Scheduling

Another common DSM approach is to limit the "business hours" of non-essential loads, like welders and mills, to times of low aggregate demand or times with surplus generation. This strategy is more commonly employed on micro-hydro, biomass, or diesel-hybrid mini-grids, but could be effective on wind or solar mini-grids that are large

[12] ITDG is now called Practical Action.

enough to support small industry. Schedules for commercial loads can either be mandated by the community or mini-grid operator, encouraged through time-of-use pricing, or technologically enforced through some form of “smart” current limiter. Commonly, a village-scale mini-grid will only host a few commercial or industrial loads, and these will be large in comparison to the residential load. This scenario simplifies enforcement of an agreement or price point, because use of large commercial equipment during peak hours would cause substantial variations in the grid and be noticeable to other customers (ESMAP 2000).

From their experience working with ITDG, Holland et al. (2002) suggest instituting time diversity for high load uses and provide the example of a mini-grid in Peru that restricted welding to afternoons. Yet another example is found in Nepal in which a system for residential lighting also serves a grain mill during the day and a water pump to fill a village reservoir in the late evening (ESMAP 2000). These measures help to both minimize the commercial impact on the residential peak loads and protect the commercial equipment and processes from damage due to low voltages. Encouraging the development and connection of commercial loads can vastly improve the economics of mini-grid installation, but these large loads must be managed appropriately to ensure that all commercial and residential consumers are provided adequate and affordable electricity service.

Restricting Residential Appliance Use

Another method of limiting peak loads and encouraging electricity conservation is to restrict the use of certain types of residential appliances (ESMAP 2000). Some mini-grids are designed solely for lighting loads and, by default, restrict the use of all other appliances. The Mera Gao system, currently being installed in villages in Uttar Pradesh, India, uses a small solar array and battery bank to provide DC electricity to over 100 households (Mera Gao 2013). Each house receives two to four high-efficiency LED lights and one cell phone charger. No electrical outlets are included and no additional appliances may be used.

On mini-grids that provide adequate electricity for some plug loads, restriction based on a verbal village agreement without technical intervention is a more difficult task. In a mini-grid case study from Laos, a low-cost generation and distribution system had been sized for one 20 W light bulb per customer, and customers were billed according to this assumed load. Despite this presumed restriction on load, all households installed at least one electrical socket as well. The logical consequence of this design was that the households attempted to use appliances, which subsequently over-loaded the system and burnt out the generator (ESMAP 2000). In the village of Ura, Bhutan, the mini-grid operator did not permit the use of large appliances, such as electric rice cookers and water boilers. However, the majority of consumers still owned at least one rice cooker and approximately 30% owned water boilers, the use of which resulted in regular brownouts (Dorji 2007). In another case study in Indonesia, a village agreement was instated to limit individual power use to 40 W (ESMAP 2000). At first, households did not follow the agreement; however, after the generator routinely shut down due to low frequency, the village leaders began to police the consumers. Culturally the village was predisposed to operate by consensus, which enabled this policing, along with peer pressure to conform, to result in consumers adapting their energy use to stay within the limits of the system. As demonstrated by these examples, village agreements without technical or community enforcement are typically ineffective at restricting load, but can be used in combination with other DSM measures, such as current limiters.

Price Incentives and Tariff Structure

A well-designed tariff structure can greatly influence electricity use on mini-grids and is critical to the economic sustainability of the system. Tariff structures commonly used on mini-grids can be divided into two broad schemes: capacity-based (or power-based) and consumption-based (or energy-based).

With a capacity-based tariff the customer is charged according to the maximum power they are allowed to use (ESMAP 2000; Rolland and Glania 2011). Often on mini-grids, several different levels of power are offered to meet the needs of customers. These allotments could be determined based on a customer's willingness to pay or by the permitted number of lights or type of appliances, and can be enforced through verbal or written agreements and/or the use of some form of current limiter. Capacity-based tariffs can make billing easier, as all parties have agreed to a set fee in advance, but they are difficult to enforce solely with an agreement, while current limiters are often subject to tampering and fraud (ESMAP 2000; Rolland and Glania 2011). Capacity-based tariffs are appropriate for use on micro-hydro and other power-limited mini-grids as they inherently limit and equitably distribute power at any given instant. Additionally, some form of capacity-based tariff or a current limiter may be used in conjunction with an energy-based tariff on other types of mini-grids.

A consumption-based tariff is charged based on metered energy consumption and can therefore encourage energy conservation (ESMAP 2000; Casillas and Kammen 2011; Rolland and Glania 2011). This ability to encourage conservation makes consumption-based tariffs appropriate for mini-grids that are energy-limited, such as solar and wind mini-grids. Grids that are only power-limited and are not vulnerable to excessive energy consumption, such as micro-hydro mini-grids, do not typically require metering (ESMAP 2000). The appropriateness of metering on a biomass or diesel grid depends on the intermittency of the generation, the cost of the fuel, and the efficiency curve of the generator. In cases where the system is not dependent on a battery bank and the fuel consumption of the generator varies little with the generator output or the cost of fuel is negligible, a capacity-based tariff would be more suitable because energy conservation is not critical (Schnitzer 2013, pers. comm.). While energy conservation can be achieved through metering alone, for isolated mini-grids, peak demand must also be limited to prevent system overloads (Rolland and Glania 2011).

Several options exist for the structure of a consumption-based tariff. Electrical utilities in industrialized nations are increasingly implementing dynamic electricity rates, such as real-time pricing and critical-peak pricing to limit demand during peak periods and encourage energy conservation for grid-connected customers (Borenstein 2005; Orans et al. 2010). In addition to these more sophisticated rate structures, simpler ones that have been in wide use for central grid customers in industrialized countries, such as time-of-use or inverted block (or tiered) rates, can be applied to mini-grids in both developed and developing countries. As discussed previously in reference to commercial load scheduling, time-of-use rates can be applied to mini-grids, but are often only used for large commercial customers who can be easily monitored or afford a more expensive meter (ESMAP 2000). Other researchers investigating tariffs for rural utilities argue that use of an inverted block rate can be regressive within a given block, may be confusing to the consumer and can penalize consumers with connections shared by multiple households (Boland and Whittington 2000). Based on economic theory, these researchers suggest using a flat-rate tariff equal to the unsubsidized marginal cost of the service in combination with a lump-sum rebate to ensure that low-income households can meet their "essential" needs (Boland and Whittington 2000). It should also be noted that on some mini-grids, electricity rates may be highly subsidized so that they no longer provide the necessary price signals to encourage conservation. Pelland et al. (2012) found that mini-grid customers in Canada were using inefficient electric baseboard heaters and suggested that adding an inverted block rate would encourage conservation behavior on the diesel mini-grid.

Some advanced metering systems, which are presented later in Table 3, offer additional variations on the consumption-based tariff that are particularly suited for the constraints of an isolated, energy-limited grid. As many mini-grids rely on battery banks that are sized to provide storage on the order of days, using a tariff that limits a consumer's daily consumption provides the most effective regulation. Some of these metering systems charge a tariff based on a pre-determined daily or weekly energy allotment or rate of available energy (CAT Projects 2011; Briganti et al. 2012; INENSUS 2012; Powerhive 2012; SharedSolar 2012).

Regardless of what tariff structure is chosen, to ensure project sustainability, at a minimum, the tariff structure must cover the marginal costs of the system, or the mini-grid's operation and maintenance costs, as well as any amortized capital costs (Rolland and Glania 2011). For effective tariff design, these costs are balanced with a realistic assessment of the consumers' willingness and ability to pay (Rolland and Glania 2011).

Community Involvement, Consumer Education and Village Committees

Integral to the functioning of nearly all of these strategies is community involvement. Educating community members as to the functioning and limitations of their mini-grid will enable these end-users to provide informed input on which DSM strategies to pursue and make the community more likely to comply with any DSM measures taken (Rolland and Glania 2011). Education can also greatly improve user satisfaction: without an understanding of why energy and power must be limited, users will complain and may ignore or bypass restrictions (Vallvé et al. 2000). Further, community agreements, whether verbal or written, can empower community members and project managers to manage and enforce decisions on tariff structure and load management.

If being introduced at the start of a mini-grid project, education and discussions on DSM may be incorporated in broader discussions on expected demand and willingness to pay, but follow-up on these subjects is important after system installation as well (CAT

Projects 2011; Rolland and Glania 2011). Topics that are useful to incorporate in community trainings and discussions include:

- technical limitations of the mini-grid and consequences of mini-grid overload
- importance of and methods for sharing and distributing electricity
- respective power ratings of various appliances
- energy efficiency and phantom loads
- technical functioning of any load management devices
- tariff structure and tariff collection
- enforcement, penalties, and disconnection/reconnection procedures
- incentives for and benefits of conscientious electricity use

Further, depending on the load management strategies chosen, additional training of any personnel responsible for operations, maintenance, or management of the mini-grid may be required. Many of the developers of the advanced metering systems described later in Table 3 emphasize the importance of community involvement and recommend practices such as hosting community meetings, facilitating small-group workshops and conducting in-home visits. The use of well-illustrated visual aids such as posters, pamphlets and props for discussion both facilitate discussion and provide reminders for consumers after a meeting or training (ESMAP 2000).

One commonly effective mechanism for eliciting community input is the development of village committees. Such committees can greatly improve the management of the mini-grid. Just as with nearly any intervention in a village, working within the structure of existing village government and ensuring the involvement of established local leaders on the committee will often improve community acceptance and facilitate interactions with the community (Rolland and Glania 2011). For just one example, in their 2003 report on distributed generation efforts in India, the Indian Government's Ministry of Power discusses their experience with community involvement and the establishment of village committees to help manage electricity consumption. As a result of the village committees' requests and actions, the villagers were educated about their electric supply and requested to be supplied with meters. With the introduction of metered electricity and the accompanying education, many residents stopped using electric heaters, which resulted in a more stable electric supply (MOP 2003). Though critical to project success, the establishment and effective functioning of village committees can require substantial training in technical topics and methods of facilitation, governance, and communication, and can easily be hindered by disinterested, disruptive or inexperienced committee members (Vaghela 2010). In her work developing several mini-grids in India, Vaghela found that an effective method of training and supporting new village electricity committees was to have experienced village electricity committee members from neighboring communities mentor the new committees.

2.2.2. DSM Technologies

Currently, a host of different technologies designed to aid with demand management on mini-grids are either in development or on the market. The technologies discussed below include basic current limiters, devices that provide "smart" DSM, conventional electricity meters, prepaid electricity meters, and devices that combine many of these concepts into one system. A description of each technology follows, along with information about its use in existing projects and potential applications on mini-grids.

Load Limiters

The most basic and inexpensive of these devices are current limiters.[13] Current limiters can be fuses, miniature circuit breakers (MCBs), positive temperature coefficient thermistors (PTCs) or electronic circuit breakers (Smith 1995; ESMAP 2000; Smith and Ranjitkar 2000; Smith, Taylor, and Matthews 2003). Most are produced for general use in the electrical or automotive industry, though some are particularly designed for installation on mini-grids. Current limiters are commonly used without additional metering on micro-hydro mini-grids, where power is limited but the energy supply is relatively constant and comes at a low marginal cost. In most of these installations, consumers are charged a flat fee for electricity based on their chosen current limit. This system can be very cost effective as it simplifies billing, eliminates the cost of a meter and the need for a meter reader, and comes at low cost (between approximately US$ 1 - US$ 15 depending on the type of limiter). On other mini- grids with intermittent generation, such as solar or wind, practitioners recommend installing current limiters in conjunction with energy metering devices to encourage conservation (ESMAP 2000). Grids with a cost associated with each unit of electricity produced, such as diesel and

[13] Current limiters are also often referred to as load limiters, current cut-outs or current cut-off devices.

biomass, may benefit from metering in addition to current limiting depending on their intermittency, the efficiency curve of the generator, and the marginal cost of electricity.

The different types of load limiters are presented in brief in Table 2; a more thorough description and discussion of load limiters can be found on pages 154-162 of the Mini-Grid Design Manual (ESMAP 2000). All of these devices come in various sizes; the minimum and maximum currents listed in Table 2 represent the range of available shut-off current ratings for these devices.   No minimum current threshold is required for these devices to operate.

Table 2. Characteristics of a variety of current cut-off devices (Reproduced from ESMAP 2000)

Attributes	Fuse	Thermal miniature circuit breaker	Magnetic miniature circuit breaker	Thermistor	Electronic Circuit breaker
Reset Mechanism	Replace	Manual	Manual	Auto	Auto
Accuracy	Poor	Poor	Medium	Very Poor	Medium-Good
Min. current (A)	0.04 A	0.05 A	0.05 A	0.01 A	0.05 A
Max. current (A)	>50 A	>50 A	>50 A	0.7 A	5 A
Availability	Good	Good for > 6 A	Limited	Limited	Very Limited
Price	Low	Low-Medium	Medium	Low	Medium-High

Though any of the above devices may be installed on mini-grids, in research conducted for this review, only two load limiters were identified that were designed particularly for use on mini-grids: the Load Checker and electronic circuit breakers.   The Load Checker, produced in India by Aartech Solonics Ltd., is a device that incorporates a positive temperature coefficient (PTC) thermistor to restrict load at levels between

0.031A and 0.4 A, depending on the model (Aartech Solonics Ltd 2012).[14] The device comes in two form factors, one enclosed in a PVC pipe for pole-mounting, and one shaped like an MCB that can be easily mounted in a typical MCB enclosure. Pole-mounting the current limiter in an inaccessible, public location reduces the risk of users bypassing the device; however, the convenience of installing and servicing the MCB form factor may outweigh this benefit. As with all thermistors, the Load Checker is self-resetting; however, all loads must be removed before the device will reset. The Load Checker's retail cost is approximately US$ 5, though prices vary based on the model.

Electronic circuit breakers are also designed particularly for mini-grids. These devices use a thyristor or transistor to disconnect the load, automatically reset and are much more accurate than the other available load limiters. Electronic circuit breakers are produced by the British company Sustainable Control Systems under the name PowerProvider and by Development Consulting Services in Nepal at a cost of around US$ 15 each (ESMAP 2000; Smith, Taylor, and Matthews 2003). Additionally, an

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[14] A PTC thermistor is a polymer or doped-ceramic circuit component whose resistance increases sharply at a critical temperature. This characteristic allows the thermistor to act as a current limiter. As current passes through the thermistor, heat is generated. If the current is high enough to cause heat to be generated at a greater rate than can be released to the environment, the device will heat up and the resistance will increase until it effectively cuts off the current to the load. This limiting process happens on the order of seconds for large loads, but may take longer for loads that are just above a given threshold. Because of this thermally-dependent process, PTC thermistors can be affected by ambient temperatures and are not precision current limiting devices. Additionally, PTC thermistors pose potential safety risks, as there are no physical contacts that open and isolate the load from the supply. They are, however, self-resetting: once the load is disconnected, the thermistor rapidly cools and the resistance decreases so that permissible loads can be used.

electronics manufacturer in Thailand suggested they could produce similar electronic breakers for approximately US$ 5 each (Greacen 2004).[15]

Though initially effective, load limiters can be unreliable and have been found to be commonly bypassed or fraudulently replaced with limiters with higher current ratings (ESMAP 2000; Dorji 2007). Additionally, load limiters require that individual access be restricted at all times, regardless of the available power on the mini-grid. This constraint results in reduced consumer welfare by limiting the appliances that consumers can use. In micro-hydro systems, this constraint can cause energy to be wasted (often sent to resistive dump loads) at times of low demand.

Distributed Intelligent Load Controller

Just as the GridShare, distributed intelligent load controllers (DILCs) are devised to address the need to limit peak demand but still enable use of the excess energy produced off-peak.[16] Smith et al. (2003) describe using the combination of load limiters and DILCs to better manage a mini-grid for a Ugandan hospital. The system managers intended to provide a secure electrical supply to the hospital and secure supply for low power applications, such as lights and TVs, in the staff residences. Realizing that excess

[15] These prices are quoted as provided in literature; values are not adjusted to 2013 US$ equivalents.

[16] It is unclear whether DILCs were installed on additional mini-grids or if any were manufactured beyond this initial pilot project in Uganda. Though this product may not be currently available on the market, the idea could potentially be replicated and provides an interesting DSM model.

electricity would be available at off-peak times, they also wanted to make this supply available for higher power appliances, such as water heaters, cookers, and irons.

To address these goals, all staff houses were outfitted with lights and outlets that were current limited at either 1 A, 2.5 A, or 5 A, which enabled the use of low power appliances at all times. Further, to facilitate the use of off-peak electricity, DILCs were installed in several of the staff houses and communal buildings. DILCs were either used to replace the control circuits on water heaters or wired to a separate, non-current limited outlet that allowed a current up to 13 A. When load on the system increased beyond the capacity of the generator, the frequency of the system would decrease. As the frequency decreased, the DILCs switched off power to the water heaters, and if the frequency continued to decrease, power would be disconnected from the high-power outlets. After installation of this load management package, the electric supply became more reliable with fewer power outages, and users expressed satisfaction with the ability to have a reliable electric supply while still being able to use high-power appliances.

Conventional Meters

Conventional meters measure kilowatt-hours of energy used by the consumer and are typically placed at the service entrance to a customer. Conventional meters place no restrictions on the amount of energy a customer can consume and typically do not limit the amount of power that can be drawn, though some may include current protection for the meter. Though meters do not actively limit power or energy consumption, the use of meters with an effective billing scheme can encourage energy conservation (ESMAP 2000; Casillas and Kammen 2011). Monitoring and billing based on energy consumption is particularly important for systems with inconsistent generation and limited storage, such as solar and wind, but may not be necessary for micro-hydro systems (ESMAP 2000). Grids with a marginal cost of electricity, such as biomass and diesel, may or may not require metering depending on the intermittency of the generation, the cost of the fuel, and the efficiency curve of the generator. As power is also limited on all of these grids, the best practice is to install meters in conjunction with either a load limiter or a form of "smart" DSM.

The installation of meters on otherwise unregulated mini-grids has been shown to decrease consumption. Casillas and Kammen (2011) found that the installation of meters on a diesel mini-grid in Nicaragua resulted in a 28% decrease in consumption. As mentioned previously, the Indian Government's Ministry of Power also found that in villages that installed meters, residential demand due to electric heaters decreased and grid power was better stabilized (MOP 2003).

Though conventional meters can be effective at reducing consumption, they come at a modestly high initial cost (~US$ 20 each plus installation) and create ongoing costs for meter readers.[17] Meter reading can also be inaccurate, and poorly managed billing practices can be controversial and lead to frustration for both the customer and the billing authority (ESMAP 2000). Additionally, low-income consumers can receive bills that are beyond their means to pay.

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[17] Note that retail price information was not collected from all companies and was quoted for quantities of 100 units.

Prepaid Meters

Since the late 1980s, prepaid meters have risen in popularity for use on both mini-grids and utility-scale grids (Tewari and Shah 2003; Nefale 2004; Ghanadan 2009; Van Heusden 2009; Ruiters 2009). Prepaid meters offer low-income customers the ability to more closely manage their consumption and make smaller, more regular payments that are often better matched to their cash flow.[18] These meters also aid the mini-grid operators in reducing account posting costs, eliminating the need for meter readers and better guaranteeing payment. The most basic prepaid meters allow a consumer to add energy (as measured in kWh) to the meter by use of a prepaid card or code. Credit can be purchased in small increments either from a local vendor or, in some cases, through a mobile phone payment system. Prepaid meters do require a higher initial investment than conventional meters (typical costs run from approximately US$ 35-US$ 50 per unit) but can often result in substantial savings from reduced billing costs and more reliable

[18] It is important to note that prepaid meters were met with substantial resistance when first installed in communities in South Africa, largely because they were seen as being installed in response to the politicized payment boycotts associated with the anti-apartheid movement (Tewari and Shah 2003; Van Heusden 2009). Prepaid meters individualized payments so that communities could no longer organize effective boycotts, and had the connotation that customers were not credit-worthy. Additionally, the prepaid meters imposed new limitations on customers who previously had not faced immediate restrictions on their energy consumption, so consumers who previously were only cut off every few months were now having their electricity cut off several times a month (Nefale 2004; Ruiters 2009). Projects have found that when installed in less politicized circumstances and when accompanied by appropriate informational campaigns, prepaid meters are appreciated by communities as they enable consumers to better budget their energy use, avoid additional reconnection fees and minimize conflict with the utility (Ghanadan 2009; Ruiters 2009).

payments from customers.[19] An additional cost or opportunity that should be considered with the installation of prepaid meters is the need for a vendor of the prepaid cards or codes.

Just as with conventional meters, prepaid meters do not necessarily restrict peak power use, though some do come with this feature available (Conlog 2013; Itron 2013). On mini-grids, it is again best practice to use these meters in conjunction with a load limiter or “smart” DSM to both encourage energy conservation and restrict power demand. Some prepaid meters are designed to provide another form of DSM through primary and auxiliary circuits; while load-limited primary circuits are always available, higher-power auxiliary circuits can be controlled to disconnect during peak periods (Landis+Gyr 2012). More sophisticated meters combining prepaid meters with either DSM or centralized energy management systems are described in the next section.

Advanced Metering Systems with Centralized Communication

Recently, several researchers and social venture companies have designed and installed advanced mini-grid control systems, which typically involve a variant of prepaid metering along with a supervisory control system that manages energy generation and storage while simultaneously creating potential for DSM interventions (Table 3). Though they are all relatively new, some of these systems have undergone successful field trials; these include the Circutor Electricity Dispenser, Inensus Micro Utility

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[19] Note that price information was not collected from all companies and the approximate retail price was quoted for quantities of 100 units. Price estimates are from 2013.

Solution, CAT Projects's Bushlight India and SharedSolar (CAT Projects 2011; Briganti et al. 2012; Circutor 2012; INENSUS 2012; SharedSolar 2012; Soto et al. 2012). Other systems, including Powerhive and Gram Power's Smart Microgrid, are currently undergoing their early pilot or demonstration projects (Powerhive 2012; Gram Power 2013). An additional start-up, Lumeter, is in the process of field-testing their first prototypes (Lumeter 2013).

All of these products are designed for either solar or solar-wind-diesel hybrid mini-grids. Though most could technically be installed on a micro-hydro mini-grid, thanks to the relatively consistent generation from a micro-hydro plant, the added investment in generation and load management is likely not worth the added expense of these systems. Unfortunately, price estimates could not be obtained for all of the available products. Nevertheless, these devices appear to be more expensive than standard prepaid meters. The companies that did report values indicated per unit prices on the order of US$ 100 to US$ 200. The cost of adding prepaid card "vending" devices and centralized control modules could be substantially more. Most of these metering systems would result in a higher capital cost for the mini-grid, though they could potentially be financed through elevated tariffs over time. Each of these advanced metering systems is summarized in Table 3 and described in more detail below.

Table 3. Summary of Advanced Metering Systems with Centralized Communication

Company and Product	**Payment System**	**DSM Capability**	**Countries of Activity**
Circutor *Electricity Dispenser*	Monthly subscription to “Energy Daily Allowance”; a local vendor programs the EDA and power limit onto a card that is used to activate meter	-Power limit -Energy usage limited to pre-arranged rate -Enables loadshedding -Can use “pricing” signals to encourage DSM	Cape Verde, Morocco, Ecuador, Chad
INENSUS *Micro Utility Solution*	Monthly purchase of weekly “electricity blocks”; an INENSUS sales agent adds credits to a card that is used to activate the meter. The number of electricity blocks purchased by each household is negotiated every six months.	-Power limit -Energy usage limited to pre-arranged amount -Enables loadshedding -Strong emphasis on education and community involvement	Senegal
CAT Projects *Bushlight India*	Monthly subscription to a fixed daily energy budget (between 0-10 kWh/day) that is programmed on to the household meter.	-Power limit - Maximum daily energy limit -Enables loadshedding -Strong emphasis on education and community involvement	India (based on program from Australia)
Modi Research Group Columbia University *Shared Solar*	Customers purchase scratch cards from a local vendor for electricity credits and then send an SMS message to the central computer to add credit. Multi-channel meters are centrally located.	-Power limit -Maximum daily energy limit -Pre-paid metering -Plan to incorporate additional DSM measures	Mali and Uganda
Powerhive	Customers purchase electricity credit through mobile money systems. Multi-channel meters are centrally located.	-Power limit -Maximum daily energy limit -Pre-paid metering -Plan to incorporate additional DSM measures	Kenya
Gram Power *Smart Microgrid*	Customers purchase electricity credit from local vendor who programs individual meters.	-Power limit -Pre-paid metering -Plan to incorporate additional DSM measures	India
Lumeter	Customers purchase credits from local vendors who provide a code that can be programmed into the meter. Back-end accounting enables reimbursement of project developers based on electricity purchases and subsidizes the initial cost of the meter.	-Power limit -Pre-paid metering -Enables loadshedding	Soon to be installed in Peru

2.2.3. Summary of DSM Measures

As evident from the review above, the GridShare fills a space in a wide spectrum of DSM measures used to improve electricity service on mini-grids. Clearly, certain strategies and technologies should be considered for use on nearly every mini-grid. Foremost, the use of efficient light bulbs and, when affordable and available, efficient appliances, can greatly improve the overall efficiency of the system. By both encouraging conservation and reducing peak loads, these measures can allow an existing grid to serve more households and reduce the required initial investment in generation and distribution capacity for a new grid. Similarly, when feasible, the strategy of encouraging the use of large commercial loads during periods of low aggregate demand or times with surplus generation should be considered for most mini-grids with commercial or industrial loads. Appropriately scheduling commercial loads is a relatively low cost strategy that can provide substantial rewards through reducing peak load and increasing load factor.

Additionally, as all isolated mini-grids are power-limited, some form of load limiter should be included in the system design to ensure equitable power use. For systems which typically produce excess generation throughout the day, such as micro-hydro mini-grids with no storage, “smart” load limiters, such as the GridShare or Distributed Intelligent Load Controllers, should be considered. These technologies may require more investment and management than a simple fuse, MCB, PTC thermistor or electronic circuit breaker, but the enhanced ability to use high-power appliances at off-peak times can improve both user satisfaction and compliance.

As discussed above, the tariff structures and other DSM strategies will differ between mini-grids that are primarily power-limited, such as micro-hydro, and those that are also energy-limited, such as wind and solar. On mini-grids with more limited generation, higher marginal costs of electricity and energy storage constraints, metering electricity can help to encourage conservation. Metering is not typically required on a micro-hydro mini-grid, as power is usually the limiting factor on these grids, but some form of metering should be included with a solar or wind-based grid with limited storage. Metering may also be advisable for biomass and diesel grids, depending on the intermittency of the generation, the cost of the fuel, and the efficiency curve of the generator.

As described above, when introduced appropriately, prepaid metering often results in benefits for the consumer and enables a more secure investment for the project developer. These benefits of pre-paid metering primarily result from the improvement in customer tariff collection relative to systems that depend on bill collectors or customers making payments at a central office. In recent years, researchers and businesses have begun to innovate on the incorporation of advanced meters in mini-grid development, spawning at least seven new models of system management and business design. Each of these models shows promise in terms of providing reliable electricity service for rural customers and the coming years will determine their success as sustainable business models. Finally, though effects of DSM consumer education are typically short-lived without some form of enforcement, discussions about load management are key to the success of all of the other strategies and technologies and should be incorporated into the development of any mini-grid.

The country of Bhutan was mentioned several times throughout this review of mini-grids and appropriate DSM measures. Thanks to its rugged geography which both isolates communities and provides ample resources for micro-hydroelectric generation, Bhutan hosts eleven active mini-grids, some of which suffer from poor load management. The following section provides background on Bhutan to better present the setting of the pilot installation on the Rukubji micro-hydroelectric mini-grid.

2.3. Bhutan

Bhutan is a small, mountainous country in the Himalayan region of South Asia, bordered to the west, south and east by the Indian states of Sikkim, West Bengal, Assam and Arunachal Pradesh, and to the north by the Tibetan region of China (Figure 4). Bhutan spans approximately 38,390 sq. km with a landscape that ranges from the southern foothills, with elevations as low as 100 m above sea level and a subtropical climate, to the high Himalayas, with peaks rising above 7500 m and harsh alpine conditions (Uddin, Taplin, and Yu 2007; World Bank 2013). Much of the country's population resides in the broad river valleys of the inner Himalayas, which offer arable land and a temperate climate at elevations between 1000 to 3000 m (Uddin, Taplin, and Yu 2007; MoWHS 2008). The country has several large population centers, of which the capital Thimphu is the largest, and is divided into 20 districts, or Dzongkhags, which are further divided into 205 Geogs, or regional blocks, which each comprise several villages (National Assembly of Bhutan 2007; RGoB 2013).

Figure 4. Map of Bhutan. The national capital, Thimphu is highlighted with a red star. The pilot project was located in Rukubji, a village in the center of the Wangdue Phodrang district, approximately 4 hours east of Thimphu.
(Image adapted from: http://www.landkartenindex.de and www.wikipedia.com).

In the past decade, population estimates for Bhutan have varied widely from 690,000 people to over 2.1 million, though the Royal Government of Bhutan (RGoB) currently reports a population of 720,679 (Zurick 2006; RGoB 2013; CIA 2013).[20]

[20] Population estimates vary largely because of the lack of an accurate census prior to 2005, varying estimates of population growth rates and the decision on whether to include refugees from Bhutan in the estimate (Zurick 2006; CIA 2013).

Despite the recent trend toward urbanization, with an urban growth rate of between 3% - 7% per year, 64% of Bhutan's population is rural and the country has a low population density of less than 19 people per km sq., (MoWHS 2008; World Bank 2013). Bhutan's distinct combination of geographic isolation, diverse landscapes and low population density have all contributed to the country's rich cultural heritage and unique governmental history.

2.3.1. Government and History

Bhutan has been considered an independent state since the mid-1600s, though it was largely ruled by feuding district governors until 1907, when the crowning of the first king created a unified kingdom (Zurick 2006). While the country maintained a self-imposed isolation from the Western world, the early hereditary kings worked to stabilize the country and establish initial reforms, such as the introduction of an education system and the establishment of a national taxation system in place of feudal taxes paid to the district governors (Zurick 2006; Uddin, Taplin, and Yu 2007; RGoB 2008). During this time of isolation, most of the population continued to live an agrarian lifestyle without most modern conveniences. There were no roads and no motor vehicles in the country; mules and horses were the dominant mode of transportation. Further there was no electricity and no means of communication such as a postal or telecommunication system (RGoB 2000). In the 1950s and 1960s, the third king oversaw the first steps toward the modernization of Bhutan; in 1961, the country created its first Five-Year Plan, opened its borders to the outside world and introduced the first modern infrastructure including roads, power and telecommunications (RGoB 2000; Uddin, Taplin, and Yu 2007). The fourth king continued to encourage the development of the country and established the guiding principle of Gross National Happiness (GNH), while also working to decentralize and democratize the government (RGoB 2000; Zurick 2006; RGoB 2008). In 2008, under the reign of the fifth and current king, the Bhutanese adopted their first constitution and voted in popular elections which marked the peaceful transition from the existing absolute monarchy to a democratic constitutional monarchy (GNHC 2008).

In recent planning documents, Bhutan has prioritized the concept of GNH over that of Gross National Product (GNP) to encourage development that seeks to maximize happiness rather than economic growth. Though the concept was first introduced in 1989, successive documents have shaped its definition, application and quantifiable indicators. In Bhutan's development strategy paper, *Bhutan 2020: A Vision for Peace Prosperity and Happiness*, the authors expound upon the concept as follows:

> The key to the concept of Gross National Happiness cannot be found in the conventional theories of development economists and in the application of such measures as utility functions, consumption preferences and propensity and desire fulfillment. It resides in the belief that the key to happiness is to be found, once basic material needs have been met, in the satisfaction of non-material needs and in emotional and spiritual growth. (RoGB 1999)

To help define and assess the GNH concept, Bhutan identified four elements which contribute to happiness: economic development, environmental preservation, cultural preservation and promotion, and good governance (RGoB 2000).

2.3.2. Culture, Language and Literacy

The GNH concept shares core values with the country's dominant Buddhist religion, which encourages practitioners to seek spiritual fulfillment by "avoiding dissatisfaction (which emanates in part from unmet material needs), enriching cultural values, nurturing a healthy and productive natural environment, and enabling freedom of choice" (Zurick 2006). Approximately 75% of the country practices some form of Vajrayana Buddhism, which was introduced to the region between the 7th and 17th centuries by various Tibetan lamas (RGoB 2000; Zurick 2006). Scholars suggest that the compassion-based collectivism and moral lessons present in Buddhism tend to encourage unselfish individual behavior that benefits the community (Daniels 1998).

Though often Bhutan is portrayed as having a single, unified cultural identity, in reality, the country comprises many ethnic groups, the three largest being the Ngalong in the west, the Sharchop in the east, and the Lhotshampa in the south (Zurick 2006). The Ngalong and Sharchop account for approximately 50% of the population; both follow sects of Buddhism and speak Tibeto-Burman languages (Van Driem and Tshering 1998; Zurick 2006; CIA 2013). The Lhotshampa make up a large portion of Bhutan's ethnic Nepalese population, which accounts for 35% of Bhutan's total population (CIA 2013). Like most of the ethnic Nepalese, the Lhotshampa practice Hinduism and speak a form of Nepali (Van Driem and Tshering 1998; Zurick 2006). The Ngalong primarily live in the more-developed western districts of Bhutan, including the Thimphu, Paro, Punakha and Wandi Phodrang districts, and are native speakers of the national language, Dzongkha (Van Driem and Tshering 1998).

While over 20 different native languages are spoken in Bhutan, Dzongkha, or "the language of the Dzongs," was named the national language in 1961 by royal decree (Van

Driem and Tshering 1998).[21] Formal written Dzongkha is nearly identical to Classical Tibetan (known in Bhutan as Chöke) and is used in spiritual and scholarly texts (Van Driem and Tshering 1998). Few, aside from Dzongkha scholars and religious clergy, are competent in the formal written text. Less formal written Dzongkha is based on the vernacular language as spoken in formal situations, while a more colloquial form of the language is typically spoken by the Ngalong. Though Dzongkha is the native language of less than 25% of the population, students throughout the country are instructed in both Dzongkha and English, and Dzongkha is used as the *lingua franca* nationwide (Van Driem and Tshering 1998).

As of 2007, Bhutan witnessed an adult literacy rate of 53% (GNHC 2008). By 2011, the primary school completion rate was 95% and secondary school enrollment rate was 70%, with a nearly equal ratio of boys and girls receiving this basic education (World Bank 2013). Only approximately 9% of the college-age students continue their education past secondary school and most of these students must pursue their education outside the country, commonly in India, Australia, Europe or the USA (RGoB 2000; BPC 2011; World Bank 2013).

2.3.3. Gender Equality

In Bhutan, gender interactions tend to be more egalitarian than in many other South Asian countries. Women are treated as equals under the law and inheritance is

[21] In Dzongkha, “kha” means “the language of” while “Dzong” means “fortress”, and refer to the fortresses found throughout the country which continue to serve as centers for district government and religious activities.

traditionally matrilineal (RGoB 2000; ADC 2007). In addition to actively participating in local and regional government, in recent years women have been encouraged to hold national office. Additionally, women's participation in civil service jobs is increasing and women are active in the formal economy, particularly in retail business. At the household level, though traditionally women are responsible for caring for the children and maintaining the house, gender roles often overlap; men are likely to also cook and clean for the household while often the most capable spouse will be considered the head of the household, irrespective of gender (RGoB 2000). Despite these fluid gender roles, on average, women typically spend more time in the house and are more likely to gather firewood for the household (ADC 2007).

2.3.4. Economy

Due to modernization and the high rate of rural to urban migration, in recent years the economy of Bhutan has dramatically shifted away from agriculture toward the industrial and service sectors. Whereas in 1999, 75% of the population depended on agriculture, in a 2006 survey, only 43% were employed in agriculture (GNHC 2008). In particular, the construction and electricity industries have seen rapid growth rates in recent years due largely to the government's investment in GW-scale hydropower projects. Export of hydropower to India accounts for approximately 45% of the country's total exports along with minerals, mineral products, cement, cash crops and wood products (Zurick 2006; World Bank 2011). Though diminishing on the national level, agriculture is still critical to the rural economy. In rural areas, subsistence farming is common along with the commercial production of apples, citrus fruits, potato, cardamom, ginger and oil seeds (RGoB 2000). In 2000, cattle were owned by an estimated 95% of households, and dairy farming for milk, cheese and butter was common (RGoB 2000).

2.3.5. Energy Production and Consumption

Bhutan has very limited fossil fuel reserves and all petroleum products, including kerosene, diesel, gasoline, aviation fuel and LPG, must be imported (Uddin, Taplin, and Yu 2007). Consequently, Bhutan extensively uses their abundant water and forest resources for energy production. In 2011, over 7,000 GWh of electricity were generated by the country's hydropower plants, with 21 GWh of this produced by mini- and micro-hydroelectric plants (BPC 2011). Currently, over 116,000 business and residential customers are supplied with electricity; in 2011 these Bhutanese customers used 1,619 GWh of electricity (BPC 2011). The Population and Housing Census of Bhutan reports that of the 126,000 households in Bhutan, 57% consider electricity their primary source of lighting and 30% use electricity for cooking (NSB 2005). Fuel wood is extensively used in the residential sector for heating and cooking and constitutes approximately 75% of the total energy consumption of the country (Uddin, Taplin, and Yu 2007). Annual fuel wood consumption is estimated to be over one million cubic meters, or more than 1.3 metric tons per capita per year (Forest Resources Assessment Program 1999; Uddin, Taplin, and Yu 2007). This rate of consumption is one of the highest in the world. As Bhutan boasts maintaining over 72% of their land with forest cover, this high rate of fuel wood consumption is not alarming on a national level but is projected to result in fuel wood scarcity in certain localities (Forest Resources Assessment Program 1999; Uddin, Taplin, and Yu 2007).

Households typically rely on a diversity of fuels to meet their needs for lighting, cooking and heating. In Dorji's study of two Bhutanese villages, Ura and Chendebji, households used a mix of electricity, fuel wood, kerosene, dry cell batteries and LPG to meet these needs (Dorji 2007). While electricity was used regularly for lighting, residents used a mix of electricity, fuel wood and LPG for cooking.[22] Though the convenience and cleanliness of LPG is appealing, Dorji found that the availability and high cost of LPG limited its use in comparison to fuel wood, which could be collected for free. When adequate electricity is available, residents will often offset their fuel wood use; studies estimate that electrification results in a 25% reduction of fuel wood use in rural households (ADC 2007).

2.3.6. Energy Management

Following the passage of the Electricity Act of 2001, management of the energy sector in Bhutan was divided into three main entities: the Bhutan Electricity Authority (BEA), the Department of Energy (DoE) and the Bhutan Power Corporation Limited (BPC) (National Assembly of Bhutan 2001; Dorji 2007; Uddin, Taplin, and Yu 2007).

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[22] This same pattern of "fuel stacking" has been noted worldwide since the 1980's. As described in Masera, Saatkamp, and Kammen (2000), when feasible, many rural households will acquire less-polluting and more-efficient cooking appliances (such as an LPG stove), but will not discontinue use of their old cooking methods (such as a wood-fired stove).

Each of these institutions serves a distinct role in the management of Bhutan's electric sector. The BEA is charged with developing and enforcing regulations, performance standards, safety codes, principles and procedures relating to the generation and provision of electricity. Additionally, the BEA is the body which approves electricity tariffs and sets subsidies for project development (National Assembly of Bhutan 2001). The DoE leads the long-term planning and program development for the country's electricity. The DoE also provides solar home systems for isolated customers and shares the responsibility of installing mini- and micro-hydroelectric mini-grids with the BPC (Dorji 2007). The BPC is a government-owned company, which owns and operates nearly all of the electric power transmission and distribution infrastructure in Bhutan. Within the BPC, Electricity Supply Divisions (ESDs) maintain the distribution systems in each district. The BPC's vision statement is "to be Customer Centric, Commercially Viable and Socially Conscious, and to contribute to the Socio-Economic Development of the Country" (BPC 2011). The BPC's goals are consistent with those stated in the Electricity Act of 2001:

> i) to promote a safe and reliable supply of electricity throughout the country;
>
> ii) to develop the socio-economic welfare of the people;
>
> iii) to promote economic self-reliance of the country through the development of a financially viable and reliable electricity industry;
>
> iv) to enhance revenue generation through export of electricity.
>
> v) to promote development of renewable energy resources;

vi) to take environmental considerations into account when developing the electricity supply industry; and

vii) to promote efficiency in management and service delivery.

Each of these objectives resonates with Bhutan's national identity and substantiates the government's interest in improving the service quality on their rural mini-grids. Further, in the nation's 1999 development strategy paper, the RGoB proposed the goal to provide at least 75% of the rural population with electricity (RoGB 1999). By 2008, the country had electrified 72% of the population and so, in the 10^{th} Five-Year Plan, the RGoB accelerated their goal to provide "electricity for all by 2013" (GNHC 2008). According to the BPC's 2011 Annual Report, they were making successful progress toward this goal as 86% of all households were connected to the main grid, while the country expects that more isolated customers, or 12% of total households, are either currently or will be served by micro-hydroelectric mini-grids, wind/PV/diesel hybrid systems or solar home systems (GNHC 2008; BPC 2011; Dorji, Urmee, and Jennings 2012).

2.3.7. Micro-hydroelectric Generation in Bhutan

Micro-hydroelectric systems, also referred to as micro-hydros or micro-hydels, are classified in Bhutan as plants with installed capacity less than 100 kW, though this classification varies internationally (Khennas and Barnett 2000; Garud and Gurung 2007). All micro-hydro systems in Bhutan are run-of-the-river systems in which, ideally, a small amount of water is diverted from a stream or river at an intake weir. Run-of-the-river systems do not require a dam and a reservoir. When sited and designed properly, because these systems only divert a small portion of the total flow, micro-hydros are often considered an environmentally sound and renewable method of producing energy (Penche 1998; Khennas and Barnett 2000; Masters 2004).[23] Additionally, though a substantial initial investment is required, because of the low operating costs of micro-hydros, these systems offer one of the most economical options for rural electrification on the basis of cost per kWh electricity generated (Khennas and Barnett 2000; World Bank 2007). When sufficient resource is available, this low cost per kWh enables the use of larger appliances and commercial machinery, both of which help make the plant economically viable and further the development goals of rural electrification. In addition to the environmental and economic arguments for micro-hydro, the technology offers additional benefits as it typically generates electricity at a relatively constant and predictable rate throughout the day, though this flow may vary seasonally (ESMAP 2000; Khennas and Barnett 2000).

Description of Run-of-the-River Micro-hydro

A typical schematic for a run-of-the-river micro-hydro system is displayed in Figure 5. A portion of the river's flow is diverted at the intake weir (Penche 1998; Masters 2004). Following the intake weir, water flows through a low-slope canal which is constructed to maintain flow without losing substantial elevation. Water often passes through settling tanks to reduce the amount of debris and grit in the water column before

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[23] Of course, when designed or cited improperly, these systems can have substantial environmental and social impacts at the local level. In her Ph. D dissertation, Kibler (2011) provides a review of environmental impacts common to small hydro development, while Penche (1998) provides an extensive coverage of both impacts of and mitigation methods for small hydro development.

continuing on to the forebay tank. From the forebay tank, water flows through a steep penstock before encountering the turbine (Penche 1998; Masters 2004). After flowing through the turbine, water is returned to the river through the tail race.

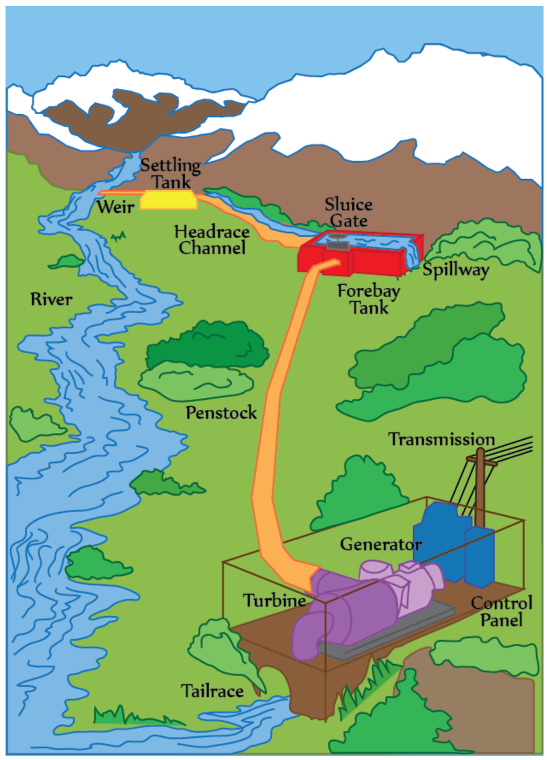

Figure 5. Diagram of a run-of-the-river micro-hydroelectric system (Image source: Image adapted by Kirstin Hervin; original diagram from R. Holland, Micro Hydro Electric Power, ITDG Publishing, 1986, available from www.accessscience.com)

The turbine is coupled with a generator which converts the resultant mechanical energy to electricity. Power (P) in watts is generated according to:

$$P = e\gamma Q H_N \qquad \text{(Penche 1998; Masters 2004)}$$

where: Q = flow (m^3/s)

H_N = net head, or the elevation difference from the water level in the forebay tank to the turbine, minus friction losses from the penstock (m)

e = efficiency of the turbine/generator

γ = specific weight of water, or the product of its mass and the gravitational acceleration per unit volume (N/m^3)

Isolated mini-grid scale micro-hydro systems typically use three-phase synchronous AC generators (Khennas and Barnett 2000; Masters 2004). Synchronous generators have a DC excitation system which allows them to produce power without being connected to an external power source, such as the main grid. This system further provides some degree of voltage, frequency and phase angle control (Khennas and Barnett 2000). Three-phase generators are typically used because they are more efficient than single phase generators and the resulting transmission systems make more efficient use of wires by either eliminating or sharing a single neutral line (Khennas and Barnett 2000; Masters 2004). Three-phase generation also enables the use of three-phase commercial loads, while residential loads are connected by tapping one of the three phase conductors to provide a single-phase connection (ESMAP 2000). On an ideal three-phase grid, each of the three circuits would serve similar loads, resulting in a “balanced” system; however, ensuring a balanced system on a mini-grid can be difficult as it requires estimating the peak load of each connection (ESMAP 2000; Masters 2004). Additionally, depending on the pattern of the distribution network, if a single phase line is strung through a more populated area, an individual phase may serve more households than the other phases, causing the system to be unbalanced (ESMAP 2000).

Existing Capacity in Bhutan

While most of Bhutan's power production is attributed to large MW- and GW-scale run-of-the river hydroelectric schemes, in 2011, over 21 GWh of generation were produced by the 16 operational mini- and micro-hydroelectric systems in Bhutan (BPC 2011; Dorji, Urmee, and Jennings 2012). Eleven of these systems are currently providing power to isolated mini-grids (Table 4). As the central grid is extended to more rural sections of the country, the government is working to interconnect many of these isolated micro-hydro systems with the main grid to provide customers with the increased utility of the central grid while still maintaining the reliability and added generation of the local micro-hydro (Norlha Associates 2008). Systems more distant from the central grid will likely continue to operate as isolated mini-grids. The potential exists for several additional plants to be constructed, though due to the requisite large initial investments, new projects will likely only be pursued if adequate grant funding is available (Arvidson et al. 2000; Dorji 2007; Uddin, Taplin, and Yu 2007).

Table 4. List of existing mini- and micro-hydroelectric systems in Bhutan

Dzongkhag	Plant Name	Donor	Installed Capacity (kW)	Start Date	Status	Grid Connection
Bumthang	Chumey	ni	1500	1988	Operational	On Grid
Bumthang	Tamshing	Japan	30	1987	Operational	Off Grid
Bumthang	Ura	Japan	50	1987	Operational	Off Grid
Tsirang	Changchey	Japan	200	1991	Operational	Off Grid
Dagana	Darachu	Japan	200	1992	Under Repair	Off Grid
Lhuntse	Rongchu	Bhutan	200	2001	Operational	On Grid
Lhuntse	Gangzur	India	120	2000	Operational	Off Grid
Mongar	Sengor	UNDP	100	2007	Operational	Off Grid
Mongar	Khalanzi	ni	390	1976	Under Repair	On Grid
Zhemgang	Kekhar	Japan	20	1987	Operational	Off Grid
Zhemgang	Tingtibi	Japan	200	1992	Operational	Off Grid
Thimphu	Lingshi	EU	10	1999	ni	Off Grid
Thimphu	Thimphu/ Jushina	ni	360	1967	Operational	On Grid
Thimphu	Gidakom	ni	1250	1973	Operational	On Grid
Trashigang	Chenari	ni	750	1972	Under Repair	On Grid
Trongsa	Tangsibji	Japan	30	1987	Operational	Off Grid
Trongsa	Sherubling	Japan	50	1987	Operational	Off Grid
Trongsa	Bubja/ Kuengarabten	Japan	30	1987	Under Repair	Off Grid
Trongsa	Chendebji	E7	70	2005	Operational	Off Grid
Wangdue	Rukubji	Japan	40	1987	Operational	Off Grid
Wangdue	Hesothankha	ni	300	1972	Operational	On Grid

ni = no information

Note: Though two of these plants have installed capacities greater than 1 MW, which would classify them as small hydros rather than mini-hydros, their current generating capacity is less than 1 MW and they are classified by the BPC as mini-hydels. Decommissioned plants are not included. (Data from: Dorji 2007; Garud and Gurung 2007; NSB 2012; Chhetri 2012, pers. comm.)

2.4. Summary

This background provides the setting for the pilot installation of GridShares in Rukubji, Bhutan. The Rukubji micro-hydro is one of eleven other mini- and micro-hydroelectric systems providing power to isolated electric grids in the hydropower-rich country of Bhutan. Much of Bhutanese culture is influenced by Buddhism, which inspires national policies focused on sustainable development and encourages collective action in private life. A supportive national government and national utility, in tandem with a community interested in the common good, provided an ideal location to pilot test a DSM device like the GridShare. The GridShare is one in a range of available devices and strategies used to manage loads on power-limited mini-grids. As mini-grids are increasingly incorporated into development plans for rural electrification, the need for effective DSM measures will grow. Studies such as this GridShare pilot project will help to test and refine technologies that can improve rural people's access to renewable, high quality electricity.

CHAPTER 3. PILOT GRIDSHARE INSTALLATION IN RUKUBJI

The Rukubji micro-hydro plant, the site of the pilot project, is located in a rich river valley in the center of the Wangue Phodrang district of Bhutan approximately four hours east of Thimphu. Electricity from the plant serves four villages which comprise approximately 90 households in total.

3.1. Village Description and Demographics

The village of Rukubji is the largest and most densely populated of the four villages. Rukubji includes approximately 43 households, an elementary school, a community center and temple. The villages of Bumiloo, Tsenpokto and Sangdo are located across the highway from Rukubji and consist of 27, 10 and 6 households, respectively (Figures 6, 7, 8 and 9). A popular travellers’ restaurant is located along the highway at the base of Bumiloo and a milk processing plant is located in the valley between Rukubji and Bumiloo.

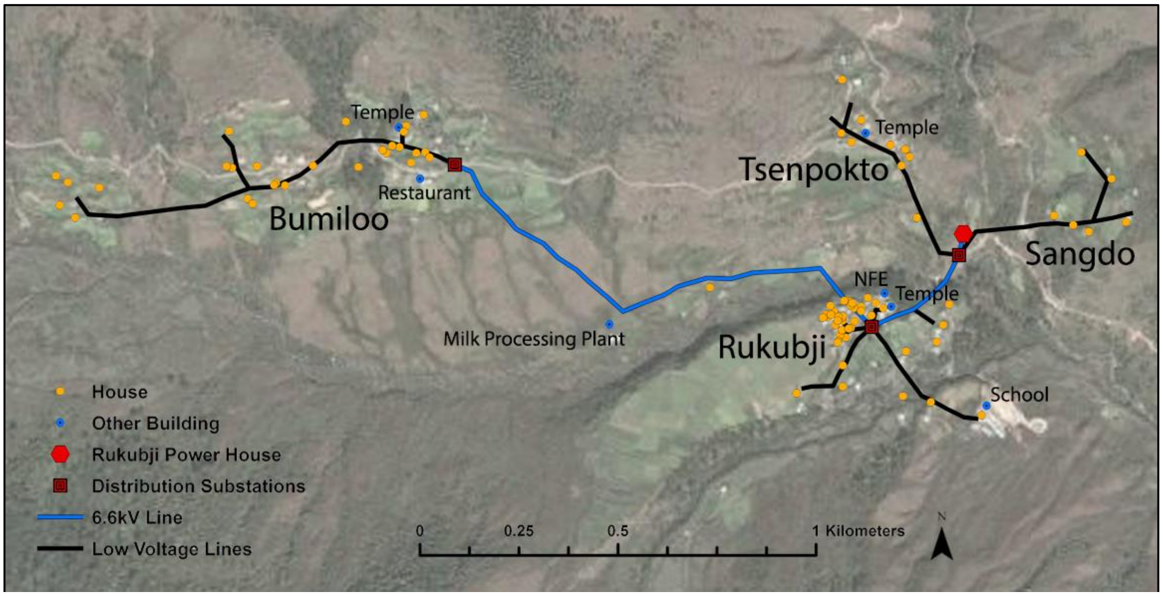

Figure 6. The mini-grid connecting the villages of Rukubji, Bumiloo, Tsenpokto and Sangdo. (Data for electrical lines provided by Dorji Namgay of the BPC, background image from Google Earth).


Figure 7. The village of Rukubji. Rukubji is densely populated and located in the valley between two rivers (Photo credit: Sonam Tobgay Tshering).

Figure 8. The village of Sangdo photographed from the village of Tsenpokto. The two villages are separated by a deep valley (Photo credit: Sonam Tobgay Tshering).

Figure 9. The village of Bumiloo set in the hills northwest of Rukubji (Photo credit: Sonam Tobgay Tshering).

According to our preliminary surveys, household size in the villages ranges from 1 to 11 people. Estimates of average household size increased from approximately four people per household in July to five people per household in January when students were home from boarding school. Just as household size varies, types of homes vary substantially, from single-room thatch structures to traditional multi-story houses with many rooms (Figure 10). In nearly all cases, the kitchens (and rice cookers) are located inside the main house. In several cases in Rukubji, families rent out rooms or sections of their house, typically to teachers from the local primary school. These landlords and boarders appear to act as separate households in terms of their cooking and daily routines.[24]

Figure 10. A view of the Rukubji village showing several different types of houses (Photo credit: Meg Harper).

[24] In some cases, the rental units were provided their own GridShare, while in others, a single GridShare was installed with a higher current limit and an extra LED box to accommodate the additional loads.

As the villages are located in a fertile river valley, daily activities largely center on agriculture. Historically most residents worked as subsistence farmers; however, in recent decades, many have begun to raise potatoes as a cash crop and over 50% of residents reported this as one of their primary activities. Many families also care for small numbers of dairy cows and make use of a cooperative milk processing facility located in between Rukubji and Bumiloo to produce cheese and butter for regional markets. Since 2004, many residents have begun to pursue an additional income source: gathering *Cordyceps* mushrooms.[25] These wild mushrooms are highly prized for medicinal use and offer variable, but typically high profits. To collect the mushrooms, residents will leave the village in the summer months of June and July to hike to the alpine slopes where the *Cordyceps* are found. With income from the *Cordyceps* harvest, the export of potatoes and the production of milk products, Rukubji and the surrounding villages are considered relatively prosperous in comparison to other villages in rural Bhutan.

[25] *Cordyceps spp.* is a type of fungus endemic to the Himalayan mountains that attacks the caterpillar larvae of the *Hepialis* moth. Fungal spores infect the burrowing larvae and the fungal mycelium quickly kills the insect. The fungus can lay dormant in the buried caterpillar for years until the conditions are right for the hyphae to emerge. A properly harvested *Cordyceps* will include both the caterpillar body and the small fungal hyphae emerging from its head. The King of Bhutan lifted the ban on *Cordyceps* harvest in 2004 and instated a policy encouraging sustainable harvest by rural residents. In Bhutan, *Cordyceps* are legally sold by auction with prices upwards of US$ 800/kg, but have been reportedly sold on international markets for over US$ 10,000/kg. (Namgyl 2008)

In addition to agricultural pursuits, several businesses are also present in the villages, including three small general shops and a popular traveler's restaurant. The restaurant serves breakfast and lunch to local buses and states that they prepare one 7-liter rice cooker of rice at 5AM, 9AM, 10AM, 11AM and 1PM every day. The other main employer in the area is the local elementary school. Several teachers and the headmaster come from outside the area for typically a two- to five-year assignment at the school.

The local language, Rukubjikha (the language of Rukubji), is a dialect of Lakha (the language of the mountain passes) formally known as Chutöbikha and is a close linguistic relative to Dzongkha, but the two are not mutually understood (Van Driem and Tshering 1998). In addition to Rukubjikha, nearly all residents spoke Dzongkha, the national language, and a few spoke English. Though no official assessment was made, some, but not all residents appeared to be literate in either Dzongkha or English. In addition to both languages being taught in the local elementary school, an evening non-formal education (NFE) program helped dedicated adult students learn to read and write in Dzongkha.

3.2. Village Government

Most village-scale decisions are made by consensus or through democratic processes at community meetings. Both Rukubji and Bumiloo also have elected tshogpas, or non-partisan elected officials who facilitate village decision making and represent the village in the local governing body (National Assembly of Bhutan 2007).

Tshogpas also work with local appointed messengers to spread information and announcements throughout the village.

3.3. Village Mini-grid and Micro-hydroelectric System

A run-of-the-river micro-hydroelectric system supplies the four villages with electricity through a mini-grid (Figure 11). The system was installed with funding from the Japanese government in 1986. The micro-hydro system is rated to produce 40 kW, but data monitoring throughout the project suggested that it typically provides between 24 and 30 kW.[26] This discrepancy is largely due to the age of the generator and the maintenance of the system. We observed direct improvements in power output immediately following system maintenance activities such as cleaning the channel, emptying settling tanks and clearing the intakes at the weir and the forebay. Power output also improved slightly after a section of the headrace channel was repaired by the BPC several months prior to the GridShare installation.

[26] As we did not monitor the power factor of the system, this range should be reported in terms of apparent power (units of kVA); however, to minimize confusion it is reported here in terms of real power (units of kW). As most of the loads on the system are resistive loads, the assumption that the power factor approaches unity, such that apparent power and real power are equal, seems acceptable. Further, the system capacity is limited by the turbine, which has a nominal capacity of 40kW while the generator is rated to produce 50 kVA.

Figure 11. The intake weir, settling tank, forebay, turbine and generator of the Rukubji micro-hydro system (Photo credits: Meg Harper).

From the powerhouse, electricity is distributed along 6.6 kV lines to three substations which step the voltage down to 230 V. The generator produces three-phase power, but nearly all customers on the mini-grid receive single phase service.[27] This arrangement required that only a single phase line and a neutral be supplied to each household. In cases where several phase lines were strung along a given span of the mini-grid, out of convenience, households were most often connected to the bottom line. In other cases, to minimize costs, a single phase line was used to extend to large sections of the villages. Both of these scenarios resulted in an unbalanced mini-grid in which one phase of the grid was forced to provide for a larger portion of the load than the other phases. The arbitrarily named B phase both is used to provide power to most of Bumiloo and happens to be the lowest line on the distribution poles, which resulted in 51 connections, or 57% of the households being connected to the B phase. The Y phase provides power to 14 households, the restaurant and school, while the R phase had 22

[27] The milk processing plant has a three-phase connection to help power the small-industrial machinery.

connections.[28] This uneven distribution of the load resulted in customers on the B phase experiencing more brownouts more often than other customers do, while households on the Y phase experienced very few problems with their electricity.

Customers have conventional energy meters and, prior to and throughout the study, were billed monthly on a per-kWh basis. Electricity tariffs for the village are the same residential rates used throughout the country. Based on a tiered structure, the first 100 kWh are sold at a rate of 0.85 Nu/kWh (~US$ 0.02/kWh). The tariff for this first tier is kept intentionally low to ensure that electricity is affordable for the poor (Bhutan Electricity Authority 2010). Most consumers in Rukubji used less than 100 kWh per month throughout the study (Quetchenbach et al. 2013).

The micro-hydro system is owned and maintained by the BPC. A village operator is tasked with performing system maintenance including cleaning the intake grates and repairing power lines. The operator is also responsible for installing new meters, reading meters and distributing bills. In cases of larger system repairs, the BPC often relies on village residents for labor.[29] Residents seemed supportive of this

[28] B, Y and R stand for the colors blue, yellow and red, but as the wires were not color coded, the names are arbitrary.

[29] Directly after the GridShare installation, a section of the channel was damaged in a landslide. The next day, the BPC held a village meeting and all agreed that one member from each household would help to repair the channel for a daily fee. Residents dug out the channel, carried rocks from the river to reinforce the channel and poured the new cement for the channel. Any who were not busy with these

arrangement as, in addition to providing a small outside income, it also reduced the downtime of the system and enabled them to play an active role in maintaining their community's electricity supply.

3.4. Household Energy Use

To assess household energy use, we surveyed residents as to their appliance and lighting use in June 2010 and again in January 2012.[30] All households connected to the mini-grid use electric lighting and, thanks to prior efforts by the BPC, most had adopted efficient lighting prior to the study. Over 70% of the light bulbs used in the households were CFLs; fluorescent tube lights and incandescent bulbs accounted for the rest of the light sources.[31] Many residents also use their electricity for entertainment and 65% of residents stated that a common evening activity was watching TV. Over 70% of residents

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tasks performed other maintenance on the system such as emptying the settling tanks and cleaning the channel.

[30] These surveys were also used to assess the impact of the GridShare installation and will be described in more detail in the following sections. Copies of the surveys are included in Appendix D.

[31] The number of CFLs increased from 326 bulbs in 2010 to 424 bulbs in 2012 and the number of incandescent bulbs reciprocally decreased from 94 bulbs in 2010 to 47 bulbs in 2012. The number of fluorescent tube lights remained the same across both surveys (43 bulbs). The efficiency gains from this apparent shift toward more CFL bulbs were assumed to be negligible for the current study due to the increased number of bulbs in use (108 CFL bulbs were added, while only 47 incandescent bulbs were discarded) and because lighting is a relatively small fraction of the overall load on the mini-grid (Quetchenbach et al. 2013).

own televisions, over 50% own radios and over 10% own DVD players (Figure 12). Other smaller or less commonly owned electric appliances include blenders, three computers, three planers, three irons, two satellite dishes, a refrigerator, an electric piano and a chili grinder. Despite a village agreement which banned the use of resistance space heaters, these heaters were observed in a few households.

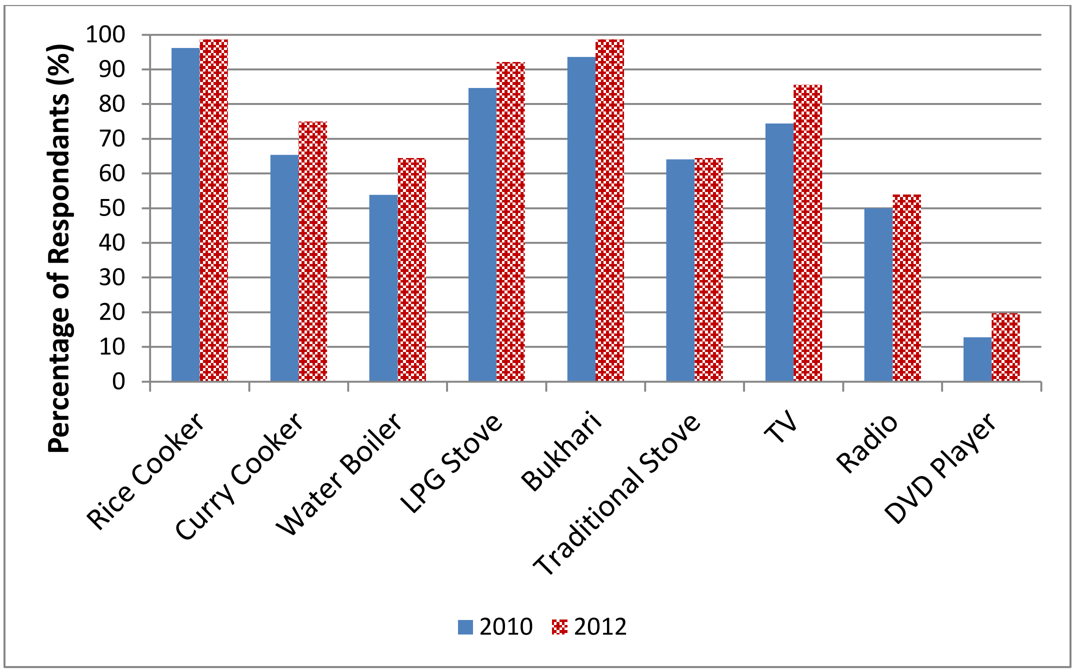

Figure 12. The distribution of ownership of cooking devices and other appliances in Rukubji. This graph demonstrates that residents owned a wide array of appliances and that some additional appliances were acquired between July 2010 and January 2012. (Data from household surveys collected during the pilot study).

Additionally, nearly all households stated that they owned at least one electric rice cooker, while many households owned multiple rice cookers of different sizes, ranging from 1 – 7 liters in capacity and with a power draw of 400 – 2000 W. Other electrical cooking appliances include curry cookers, which are 1000 W electrical skillets used to cook side dishes, and water boilers, which typically heat between 2 - 5 liters of water using between 600 -1800 W of electricity. In addition to these electrical cooking appliances, residents used several non-electric devices such as liquefied petroleum gas (LPG) stoves and wood stoves (Figure 12). Examples of these cooking appliances are displayed in Figure 13.

Figure 13. Common cooking devices from left to right: a *bukhari* woodstove with an LPG stove in the background, a traditional wood stove (Photo credits: Arne Jacobson), a three-stone fire and an electric water boiler, rice cooker and curry cooker (Photo credits: Meg Harper).

This pattern of "fuel stacking" is unsurprising as it has been observed in other villages in Bhutan and many other countries worldwide (Masera, Saatkamp, and Kammen 2000; Dorji 2007; Dorji, Urmee, and Jennings 2012). Observations and anecdotal responses from residents in Rukubji suggested that even when residents owned an array of cooking appliances, they had preferred uses for each device. A three stone fire, often located in an exterior room, is commonly used to make tea, distill *ara* or heat large pots of water for bathing.[32] Traditional wood stoves are often used to cook large

[32] *Ara* is a locally-made alcohol distilled from rice, corn or wheat and commonly served warm, at times with a poached egg and butter, as a sign of hospitality.

pots of food for household or village celebrations while small, metal wood stoves called *bukharis* are commonly used in the winter to both heat the house, heat water and occasionally cook dishes. As presented in Figure 12, 80 to 90% of the households additionally own an LPG cookstove, which is often used to prepare side dishes for daily meals. Traditional stoves, LPG stoves and *bukharis* also serve a critical role of cooking rice or boiling water when the electricity does not work properly.

Though residents have many options available to cook rice, nearly every household uses an electric rice cooker for this task. In informal conversation, residents stated that they prefer to use electricity to cook rice for three main reasons: 1) it is low cost, which can be attributed to low subsidized electricity rates, 2) it is convenient, as they do not need to gather firewood or refill propane tanks and they can simply turn the appliance on and ignore it and 3) they prefer the texture of rice cooked in a rice cooker. Rice is the main staple of the diet in the villages where 28 out of the 33 households sampled stated that they typically used their rice cookers to cook rice three times a day, whereas the other five households used their rice cooker twice a day.

Meal preparation with rice cookers, electric water boilers and curry cookers corresponds with the regular occurrence of morning and evening brownouts on the mini-grid. Prior to the GridShare installation, residents complained that brownouts would regularly occur once or twice a day. During a brownout, residents stated that their rice cookers failed to cook rice, their curry cookers would not work, their TVs flickered, their lights dimmed and their fluorescent tube lights would not turn on. With these daily frustrations, residents were eager for a solution.

3.5. Implementation Approach

In the January of 2010, our team offered village residents a potential solution. The following sections describe in brief our interactions with the villages and our approach to implementing the GridShare system.

3.5.1. Initial Visits

Initial visits to Bhutan were used to assess the village micro-hydro system and establish partnerships with the BPC, the DoE of Bhutan and the village of Rukubji. The DoE and BPC helped identify Rukubji as a pilot site and Chhimi Dorji travelled to Rukubji in January of 2010 to introduce the project idea to the village and assess their interest and willingness to participate.

Following this initial visit, three team members returned to the village in July of 2010 to gain a more thorough understanding of the village and establish agreements with all parties involved. In this month we held community meetings, surveyed each household and installed voltage and current dataloggers to monitor the electric system at the powerhouse and in several individual households.[33] Prior to the 2010 survey, each household verbally agreed to participate in the survey, and through the survey we learned that respondents from all but one household thought the project would be beneficial.[34] After receiving similarly positive responses at the community meetings, the village

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[33] Additionally, at the end of each of the three visits to Bhutan, we held a community luncheon to thank the community for their participation in the project.

[34] This individual stated that they were not sure whether the project would be beneficial.

Tsogpas confirmed the community's support for the project by signing agreements that outlined the potential risks, benefits and responsibilities associated with participating in the project.

In addition to establishing agreements with the villages, we also held formal introductory meetings with the BPC, DoE and other interested parties and created a Memorandum of Understanding (MOU) with the BPC. As part of this MOU, the BPC agreed to assign engineers and electricians to provide technical support for the installation and evaluation of the project. This agreement enabled our team to train a BPC engineer, Kuenley Dorji, on the data collection process, thus facilitating a continuous record of electrical data throughout the project. The MOU further stipulated that the GridShare team, through the HSU Sponsored Programs Foundation, provide insurance for the households to protect all parties against any damages potentially caused by the GridShare devices.

Following the establishment of these agreements, with initial data and feedback in hand, our team was able to refine the design of the GridShare. Improvements to the overall design, code and manufacturing process are described in detail in Quetchenbach (2011). These initial visits also provided the necessary background to plan both the technical installation and the educational elements of the pilot installation.

3.5.2. Installation

As described in Section 1.2, in June of 2011, our team returned to install 90 GridShare devices on 81 houses and two businesses with the help of BPC electricians and engineers. Every village household and in-home business received a GridShare. In cases where multiple households lived in a single house and accessed a single meter, multiple GridShares were installed to enable the separate households to each monitor their electricity use. Three GridShares were installed at the restaurant: one to restrict the kitchen appliances, one to restrict the lighting, and one for the attached residence. The milk-processing plant received an "indicator-only" GridShare because the plant does not operate during peak hours and because the GridShare is designed for single-phase supply. Similarly, an indicator-only GridShare was installed at the school along with educational posters so students could learn about the GridShare, but not have school-wide activities restricted by the GridShare (Quetchenbach et al. 2013).

As mentioned in the description of the "three-prong approach," customer education was prioritized during the installation. Before and after the installations, we held community meetings to discuss the installation and the function of the GridShare. During each individual installation, the BPC electrician talked with household residents about where to install the GridShare, how the GridShare worked and who to contact if they had any issues. At community meetings and in these in-home visits, bilingual posters, pamphlets and visual aids were used to communicate concepts (see Appendix A). In the weeks following the installation, all households were contacted in-person or by phone to address any initial concerns. At this time, a selection of these households was asked a short survey to help with the project evaluation. In addition to interactions with the households, our team led activities with local school children to educate them about the GridShare and the concept of load-shifting.

During this time, our team also trained BPC engineers, electricians and the village technician on the installation and basic trouble-shooting for the GridShare. To reinforce these in-person trainings, manuals and necessary tools were left with the village technician and at the BPC offices. The BPC engineer was further trained and provided with a manual on how to reprogram and read data from the microcontroller.[35] By developing this technical capacity to troubleshoot, repair or replace GridShares, we hoped to ensure that the installation could be sustainably managed beyond the immediate period of evaluation.

3.5.3. Evaluation

In the months after the GridShare installation, representatives from the DoE, BPC and HSU GridShare team visited the village several times to informally discuss initial experiences with residents, troubleshoot any issues and inspect for signs of tampering.[36] Team members were given largely positive feedback during these initial visits and no major complications with the installation were identified.

In January 2012, I returned to Bhutan to join Chhimi Dorji, Nathan Chase and two translators to conduct formal follow-up surveys and host a final community meeting to

[35] Along with this BPC engineer, Chhimi Dorji from the GridShare team and DoE was now residing in country and Nathan Chase, a recent HSU graduate, stayed in country; both were able to help monitor and troubleshoot technical problems following the initial installation.

[36] Though no tampering was evident, in one case the village technician had bypassed a GridShare in an attempt to fix an electrical outage. The team identified that the cause of the outage was a burnt fuse, separate from the GridShare, and were able to replace the fuse and reconnect the GridShare.

assess the installation and determine the course of the project going forward. These surveys, along with the other methods of evaluation will be described in more detail in the next chapter.

CHAPTER 4. METHODS OF EVALUATION

Assessment of the GridShare pilot project is constructed around five primary research questions which are investigated through the analysis of five different datasets (Table 5). While aggregate voltage and current data collected using data loggers can determine the effect of the GridShares on the power system, household-level data monitoring and household surveys are necessary to better understand what impact the GridShares had on energy consumption behavior and residents' electricity experience. Additionally, billing data from the BPC provide insight into the total electricity consumption of individual households before and after the GridShare installation. Finally, the GridShares were equipped to store several data points that could be downloaded from the device through a serial interface. These data recorded how often the GridShare displayed a red light, entered timer mode, cut power to the house and cycled the relay, each of which provide some indication of residents' experience with the GridShare. This chapter describes the methods for data collection and analysis for each of the data sets, while the following chapter presents the results of these analyses in response to each research question.

Table 5. Research questions and data presented in response

Research Question	Data Analyzed to Respond to Question
Did the GridShare installation decrease the occurrence, depth and duration of brownouts?	▪ Electrical data from powerhouse ▪ Household surveys ▪ GridShare serial data
Did the GridShares cause residents to shift the time that they use electric appliances, or result in increased fuel-switching?	▪ Electrical data from powerhouse ▪ Household surveys ▪ Household electrical data ▪ Billing data provided by the BPC
Did residents' average billed electricity usage increase or decrease?	▪ Household surveys ▪ Billing data provided by the BPC
Did the GridShares improve residents' electricity experience, were they satisfied, and did it increase the convenience and reliability of electricity?	▪ Household surveys ▪ GridShare serial data
What changes should be made to the GridShare device and GridShare implementation program?	▪ Household surveys ▪ GridShare serial data

4.1. Powerhouse Data

To assess the effect of the GridShare installation on the entire electric system, we monitored the voltage and current at the powerhouse for the year prior to the installation and a year following the installation.[37] The voltage and current produced on each phase of the micro-hydroelectric generator were measured using three 0-600 V voltage transformers and three 0-200 A current transformers connected to an Onset Energy Logger. The voltage and current on each phase of the load were measured with three 0-300 V transformers and three 0-100 A current sensors connected to three HOBO U12-013 data loggers. Data were logged in 5-minute intervals and downloaded bi-monthly by a BPC engineer. Neither power factor nor real power (kW) were recorded, so only apparent power (kVA) values are reported; however, since most of the peak load consists of resistive cooking appliances, the power factor is likely to be relatively high and the apparent power is thus assumed to be a reasonable approximation of the real power.

To process and analyse these electrical data, Tom Quetchenbach, in consultation with the GridShare team, wrote a program in the R programming language. This program compared data from the "before" period, from July 22, 2010 to June 9, 2011, to the "after" period, from July 22, 2011 to June 9, 2012. (The gap between the two periods is due to the time required to install the GridShares and verify that they were working properly.) The data were pre-processed to exclude times when the generator was offline and days with excessive missing data.[38] Additionally, prior to the installation,

[37] Much of Section 4.1 describes data collection and processing that was discussed in depth in Quetchenbach et al. (2013). As this article adequately described these methods and I played a significant role in drafting and revising this article, the text presented here varies little from that text.

[38] Blackouts or exceedingly low generation accounted for less than 5% of the complete data set and were not included in the comparative analysis. Many of these blackouts were due to planned system maintenance, though some resulted from constricted water flow or mismanagement of the micro-hydro

maintenance was performed on the headrace channel, which improved the output of the micro-hydroelectric generator. To ensure comparable "before" and "after" datasets, bounds were placed on the comparable range of generation (between 15 and 33 kVA). Within this range, each day used in the before period was matched with a day from the after period that had a similar daily average generation. This matching process excluded over 30% of the data set. The pre-processed datasets consisted of 77,130 observations (38,463 before, 38,667 after) and 270 days (135 before, 135 after).

The analysis program calculated minutes of brownout by counting observations in which the voltage dropped below 200 V. To mimic the hysteresis incorporated in the GridShare device, the brownout is considered to continue until the voltage rises above 208 V. Minutes of severe brownout are calculated by counting observations in which the voltage dropped below 190 V. The threshold of 190 V was chosen for two reasons:

1. Initial testing conducted by James Apple, Chhimi Dorji and myself in 2010 indicated that rice cooked fully and lights did not noticeably dim above this voltage.
2. The Managing Director of the BPC suggested that 190 V should be the minimum allowable voltage on these grids.

The BEA's Grid Code Regulation and European Standard EN–50160 for voltage and frequency regulation on isolated grids support this definition of a severe brownout. As mentioned earlier, the BEA Grid Code states that the national grid would be considered in an emergency state if the voltage were outside the range of 207 V – 253 V, while the

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system. Periods of low generation often surrounded the blackouts, so at least 30 minutes of data after each blackout were also discarded.

European standard states that the voltage on a 230 V nominal mini-grid should be maintained between 195.5–253 V at all times. In relation to these two standards, 190 V clearly lies below the range of acceptable voltages.

The data processing program was used to both calculate summary statistics, such as minutes of brownout per day and the percent of days with severe brownouts, and visualize the data through histograms, probability plots and exceedence curves. Additional statistical comparisons were conducted in either R or Excel. These results are presented in the next chapter to help answer whether the frequency, depth and duration of brownouts was reduced and whether the GridShare induced load-shifting or fuel-switching.

4.2. Household Data

Household-level electrical data were collected for two households, arbitrarily named House 1 and House 2, from July of 2010 to January of 2012.[39] A 0-300 V voltage transformer was installed in each household by wiring the voltage transformer to an electrical plug and plugging it in to an available outlet. Households were provided

[39] Voltage was monitored at one additional house, but these data were not analyzed beyond assessing that the voltage at the household was similar to that recorded at the powerhouse. These results are not presented here. Additionally, during the initial field visit in July 2010, voltage and current were measured at several other households. These measurements also established that household voltage differed little from powerhouse voltage and that many households used high wattage kitchen appliances commonly at meal times.

with a powerstrip or multiple outlet adapter to ensure that the installation of the voltage sensor would not interfere with the normal use of their outlets. Two 0-50 A split-core current sensors were installed in each house near the breaker box to monitor the current of the entire house and the current of only the kitchen outlets. The data from the voltage and current sensors were logged in five-minute intervals using HOBO U12-013 dataloggers. These data were collected at least once every three months by a BPC engineer and emailed to the GridShare team.

For this analysis, a program was written by the author in the R programming language to plot daily current and voltage profiles and to assess whether the time of cooking, the number of cooking events and the average cooking duration changed (see Appendix B for the program code). Cooking events were defined as periods where the current exceeded 2 A for more than 10 minutes. Unfortunately, the voltage sensor at one of the households did not provide reliable data throughout the monitoring period, despite multiple attempts at trouble-shooting (including the replacement of mouse-chewed wires). For the remaining household with adequate voltage and current data, the program further determined how many minutes the household current exceeded 2 A while the voltage was below 200 V before and after the GridShare installation. These data sets provide limited insight into how two particular households reacted to the GridShare installation; results of this analysis will be discussed in Section 5.2 on load-shifting.

4.3. Billing Data

Billing data for each household connected to the Rukubji micro-hydro plant were provided upon request by the BPC. According to BPC policy, customer meters are read and billed on a monthly basis. Records of monthly energy consumption (in kWh) and energy charges (in Nu) were provided for 4 ½ years, from January 2008 to June 2012. Though several cases exist in which the household consumption is recorded as 0 kWh for one month and recorded as twice the average consumption the next month, no attempts were made to re-process the data to correct for potential errors in reporting. Instead, average time periods were used for comparison under the assumption that reporting abnormalities would be assimilated in the average. Additionally, the analysis excluded any households that had no billing data prior to July of 2010, any households that stopped using electricity prior to July of 2011 and all non-residential buildings, such as temples, the NFE building, the school and the milk processing plant.

A program was written by the author in the R programming language to plot each household's billed consumption over the entire 4 ½ year period (examples of these plots and code are included in Appendix C for reference) and compute average monthly consumption over several different comparative periods. Comparative time periods were assigned as follows:

1. The 2 ½ years prior to any intervention (January 2008 – June 2010)
2. The year prior to the GridShare installation (July 2010 – June 2011)
3. The year after the GridShare installation (July 2011 – June 2010).

The program further calculates the standard deviation of consumption for each period and uses the Wilcoxon rank-sum test to compare individual average household consumption for each period. The Wilcoxon signed-rank test is used to compare the aggregate data from all households for each period.[40] These comparisons were used to determine if the GridShare had any discernible impact on billed electricity consumption and are presented in the next chapter.

4.4. Surveys

During the course of the evaluation, all households connected to the mini-grid were surveyed one year before the installation and six months after the installation, while an additional survey was administered to some households at the time of the installation. During the site visit in July of 2010, our team of three HSU students and three BPC employees surveyed every house connected to the micro-hydro system to determine the community's willingness to participate in the project, to understand their current experience and understanding of brownouts and to collect baseline information about electricity use for future comparison. Due to time limitations, we used two separate surveys; one was more in-depth and was only administered at 33 of the 78 houses, while the other was shorter and was administered at 45 of the 78 houses.[41] The 33-household sample was chosen as a representative sample to include households from all four

[40] The Wilcoxon ranked-sum test is a non-parametric statistical test used similarly to an independent t-test, while the Wilcoxon signed-rank test is similar to the dependent t-test for non-parametric data.

[41] Survey instruments are included in Appendix D.

villages and three phases of the grid. A comparison of this sample to the larger population is included in Appendix E.

In June of 2011, with the realization that our initial baseline information may have changed over a year, we created an additional survey to administer to the same 33 households that had completed the long survey the year before. This survey also included questions to assess the frequency with which residents used their lights and appliances to enable a pre-installation and post-installation comparison. In the five cases where residents who had completed the long survey in 2010 were not available in 2011, we chose new houses to survey using a random number generator to ensure a sample size of 30 households. Preliminary analysis suggested that the baseline information regarding the time that households cooked their meals did not significantly change between the 2010 and 2011 survey (Appendix E).

A final assessment survey was administered in January of 2012 to evaluate behavioural changes related to the GridShare and residents' satisfaction with the GridShare program. Just as in the summer of 2010, two surveys were administered, a short survey and a long survey. The long survey was administered to a total of 34 households which consisted of all the available households that were given the long survey in 2010 and the pre-installation survey in 2011. The short survey was administered to the other 42 households.

In all surveys, an adult member of the household was interviewed without regard to gender or household role. When possible, for the follow-up surveys, the same member of the household was surveyed as in the prior surveys; however, due to scheduling conflicts and time restrictions, this attempt was not always be feasible and in practice, only occurred in 52% of the cases. Therefore, comparative analysis will be constrained to the household level. Though this restriction is less than ideal, the observations that household roles are less rigid than in many cultures and that typically, many different household members take part in cooking meals (or at a minimum, turning on the rice cooker) makes this assumption more tolerable. A further discussion of the effect of gender and household role based on analysis of our initial survey is presented in Appendix E.

Surveys were administered verbally in Dzongkha, the national language. Three groups consisting of one Bhutanese translator, fluent in Dzongkha and English, and one HSU team member conducted the surveys throughout the village.[42] Professional translators were not recruited for these surveys; rather local teachers, BPC engineers and university students helped fill this need. A more detailed discussion of methods used to consistently translate the surveys is included in Appendix F. All respondents were provided an informational sheet, offered in Dzongkha and English, which described the study and the goals of the survey. While all participants were advised that they did not have to participate in the survey, no one declined to respond. The surveys and overall research plan were approved and renewed by the HSU Institutional Review Board (Human Subjects log number 09-58).

[42] In the case where Chhimi Dorji conducted surveys, he typically conducted them alone as he was both fluent in Dzongkha and English and was part of the HSU GridShare team.

A few notes should be made regarding the conceptualization and operationalization of certain variables in the final assessment survey.[43] These are presented below with regard to the overarching research questions.

4.4.1. Did the GridShare decrease the occurrence, depth and duration of brownouts?

When analyzing the voltage and current data collected from dataloggers, we have defined a brownout as any period where the voltage on the grid, which should be 230 V, drops below 200 V. A severe brownout is defined as any 10 minute period where the voltage has stayed below 190 V. As residents are not using voltmeters to actively monitor their voltage, the conceptual definition of a brownout for the purpose of the surveys is a time where the lights dim or flicker and appliances do not work properly. Poorly cooked rice may be the brownout symptom with the highest impact on residents. After the GridShares were installed, the definition of a brownout may have become synonymous to the users with times when the red LED light is displayed. In the GridShare settings, the red light appears when the voltage drops below 200 V, and only switches to a green light when the voltage has remained above 208 V. In our research experience, symptoms of brownouts are usually noticeable as the voltage drops lower, below 190 V.

The occurrence of brownouts is defined as whether or not a brownout, as defined above, happened. Occurrence is measured as a frequency, both on a monthly basis and

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[43] *Conceptualization* is defined as providing a specific definition for a variable of interest and *operationalization* means specifying the exact methods of measuring each variable.

on a daily basis. Duration of brownouts is defined as how long an individual brownout lasts on average. The depth of brownouts is more difficult to define from a respondent's perspective. In terms of the electrical data, depth is defined as the lowest voltage of an individual brownout, but for the surveys, depth may only be assessed if residents do recognize a difference between times when the red light is on, which could be caused by a shallow or a deep brownout, and times when symptoms of deep brownouts occur, where lights dim and flicker and appliances don't work properly. On the final survey, questions are intended to assess the occurrence and duration of brownouts, as well as parse out whether users define brownouts as times when the red light is on, or if the two concepts are separate.

4.4.2. Did the GridShares cause residents to shift the time that they use electric appliances, or result in increased fuel-switching?

As discussed previously, from our initial surveys in 2010, we found that most residents have multiple ways of cooking. Many noted that they prefer to cook rice using rice cookers, as it is more convenient, cheaper and usually produces a good product. From an environmental perspective, cooking with electricity from a micro-hydroelectric plant reduces carbon emissions, improves indoor air quality and reduces the need to collect firewood. While cooking rice with LPG is similarly convenient and is often presented as a low-carbon, healthy alternative to firewood, Rukubji residents stated that LPG was more expensive than electricity. The use of LPG also required purchasing and arranging shipment of LPG canisters from Thimphu or Wangdue. Therefore, it is important to determine whether residents are reacting to the GridShare by changing the time that they use their electric rice cookers, or just using LPG (liquid petroleum gas) or firewood instead. The question of load-shifting and fuel-switching was addressed through comparative questions from the 2011 and long 2012 surveys that provided information on households' use of various fuels and the average time of day that they used their rice cookers.

4.4.3. Did the GridShares improve residents' electricity experience, were they satisfied, and did it increase the convenience and reliability of electricity?

For the purposes of this study, satisfaction is defined as whether the benefits of a GridShare installation outweighed any drawbacks. Convenience can be conceptualized as whether the GridShare was easy to use and understand, and whether it was more or less difficult to use electricity to accomplish desired tasks. Reliability refers to whether a resident could be more certain that the electricity supply would be adequate at any given time.

Satisfaction, convenience and reliability are all difficult concepts to measure. Common methods for assessing satisfaction include directly asking users how satisfied they are, creating multi-question scales to compare expected quality and perceived quality, and asking related, but more concrete questions from which one can infer satisfaction (Parasuraman, Zeithaml, and Berry 1986; Greacen 2004; Upadhayay 2009; Sharma 2010; Dorji, Urmee, and Jennings 2012). The final survey does not use multi-question Likert scales, but does directly and indirectly assess satisfaction through several questions. Convenience is assessed indirectly through questions about shifting the time or mode of cooking, and through open-ended questions relating to the overall GridShare program. Reliability is assessed indirectly through the change in frequency of brownout symptoms.

4.4.4. What changes should be made to the GridShare device and GridShare implementation program?

An essential part of the survey is gaining direct feedback as to the three main aspects of the GridShare program: Education, Indication and Enforcement. Evaluative questions about the education program, the LED indicator lights and the enforcement mechanism were asked to provide the GridShare team with advice on how to alter the program in future installations.

4.5. GridShare Serial Data

Each GridShare is programmed to store four data points that record how often the GridShare displayed a red light, entered timer mode, cut power to the house and cycled the relay over the lifetime of the device.[44] These data were downloaded using a "test clip" that grasps the microcontroller and enables the chip's serial output to be read through a serial adaptor and laptop computer.[45] Though this process was easily reproducible in the lab, in the field, it was difficult to consistently create a connection

[44] The GridShare circuit uses a PIC16F688 microcontroller which has 256 bytes of non-volatile EEPROM memory (Quetchenbach 2011). In reality, these data points are recorded over the lifetime of an individual microcontroller and would be reset if the microcontroller were reprogrammed. In all cases analyzed, once the GridShares were installed, microcontrollers were not changed or re-programmed.

[45] Tom Quetchenbach's GridShare program enabled the serial data to be output and read. Kyle Palmer created an additional program in the AutoIt language that enables the serial output to be accessed through a user-friendly graphical user interface (GUI).

with the test clip because of the angle of the mounted GridShares, the fragility of the test clips and the erratic behavior of the USB-to-serial adapter. Due to the difficulty of collecting these data and applicable time constraints, these data were collected from a random sample of 42 households, rather than the entire installation. To create both a representative and random sample, the data frame of all of the households was divided by village and phase, and a random sample of GridShares was selected in proportion to the total number of households on each phase and in each village.

These data were processed using Excel to determine the average, range and standard deviation of each parameter for the entire sample and for each phase. Additionally, the ratios of brownouts per day, power cuts per day, timer modes per brownout, power cuts per brownout and cycles per power cut were calculated for the full data set and the individual phases. These results are presented in the next chapter to help assess the occurrence of brownouts, the customers' experience with the GridShare and the need for improvements in the GridShare device and education program.

CHAPTER 5. RESULTS AND ANALYSIS

The evaluation of the GridShare installation is presented below in answer to the five main research questions: 1) Did the GridShare installation decrease the occurrence, depth and duration of brownouts? 2) Did the GridShares cause residents to shift the time that they use electric appliances, or result in increased fuel-switching? 3) Did residents' average billed electricity usage increase or decrease? 4) Did the GridShares improve residents' electricity experience, were they satisfied, and did it increase the convenience and reliability of electricity? 5) What changes should be made to the GridShare device and GridShare implementation program?

5.1. Occurrence, Duration and Depth of Brownouts

The effectiveness of the GridShare installation at reducing the occurrence, duration and depth of brownouts was assessed by analyzing electrical data from the powerhouse, survey responses and data downloaded from the individual GridShares. Findings from the powerhouse data and survey responses were reported in Quetchenbach et al. (2013) and are summarized here. As in this previous paper, for simplicity, only results from the R phase are presented in the graphs in this section. The online appendix of Quetchenbach et al. provides the figures for all three phases of the grid. As described previously, the B phase was severely over-loaded, while the Y phase was somewhat under-loaded, causing residents on the B phase to experience the greatest fluctuation in their electricity, while users on the Y phase rarely experienced the effects of brownouts.

The R phase serves as a moderate alternative between these two extremes; unless otherwise specified, only data from the R phase are presented in this section.

The comparison of data from a year before and a year after the GridShare installation indicates a 92% reduction in the occurrence of severe brownouts, or brownouts where the voltage dropped below 190 V (Figure 14). For two of the three phases, this decrease in the occurrence of brownouts is statistically significant (2-proportion *z*-test, 1-tailed, p<0.001).[46]

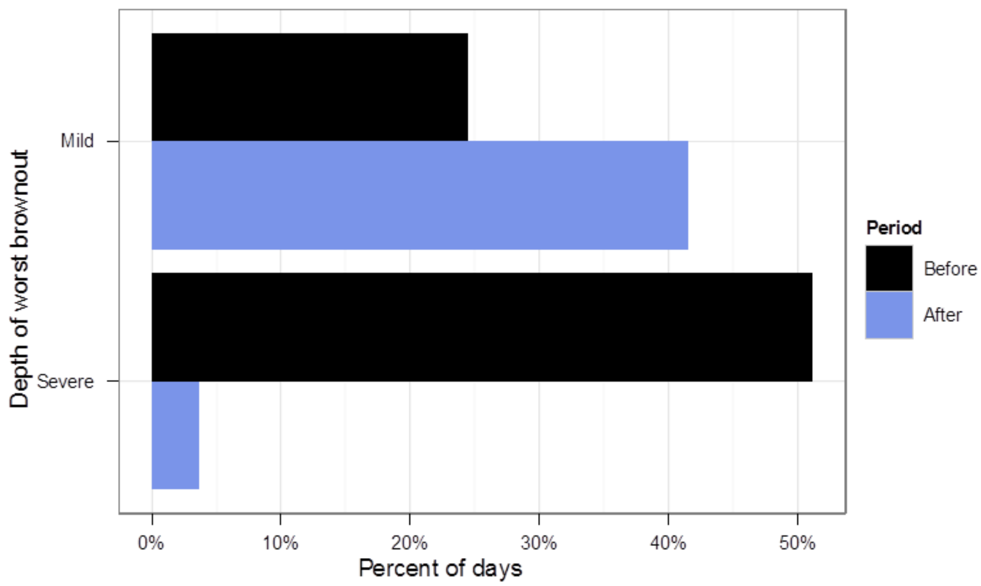

Figure 14. The percent of days with a severe or mild brownout before and after the GridShare installation on the R phase. The percent of days with a severe brownout drastically decreased, while the percent of days with mild brownouts modestly increased (Quetchenbach et al. 2013).

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46 As described previously, both before and after the GridShare installation, due to uneven loading of the grid, customers connected to the Y phase rarely experienced severe brownouts. With this small sample size of days with brownouts, data from the Y phase did not meet the assumptions of the *z*-test.

As noted in Figure 14, the number of days with mild brownouts (brownouts where the voltage dropped to between 200 V and 190 V) actually increased following the GridShare installation. This increase can likely be explained as times when the voltage starts to drop but the indication and enforcement of the GridShare does not allow additional loads to be added and thus stabilizes the voltage. Previously, a similar situation would have resulted in additional loads further reducing the voltage, causing a severe brownout.

Similarly, the duration of brownouts, and particularly severe brownouts, decreased after the installation (Figure 15). On the R phase, prior to the GridShare installation, severe brownouts occurred for an average of 30 minutes a day, while mild brownouts occurred for an additional 15 minutes. Following the installation, on average, less than one minute was spent in severe brownout, and mild brownouts occurred for only 7 additional minutes. Similar reductions in brownout duration were observed on the other two phases and these decreases were significant across all phases (1-tailed Wilcoxon rank-sum test, $p<0.001$). This observation again relies on the same explanation as before, that the indication and enforcement provided by the GridShare's red light is regulating use of large loads during peak periods and thus enabling the voltage to recover much faster than before.

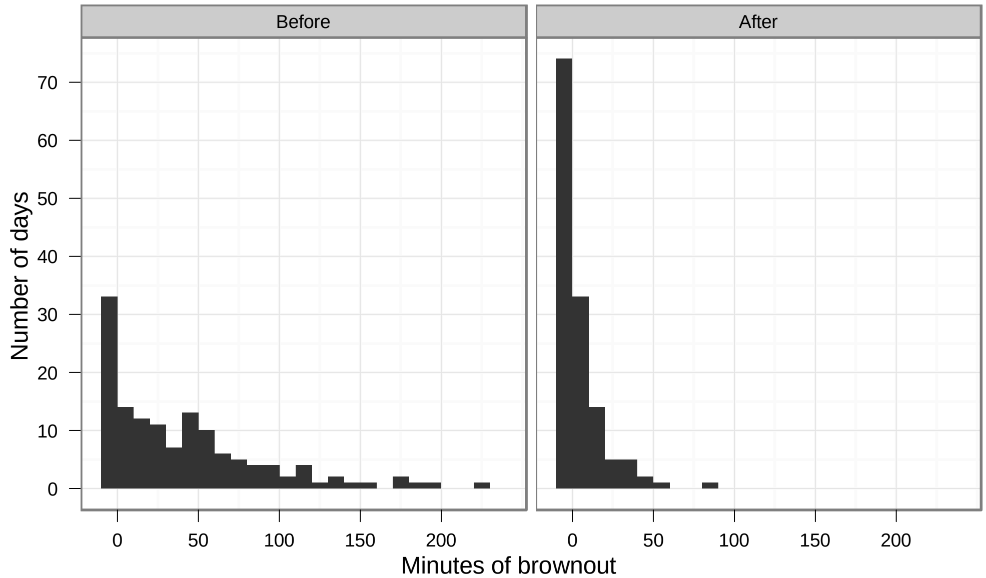

Figure 15. Histogram of minutes of brownout per day on the R phase, binned by 10-minute intervals. Following the GridShare installation, the number of days with no brownouts increased while the number of days with long periods of brownout decreased (Quetchenbach et al. 2013).

Though the serial data from the GridShare cannot indicate the severity of a brownout, the data do confirm that residents are regularly seeing the red light, as indicated by both the electrical data and surveys. The serial data suggest that GridShares are showing the red light on average 2.3 ± 1.1 times per day.[47]

Results from the follow-up surveys support the conclusion from the electrical data that the severity of brownouts decreased after the GridShare installation. To assess the

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[47] Split by phase, the average number of times the GridShare shows the red light were: 2.7 ± 1.0 on the B phase, 2.2 ± .5 on the R phase and 0.8 ± 0.2 on the Y phase. These averages were calculated by dividing the total number of brownouts the GridShare had indicated by the total number of days the device had been in operation. Variation in the data is represented by the standard deviation.

occurrence of severe brownouts residents were asked how often their lights dimmed and rice cooked poorly before and after the GridShare installation. Before the GridShare installation, 99% of respondents stated that they experienced impacts associated with severe brownouts; whereas after the GridShare installation, 54% reported that they experienced these conditions.

The follow-up survey results also confirmed the expectation that residents would see the red light frequently, as would be expected by the continuing presence of mild brownouts in the electrical data and the indications from the GridShare serial data. When given the choices of whether they saw the red light every day, occasionally or never, 22% of respondents estimated that they saw the red light every day and the other 78% of respondents stated that they saw the red light occasionally. The combination of residents seeing the red light, but less commonly experiencing conditions of a severe brownout supports the findings from the electrical data. After the GridShare installation, the grid voltage still dropped below the brownout threshold, but the voltage rarely dropped low enough to affect the performance of electrical appliances.

5.2. Load-Shifting and Fuel-Switching

After establishing that the severity of brownouts was reduced following the GridShare installation, the question of whether the GridShares induced load-shifting or fuel-switching was investigated by further analyzing electrical data from the powerhouse, electrical data from two individual households, survey responses and billing records. As before, the findings from the powerhouse data and survey responses were reported in

Quetchenbach et al. (2013) and are summarized here, while complimentary information from the two households and billing records is included as new material. Again, results from only the R phase are presented in the graphs in this section.

5.2.1. Electrical data and Survey Responses

The GridShare concept centers around the idea of load-shifting, yet electrical data from the powerhouse suggested that there was little change in the timing of brownouts or the time that residents used electricity before and after the GridShare installation. After the GridShare installation, the probability of experiencing a brownout substantially decreased, but the time that the brownout was likely to occur was similar to before (Figure 16). This finding is unsurprising, as even if load-shifting had occurred, peak energy use would still likely occur during breakfast and dinner and occasionally exceed the available supply.

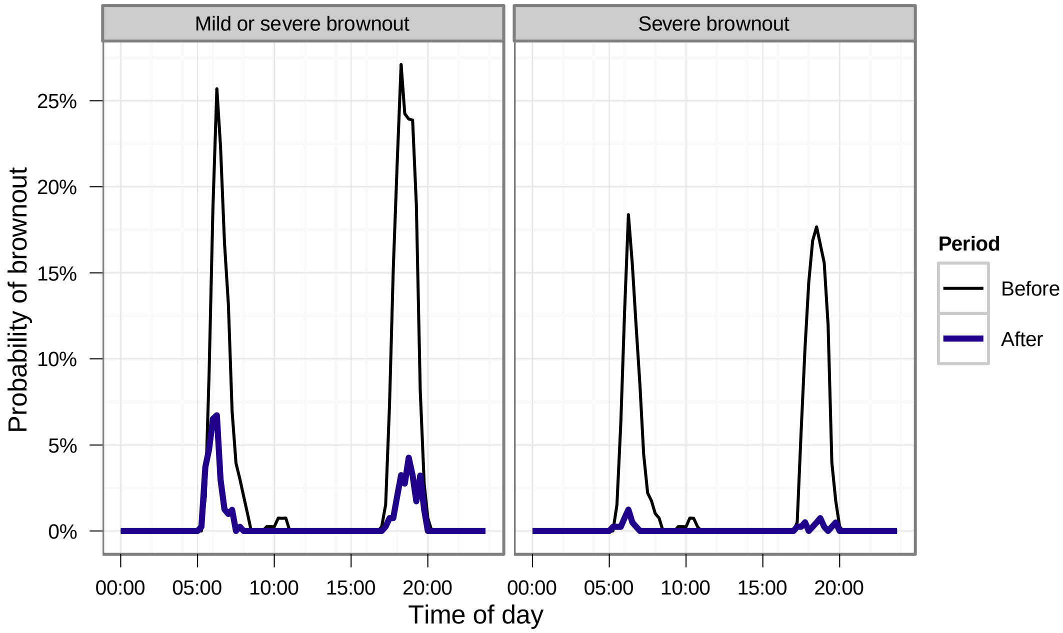

Figure 16. The probability of brownouts before and after the GridShare installation on the R phase. The thick blue lines indicate that the probability of any brownout occurring after the GridShare installation is much lower than before, with the probability of a severe brownout falling to less than 2% (Quetchenbach et al. 2013).

The data from the powerhouse also enabled the creation of a daily median load curve for the before and after periods (Figure 17). If substantial load-shifting had occurred, the load curve after the GridShare installation would have wider and shorter peaks as residents chose to cook earlier or later than the typical time. Figure 17 instead displays only minimal change in the timing of the load. Residents appear to be cooking breakfast slightly earlier and dinner slightly later than before, but the total width of the load curve has remained the same. Though these data do not suggest that load-shifting resulted in a reduction of peak power use, the peaks of the median load were shorter following the GridShare installation, suggesting that there was a reduction in the total connected load at any one time.

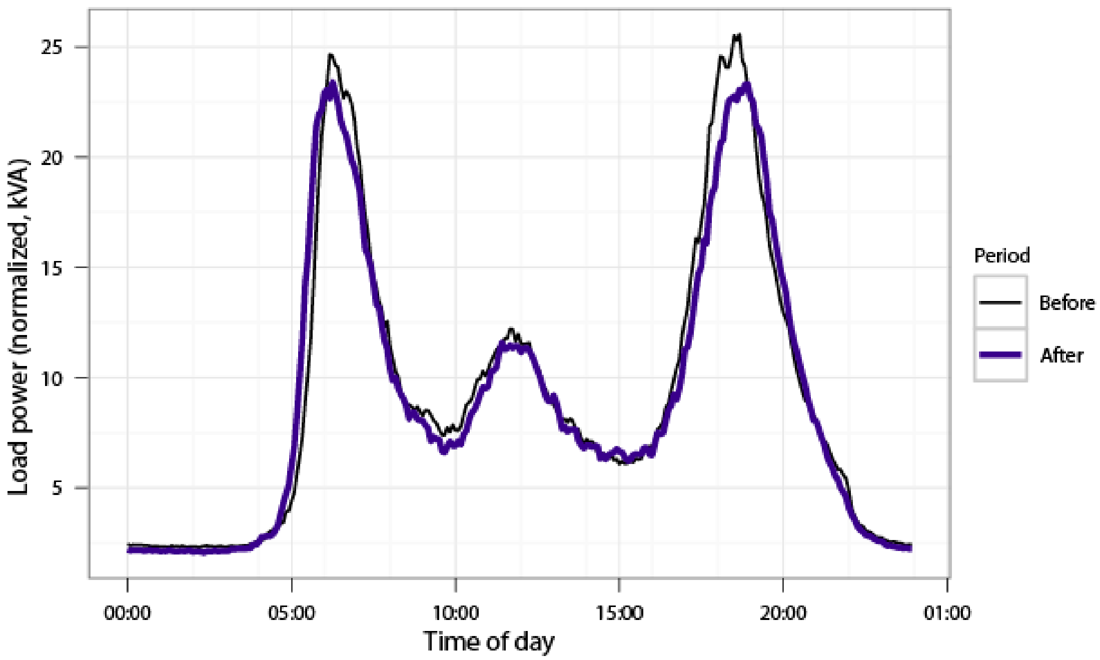

Figure 17. Median load power throughout the day before and after the GridShare installation on the R phase. The graph is adjusted to estimate the power that the connected load would draw if adequate power could be provided and the voltage were able to be maintained at the nominal voltage of 230 V (Quetchenbach et al. 2013).[48]

Though the electrical data do not demonstrate substantial load-shifting, the survey data do suggest that residents were changing the time that they cooked their rice. In the follow-up survey, 42% of respondents stated that they intentionally cooked either earlier or later than their normal cooking time at least once a week and 91% of respondents stated that to avoid cooking when the red light was on, they typically either cooked

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[48] Because the graph of measured apparent power is limited by the fact that power demand can never exceed the supply, this graph offers a more instructive comparison of the total wattage of appliances plugged in at a given time. The normalized power is calculated as $P_{norm} = P_{actual} * (V_{nom}/V_{actual})^2$, where: V_{nom} is 230 V, P_{actual} is the measured apparent power ($V_{actual} * I_{actual}$) and V_{actual} is the measured voltage (Quetchenbach et al. 2013).

earlier or waited to cook until later. Both of these findings suggest that load-shifting had occurred, and the surveys administered to a representative subset of households (n=33) support this conclusion to some extent. In these surveys before and after the installation, respondents were asked to state the time they cooked the rice for dinner. A comparison of these time estimates found that 70% of individuals changed the time that they cooked by between ½ to 2 ½ hours. In addition these reported changes in individual behaviour, when cooking times are examined in aggregate, a pattern of time-based load-shifting is apparent.[49] As with the electrical data, the peak is slightly shorter and is shifted to later in the evening, but the survey data also indicate that the shape of the load curve widened, suggesting that load-shifting occurred (Figure 18). Though this change is visually convincing and shifted from a median cooking time of 6:00 PM before the installation to a median cooking time of 6:45 PM after the installation, statistically there is no significant difference in the median time that the peak load occurs ($V(23) = 54$, $p>0.05$).

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[49] This statement differs from what was reported in Quetchenbach et al. (2013). When analyzing the data for Quetchenbach et al., I included all survey responses in the analysis. On further review, I realized that only those respondents who provided a time estimate both before and after the GridShare installation should be included in the comparison. After eliminating respondents that only provided a response in one, but not both time periods, a proper matched comparison was performed. With this adjustment, the data now visually suggest that load-shifting occurred, but statistically, no significant difference was observed between the two time periods.

Additionally, the change in the distribution of the load is not statistically significant ($D(23) = 0.27$, $p>0.05$).[50]

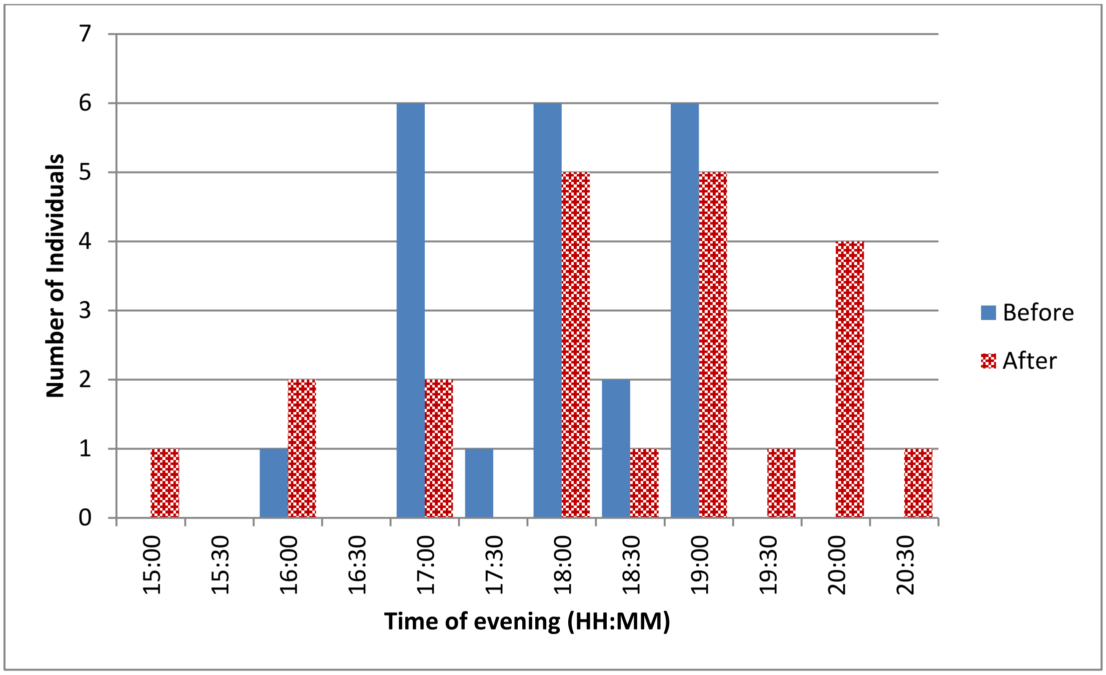

Figure 18. Time that respondents stated they cooked their rice for dinner before and after the GridShare installation across all phases. Though changes in the load curve are visually apparent, these changes were not statistically significant.

Another behaviour that could have been induced by the GridShare and resulted in the reduction of brownouts is fuel-switching. Indicators of fuel-switching include shorter peaks of the median load curve and respondents reporting decreased use of electric appliances and increased use of alternative cooking methods. Although the peaks of the median load curve are slightly shorter, the survey data do not indicate that

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[50] In the report of these statistics, V is the test statistic for the Wilcoxon signed rank test, while D is the test statistic for the Kolmogorov-Smirnov test. The use of non-parametric tests and the small sample size drastically limited the statistical power of tests, making finding significance difficult in many cases.

fuel-switching occurred with greater frequency than before. While 51% of respondents (n=76) stated that they at times use a non-electric appliance to avoid cooking when the red-light is on, surveys administered to a representative subset of households (n=33) asked questions regarding frequency of use of different cooking methods before and after the installation. Responses to these surveys indicate that the majority of households used their electric rice cookers with the same or greater frequency than before the installation, the use of LPG decreased overall and only one household used wood more frequently than before.[51] Further, the billing records do not support the idea that substantial fuel-switching occurred, as will be discussed in Section 5.3.

As suggested in Quetchenbach et al., given the lack of evidence to suggest substantial load-shifting or fuel-switching occurred, an alternate hypothesis is proposed to explain the reduction in severe brownouts: the higher voltage enables rice cookers to cook faster and thus allows more people to cook in the same time periods without overtaxing the system. In this scenario, rather than a single rice cooker drawing power for an hour at an insufficient voltage, three rice cookers are able to fully cook rice in succession at an adequate voltage in the same amount of time. Though the existing data are not structured in a way to support or refute this hypothesis, this explanation addresses

[51] This household stated that they used wood to first heat the water for many uses and then added the hot water to the rice cookers to cook the rice. It is unclear whether this practice was a behavior change due to the GridShare or whether this nuanced information was not captured on the first survey.

the reduction in brownouts along with the lack of substantive change in the daily load curve and use of electric appliances (Quetchenbach et al. 2013).[52]

5.2.2. Individual Household Monitoring

Ideally, monitoring the voltage and current at individual households would help test this hypothesis; however, due to technical, funding and personnel limitations, only two households were monitored. The electrical data from these two individual households do little to address this hypothesis, but do provide further insight into the diversity of households and reactions to the GridShare installation. Throughout the two years of monitoring, the two households showed very different profiles of current usage. House 1 used electric appliances throughout the day, and on some days current spikes of greater than two amps occurred more than ten times. House 2 typically presented the expected pattern of using a high power appliance (such as a rice cooker) in the morning, afternoon and evening, as demonstrated by two or three large current spikes present during the day (though in the particular example below, a high power appliance was used five times). Figures 19 and 20 display individual days from these two households before and after the GridShare installation. The dates (November 2nd and November 6th) for these examples were chosen by identifying two days with matching generation profiles from the electrical data analysis that were within a few calendar days of each other.

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[52] The household surveys do offer some limited support for this theory as 52% of respondents thought that it took less time to cook rice after the GridShare installation, while only 2% thought that it took more time.

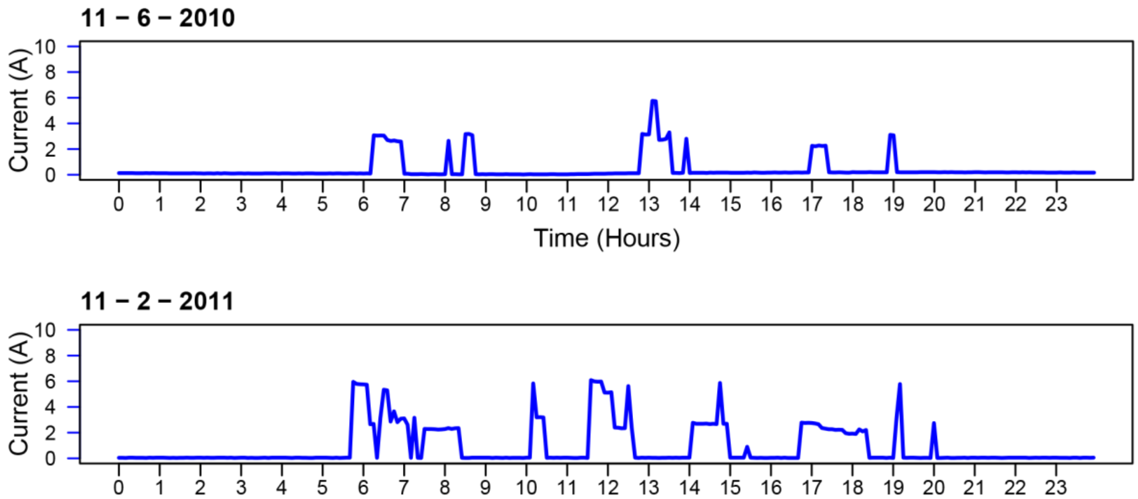

Figure 19. Example daily current profile at House 1 before (2010) and after (2011) the GridShare installation. House 1 had an erratic pattern of electrical use and did not display the expected cooking pattern observed at other households.

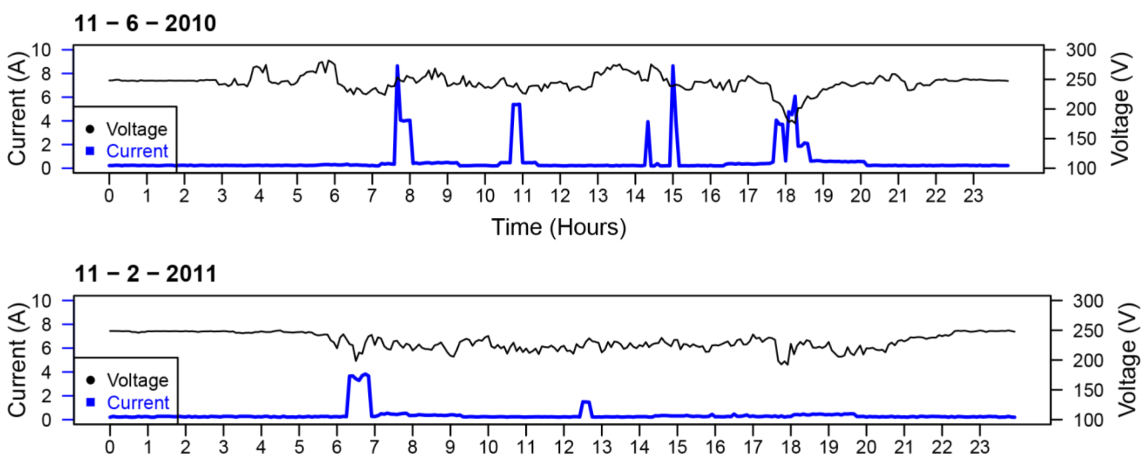

Figure 20. Example daily current and voltage profile at House 2 before (2010) and after (2011) the GridShare installation. The comparison of this individual day suggests that following the GridShare installation, the residents cooked breakfast earlier and either did not cook or switched to using a different fuel to cook dinner, perhaps due to a mild brownout around 5:45 PM.

Following the GridShare installation, House 1 increased the number of times they cooked from 4.0 times per day to 4.7 times per day and increased the average duration of their cooking events from 31 minutes to 35 minutes. Both of these changes were significant at the 95% confidence level (see Appendix B for statistical results). Their family size, the current draw of their devices and their erratic pattern of electricity usage did not substantially change following the installation. Despite the respondent stating that the household at times used LPG when the red light was on, these findings do not indicate that fuel-switching occurred and do not enable an analysis of whether load-shifting occurred. It is unclear that the GridShare had any impact on the family's behavior.

House 2 portrayed a much different story and decreased their use of electricity after the GridShare installation: on average they cooked 1.9 times a day rather than 2.7 times a day, used 0.51 A less current in each cooking event and cooked for 9 fewer minutes each time. The change in the average number of cooking events per day, current use and cooking duration are all significant at the 95% confidence level (see Appendix B for statistical results). These changes can be explained by a combination of fuel-switching and changes in household demographics as reported in the survey responses. While on average, the village population decreased by one person per household over the course of the study, House 2 reported having four to eight residents in 2010/2011, while they only reported having two residents in 2011/2012. This drop in household size may have influenced the number of cooking events and also resulted in the residents using a smaller rice cooker or curry cooker, as evidenced by the lower average current. Because of the likelihood that the residents are using a smaller appliance, the reduction in cooking duration cannot necessarily be attributed to the GridShare regulating the electricity system, though this explanation remains a possibility.

In addition to the influence of the reduction of household size, the household does also appear to be fuel-switching at times. Of the 27 households that responded regarding the frequency of LPG use before and after the GridShare installation, House 2 was the only household that increased their use of LPG, stating that their use increased from "Almost Never" to "1-2 Days per Week".

Household electrical data was also used to investigate whether load-shifting had occurred. Because House 1 did not demonstrate a daily pattern of cooking at routine times, only data from House 2 were analyzed to determine if the average time the household started cooking changed. In the mornings in the year prior to the GridShare installation, the average time the household started cooking was 6:25 AM (SE = 5.1 minutes), while after the GridShare installation, cooking started on average at 6:17 AM (SE = 6.4 minutes); this difference was not significant ($t(275) = 0.87$, $p>0.05$).[53] Midday cooking was defined as being between 10AM and 3 PM. In the year prior to the GridShare installation, the average time during the midday that the household started cooking was 12:42 PM (SE = 7.9 minutes), while after the GridShare installation the average time was 12:30 PM (SE = 11.5 minutes); again, this difference was not significant ($t(124) = 0.87$, $p>0.05$). In the evenings in the year prior to the GridShare installation, the household's average cooking time was 5:24 PM (SE = 3.6 minutes),

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[53] Standard error is represented by SE, t is the test statistic for the t-test with degrees of freedom in parenthesis and p is the p-value. At a 95% confidence level, the p-value must be less than 0.05 for the difference between the two samples to be considered significant.

while after the GridShare installation, the average evening cooking time was 5:32 PM (SE = 5.6 minutes); this difference also was not significant ($t(227) = 1.19$, $p>0.05$). Additionally, no evidence suggests that the household began to cook more often in the afternoon than the evening, the number of cooking events decreased nearly equally across all time periods (35% fewer cooking events in the morning, 34% fewer from 10 AM to 3 PM and 40% fewer in the evening). The lack of evident load-shifting is not surprising in the case of House 2 as the household appears to have adapted through fuel-switching.

The combination of a smaller household size, fuel-switching and the voltage of the system being better regulated enabled this household to avoid cooking when the voltage was low. Prior to the GridShare installation, the household spent on average 35 minutes per day cooking when the voltage was below 200 V, whereas after the GridShare installation, the household spent less than 5 minutes per day cooking when the voltage was below 200 V. This finding is supported by the respondent stating on the survey that after the GridShare installation, if they plug in while the green light is on, they are now more sure that their rice will cook well.

5.3. Change in Billed Energy Use

Analysis of the billing data and surveys suggested that the GridShare installation had little impact on total electricity consumption. The devices themselves have a very low parasitic load and were not expected to substantially affect customers' energy use, but the GridShares could have encouraged increased fuel-switching, which would have been evident from a distinct decrease in energy consumption. On average, there was a slight decrease in energy consumption of 3.7 kWh per household per month, but this decrease was not statistically significant.[54] Additionally, the billing data show that 67 households did not significantly change their average energy consumption between the 12 months prior to the GridShare installation and the 12 months after the installation. Between these same periods, three households significantly increased their electricity consumption, while eight households, of which six were on the B phase, decreased their consumption. The medians for each period and results of the statistical tests are presented in Appendix C.

The surveys similarly indicate that most residents did not change their energy consumption following the GridShare installation. When asked whether they felt that they used more, less or the same amount of electricity following the GridShare installation, 57% of respondents stated they used the same, 15% thought they used more and 8% thought they used less. The remaining respondents were not sure or provided no response. Additionally, when asked about the benefits and challenges of the GridShare, two respondents mentioned that they thought their bill had increased, while six respondents stated that their bill had decreased; all others did not comment on their

[54] In total, this average reduction would equate to a loss of approximately 300 kWh per month or 6% of the total consumption. At the subsidized rate of 0.85 Nu/kWh (~US$ 0.02/kWh), this represents a loss of revenue of approximately 260 Nu (~US$ 6) per month across all customers connected to the mini-grid system.

energy use or bills.[55] These results suggest that electricity consumption did not change substantially and do not support the idea that aggregate fuel-switching increased following the GridShare installation.

5.4. Customer Satisfaction

Customer satisfaction with the GridShare installation was assessed through survey responses and data downloaded directly from the GridShare devices. Some of the survey responses were reported in Quetchenbach et al. (2013) and are summarized here, while additional information from the surveys and GridShare data are presented as well.

The serial data downloaded directly from the GridShare cannot directly assess customer satisfaction, but can help to understand residents' experience with the GridShare in terms of the number of times the red light appeared and the number of times their power was cut off. As stated previously, the serial data show that GridShares displayed the red light on average 2.3 ± 1.1 times per day.[56] The data also suggest that

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[55] One of the customers who stated that their bill had increased thought that the issue was due to the meter not being read regularly, not because of increased use. Other consumers also registered complaints about late fees and billing practices, but these are not included here.

[56] As the serial data only counted incidences of the GridShare entering brownout mode, this data provides no information as to the timing or duration of these brownouts. Two incidences in one day could have occurred directly in succession in less than five minutes or been separated by hours and lasted for indefinite time periods, and the ~460 instances could have occurred all in one month or been evenly distributed over the six month period.

on average, households had their power cut off during 10% ± 7% of these brownouts, which implies that the average household experienced having their power cut off approximately once every five days. These power cuts would occur at times when GridShare had entered brownout mode and the user subsequently exceeded their current limit by plugging in a large appliance or attempting to use too many small appliances. The serial data also recorded how many times the GridShare cycled power on and off to the house during a power cut. On average, power was cycled 6.0 ± 5.1 times per power cut, which suggests that during a power cut, an average household might spend approximately 4.0 ± 3.4 minutes with their power disconnected.[57] In cases where the consumers were already exceeding the power limit when the voltage dropped, the GridShare would enter timer mode rather than brownout mode. The serial data found that during 37% ± 17% of the brownouts, the average GridShare was in timer mode, thus enabling residents to continue using their large appliances for one hour. Finally, these data show that all residents experienced all four modes of GridShare operation: normal, brownout, power cut and timer mode.

With the assumption that residents had ample experience of both the conveniences and inconveniences presented by the GridShare, we conducted a survey in January 2012 to assess residents' satisfaction with the GridShare. Responses were

[57] When the GridShare cuts power to the household, the power is disconnected for 30 seconds and then the power is reconnected for 10 seconds to check to see if either the load has been reduced or the voltage has recovered. This 40 second process is considered one cycle.

largely positive and demonstrated that following the installation, residents found their electricity to be more predictable and reliable. As evidence of this statement, 92% of respondents said that if they plugged in their rice cooker when the green light was on, they were now more certain that their rice would cook well and 52% of respondents stated that their rice took less time to cook than before the installation. In the more-detailed surveys administered to a representative subset of households (n=33) respondents were asked about the frequency with which they cooked dinner at the time they wanted to, their rice spoiled and their lights flickered before and after the GridShare installation. Of the 26 respondents that provided responses on both surveys, 54% (95% CI [33%, 73%]) cooked at the time they wanted to more frequently while only 12% (95% CI [2%, 30%]) stated this occurred less frequently.[58] Similarly, 65% (95% CI [44%, 83%]) reported that when they cooked with electricity, their rice spoiled less frequently than before. In fact, after the GridShare installation, only four respondents said that their rice spoiled "1-2 times per week", all others stated that this occurred "almost never". Of the 25 respondents who reported frequencies of their lights dimming or flickering in both time periods, 68% (95% CI [47%, 85%]) stated that this occurred less frequently than before. Very few, only 8% (95% CI [1%, 26%]) of households reported increases in their rice spoiling or lights flickering.

[58] The 95% confidence intervals (CI) were referenced from Beyer (1983). All values are either taken directly from tables on pages 222-226 or interpolated linearly between these values.

All respondents were asked to list any ways the GridShare installation had benefitted them. A majority of residents stated that the primary benefit was that the GridShare communicated the status of the grid so that they now knew when to cook and plug in devices. Many thought that this ability to plan improved the quality of their rice and the predictability of cooking. Others noted that a key benefit was the ability to use low-power electrical devices, such as lights, TVs and DVDs, at all times and several respondents stated that their lighting quality and TV service had improved after the GridShare installation. A few respondents provided unanticipated benefits, saying that the GridShare enabled them to know when problems with the electricity were widespread issues on the grid or problems with wiring at their house. Some other respondents said that the GridShares helped identify times when the micro-hydro system was running poorly and enabled customers to encourage the operator to clean the grates or address problems at the powerhouse.

Though reactions to the GridShare installation were mostly positive, some residents at the community meeting and in the surveys did articulate some drawbacks and inconveniences. These frustrations help to explain why, when asked about the quality of their electrical service, only 38% stated that their electricity service had improved, while 58% stated that it was the same as before the GridShare and 4% thought that it was poorer than before. As would be expected, many were frustrated by red light and the subsequent enforcement mechanism. Some noted that it was inconvenient to wait for a green light to cook when one was in a hurry, such as when getting children ready for school in the mornings. Though LPG usage did not substantially increase, many respondents stated that they would switch to LPG when the red light was on. Residents also expressed the valid concern that having their power turned on and off could damage sensitive appliances.

Though some residents were frustrated by the enforcement mechanism, 55% of survey respondents thought the enforcement was necessary because it forced residents to be aware of the red light and prevented the grid from being overloaded. Another 25% of residents did not think the enforcement was necessary as they did not like being unexpectedly left in the dark or prevented from using appliances. The remaining 20% were uncertain how they felt about the enforcement mechanism. Though a substantial proportion of respondents did not think the enforcement was necessary, all but four respondents thought it was fair.

All of these listed benefits and concerns were confirmed by the residents who attended the final community meeting to share their comments and decide whether to keep the GridShare installed. In light of the benefits that the GridShare offered, the representatives at the community meeting decided by consensus to keep the GridShares installed.

5.5. Recommended Changes for Improvement

Though the GridShare installation appears to have worked as intended and has continued functioning well to date, the pilot installation identified several opportunities for improvement to both the technical device and the education program. These opportunities were ascertained through the household surveys, serial data and informal observations during and after the installation.

Technical changes to the GridShare include measures to reduce the cost, improve the performance and enable more efficient monitoring and maintenance. As presented in the literature review, the GridShare is one device in a wide spectrum of devices which can provide demand-side management for mini-grids. As the GridShare does not provide metering and does not provide other advanced services (such as regulating energy consumption), ensuring that it is a low cost alternative to these more complex devices is imperative. For the pilot installation, the GridShares were manufactured for just under $100 per unit. One way we have identified to reduce this cost is to incorporate the circuit breaker and GridShare circuit into one enclosure, thus eliminating the cost of one of the enclosures, as well as some additional wiring and installation time. Ideally, the new enclosure would also provide easier access to the circuit board for monitoring and repairs. Though the circuit component most susceptible to failure, the relay, is expected to last up to 20 years, making the circuit board easily accessible could reduce long-term maintenance and replacement costs.[59] Additionally, the current design of the circuit and enclosure makes it difficult to program and access data. Either re-

[59] As the relay involves moving parts, several collaborators were concerned about the lifetime of the relay limiting the lifetime of the GridShare device. Relay life is estimated by the manufacturer in terms of cycles; the relay used in the GridShare was rated with a lifetime of 30,000 cycles. According to the serial data from the GridShares, the GridShare with the highest number of cycles recorded 795 cycles in the 200 days. At this rate, the relay would last just over 20 years before reaching 30,000 cycles.

designing the device to enable easier access or adding remote-monitoring capability to the GridShare, perhaps through the mobile phone network, could help managers to monitor and troubleshoot an installation. A final design change would be relatively easy to implement as a change to the GridShare programming. Currently the software does not limit electricity use during timer mode. In conversation with some users, we found that some residents were plugging in additional appliances during timer mode, despite the expectation that this mode would simply allow the user to finish using the appliance that was currently plugged in. Changes to the code could be included that would prevent residents from increasing their loads after entering timer mode, thus better regulating the grid during periods of low voltage.

In addition to these design changes, the surveys identified areas for improvement of the education program as well. While outreach was presented through community meetings, posters, pamphlets, school-programs and presentations, most respondents stated that the in-home visits were the most effective way to learn about the program. Any future installations should ensure that in-home demonstrations and follow-up visits continue to be prioritized. As evidenced by survey responses, through these visits and education materials, residents generally understood *how* the GridShare worked, but many residents did not fully understand *why* they should not plug in during a red light or *why* their power will be cut off if they do. Though the education program was designed to address these questions, more emphasis should be placed on these explanations, particularly during the in-home visits, as understanding the reasoning behind the restrictions can make the inconveniences much more palatable.

The surveys also indicated that a majority of respondents did not fully understand the purpose of timer mode or the indication for this mode by illuminating both the red and green light. This mode needs to be better explained in the education materials and in-home visits and may entail a technical design change, such as adding a third LED to better indicate timer mode. Though these two explanations call for some improvement, many respondents volunteered to say that the education program was clear and helpful, and the success of the pilot project speaks to the successful implementation of the education component.

CHAPTER 6. CONCLUSION

The assessment found that the GridShare installation in Rukubji was successful at reducing the occurrence of severe brownouts in the village. Though the program did not completely eliminate the brownout problem, the GridShares made the grid more predictable and provided information necessary for residents to plan, discuss and make informed decisions regarding their power use. As expected, all three elements of the GridShare design were critical to the success of the project. Education about load-shifting enabled residents to understand how their actions can reduce the occurrence of brownouts, while the indicator lights informed residents of times they could use their large appliances. The enforcement element was necessary both to call attention to the red light and to limit the depth of a brownout, thus ensuring that users who plugged in during a green light could successfully cook their rice. With the relative success of the project, residents decided by consensus to keep the GridShares installed, and our project partners, the Bhutan Power Corporation (BPC), agreed to continue to monitor and maintain the GridShare installation.

As emphasized in Quetchenbach et al. (2013), though mini-grid developers and operators should consider GridShares for use on their grids, one must understand that this technology is not appropriate for all remote mini-grids. GridShares are designed for micro-hydroelectric mini-grid systems, and certain biomass or diesel systems, that operate continuously and provide a constant supply of power throughout the day. Because GridShares only limit instantaneous power use and do not address energy consumption over time, they would not be an ideal solution for a solar or wind mini-grid that uses a battery bank to provide storage for its intermittent generation. Additionally, even though load-shifting was not evident in Rukubji, the concept and potential for load-shifting is still fundamental to the GridShare concept. For this reason, large consumer loads must be able to be used at slightly different times of the day for load-shifting to be a feasible solution. In the case of Rukubji, the common use of rice cookers and water boilers created an ideal context for load-shifting, whereas the solution would be ineffective, for example, on a mini-grid dominated by lighting loads. Additionally, consumer loads must be large enough to cause a significant brownout problem as well as provide per-customer consumption levels to justify the cost of the GridShare system.

Two scenarios where a GridShare installation may be an ideal solution include:

1. A mini-grid similar to that of Rukubji where the operator desires to limit consumers to a low-wattage subscription during peak times, but allow larger loads at other times.
2. A mini-grid where consumers subscribe to different wattage allowances, but where the operator desires to ensure that all users have equal access to electricity at peak times. In this scenario, consumers with very low-wattage subscriptions could be limited with a cheap and simple load limiter, while consumers who wish to use larger loads could be limited by a GridShare. The GridShare would allow the consumers with higher-wattage subscriptions to use their large loads during off-peak times, but limit their use during peak hours.

In addition to the technical considerations, one must also consider whether restrictions of the GridShare system would be socially acceptable in a given community. The villages served by the Rukubji power plant are all small, well-functioning communities with established leadership and a cultural disposition toward communal welfare and cooperative decision-making. These attributes facilitated project implementation and created a community which was typically willing to endure a small sacrifice (limited power) for the communal good (reduction of brownouts). Additionally, because Rukubji had suffered from brownouts for several years prior to the GridShare installation, residents may have been more receptive to the solution, including the limitation on power use than a community who had never experienced the frustration of brownouts. Further, management and operation of the project was substantially aided by the fact that the mini-grid was owned and operated by a well-organized utility company tasked with providing quality electricity for their customers.

Given this context, Rukubji served as an ideal location to pilot test the GridShare technology and effectively demonstrate that user-interactive demand-side management strategies can reduce the severity of brownouts on a rural mini-grid. A critical next step will be to reproduce installations in communities of different sizes and social structures to better understand the applicability and scalability of GridShare technology.

NOTES

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APPENDIX A: EDUCATIONAL MATERIALS

Below are examples of some of the educational materials used during the GridShare installation in Rukubji. The graphic design work for these materials was done by Kirstin Hervin with input from the GridShare team. All materials were translated into Dzongkha by Tandin Gyeltshen, but presented bilingually as some residents were more comfortable reading in Dzongkha and some in English. The brochure was handed out to every household during the installation and the "cheat sheet" was posted in each house near the LED box.[60] Other educational materials which are not presented here included posters designed for both children and adults describing the GridShare and the microhydro system and props for discussions at the community meeting and for interactive games with the local school children. The props included pictures of various household appliances, timelines to think about load-shifting, and pictures of the GridShare to facilitate discussions of its functions.

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[60] One lesson learned was a cultural faux pas of making the "cheat sheets" double-sided. During the installation, one of the team members noticed that most people were hanging the cheat sheets so that the side written in Dzongkha faced out, even in households where the residents were more comfortable reading in English. Evidently, because Dzongkha is also the language of the scriptures, it would be irreverent to hang the language upside-down and toward the wall, so most households did not feel comfortable hanging the cheat sheet with the English side facing out.

Figure A-1. Tri-fold brochure for GridShare installation

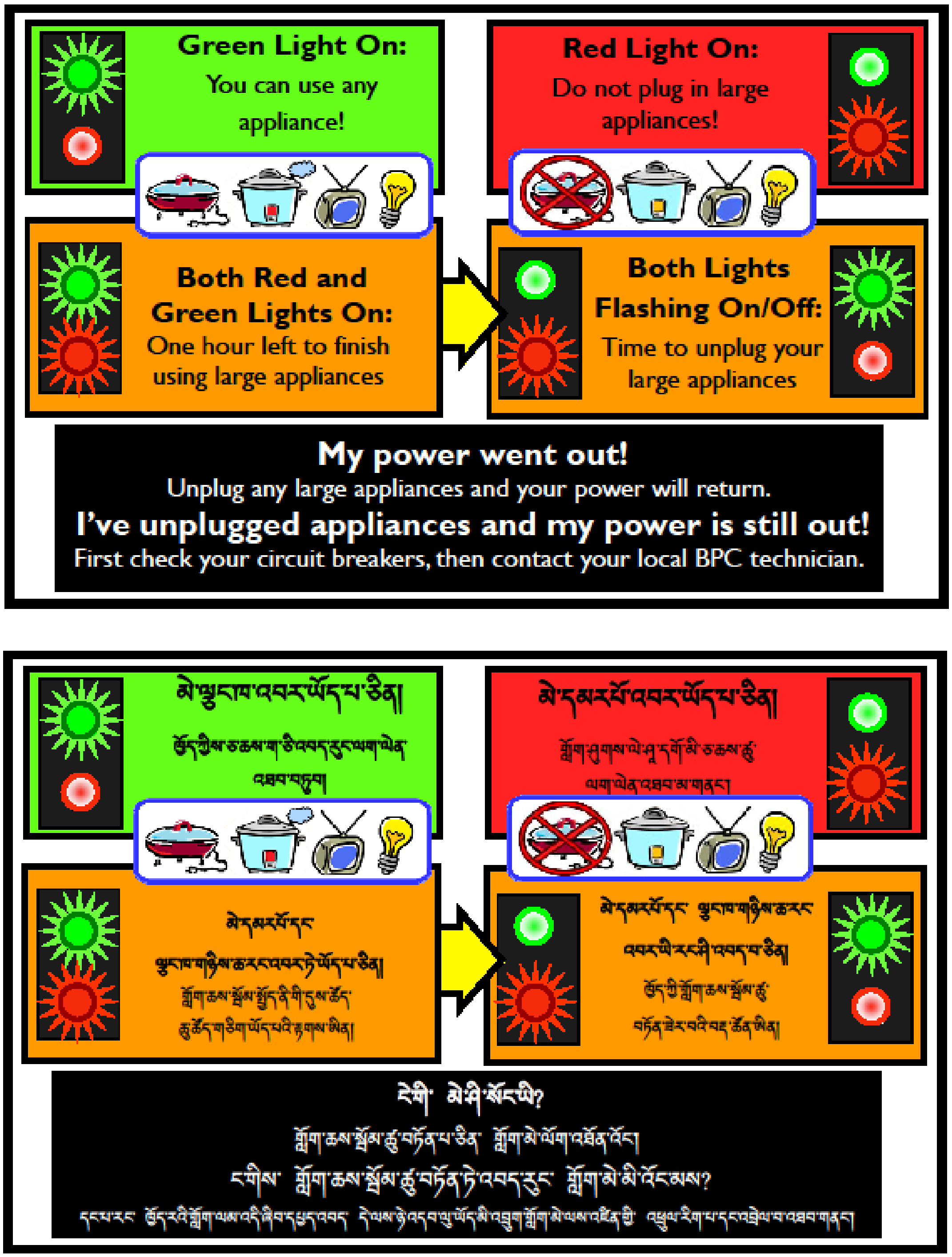

Figure A-2. "Cheat sheet" hung next to LED box in each household

APPENDIX B: HOUSEHOLD ELECTRICAL DATA CODE AND RESULTS

The following text is the code written by the author in the R-programming language that was used to plot and analyze household energy use according to the current and voltage dataloggers installed at three of the households. This code was written using advice from the R-programming manual and other online forums.[61] Data from two of the households, arbitrarily named House 1 and House 2, were analyzed using this script. Analysis for House 1 included data from July 22 to Jan 5 of 2010 and 2011, while House 2 included data from August 13 to Jan 5 of each year. These dates differ from the powerhouse data as the household data loggers were installed and removed at different times. No pre-processing was performed on these data. Additional details on the analysis of the household current dataloggers are presented in Section 4.2 and the results are described in Section 5.2. Tables of detailed statistical results are presented in this Appendix following the code.

```
#Meg Harper
#11/21/13
#Rukubji Household Current Plotting Code

setwd("C:/Users/meg/Documents/Dropbox/Thesis/P32012/Household")
#clear all dataframes, read in data from file and create blank dataframe.
#Choose datafile with # below.
rm(list=ls(all=TRUE))
```

[61] Plotting code built on examples from: http://cran.r-project.org/doc/manuals/R-intro.html, www.ats.ucla.edu/stat/r/faq/angled_labels.htm, http://rwiki.sciviews.org/doku.php?id=tips:graphics-base:2yaxes and www.harding.edu/fmccown/r/#autosdatafile .

```
inputs=2 #chooses what file to process and output
	if(inputs==1){
		datafile="HouseXVC2010.csv"
		outputfile="cookingX2010.csv"
		plotoutput="HouseholdCurrentPlotX2010.pdf"
		plottitle="Household 1 Current and Voltage 2010"
	}
	if(inputs==2){
		datafile="HouseXVC2011.csv"
		outputfile="cookingX2011.csv"
		plotoutput="HouseholdCurrentPlotX2011.pdf"
		plottitle="Household 1 Current and Voltage 2011"
	}
	if(inputs==3){
		datafile="HouseXXVC2010.csv"
		outputfile="cookingXX2010.csv"
		plotoutput="HouseholdCurrentPlotXX2010.pdf"
		plottitle="Household 2 Current and Voltage 2010"
	}
	if(inputs==4){
		datafile="HouseXXVC2011.csv"
		outputfile="cookingXX2011.csv"
		plotoutput="HouseholdCurrentPlotXX2011.pdf"
		plottitle="Household 2 Current and Voltage 2011"
	}
	Current = data.frame(read.csv(datafile),header=T)
	indexMax=nrow(Current)
	noChange <-data.frame(index=rep(NA,indexMax),month=rep(NA,indexMax),
	day=rep(NA,indexMax),year=rep(NA,indexMax),hour=rep(NA,indexMax),
	minute=rep(NA,indexMax),stringsAsFactors=FALSE)
	cookmin<-c(0,0,0)
	cookmax<-c(0,0,0)
	cookflag=0
	cooking<-data.frame(Month=rep(NA,indexMax), Day=rep(NA,indexMax),
	Year=rep(NA,indexMax), StartHour=rep(NA,indexMax), StartMinu=rep(NA,indexMax),
	StartCurr=rep(NA,indexMax), EndHour=rep(NA,indexMax), EndMinu=rep(NA,indexMax),
	EndCurr=rep(NA,indexMax), CookTime=rep(NA,indexMax))
	time=0
	brownoutUse=0
	j=0

	#create file to print to, set parameters: 5 plots per page, set plot margins and outer margins
	pdf(file=plotoutput)
	par(mfrow=c(5,1),mar=c(2,2,2,3)+.01, oma=c(2,2,2,2))

	#For each day, create a plot of the voltage and current in the household.
	#As with the billing data code, this code is not written as efficiently as it could be in R,
	#but is reasonably fast (~1 min) thanks to the small data set (~42000 measurements). The
	#noChange dataframe is used for error checking and essentially as a placeholder operation
	#in the if statement.
	i=0
	for(i in 1:(indexMax-1))
```

```
{
if(i==1) {
	MinDay=1
} else if(Current[i,2]!=Current[(i-1),2]) {
	MaxDay=(i-1)
	xTicMax=288
	hours=c("0","1","2","3","4","5","6","7","8","9","10","11","12","13","14","15",
		"16","17","18","19","20","21","22","23")
	limity=c(0,10)
	spacing1=c(0,2,4,6,8,10)
	spacing2=c(0,50,100,150,200,250,300)
	par(adj=.5)
	plot(Current[MinDay:MaxDay,6],axes=F,xlab="",ylab="",ylim=limity,
			type="l",col="blue",lwd=2,lty=1)
	axis(2,ylim=limity,col="blue",las=1,at=spacing1)
	mtext("Current (A)",side=2,line=2,cex=.8)
	mtext(plottitle,outer=TRUE,line=.25)
	#lines(Current[MinDay:MaxDay,6],pch=2,lty=1,lwd=2,col="red")
	axis(1,at=seq(1,xTicMax,by=12),lab=F)
	mtext("Time (Hours)",side=1,col="black",line=2,cex=.8)
	#axis(2,las=1,at=spacing1)
	text(seq(1, xTicMax, by=12), par("usr")[3], labels=hours, pos=1, offset=.8, xpd=TRUE)
	box()
	par(adj=0)
	title(main=paste(Current[MinDay,1],"-", Current[MinDay,2],"-",Current[MinDay,3]))
	par(new = TRUE)
	plot(Current[MinDay:MaxDay,8],type = "l", axes = FALSE,
		bty = "n", xlab = "", ylab = "",ylim=c(100,300),col="black")
	axis(side=4, ylim=c(100,300),at = spacing2,col="black",col.axis="black",las=1)
	mtext("Voltage (V)", side=4, line=3,col="black",cex=.8)
	legend("bottomleft",legend=c("Voltage","Current"),text.col=c("black","blue"),
		pch=c(16,15),col=c("black","blue"))
	MinDay=i

} else {
	noChange[i,]<-c(i,Current[i,1],Current[i,2],Current[i,3],Current[i,4],Current[i,5])
	#Calculate length of cooking events (current greater than 2A),number of 5 minute
	#intervals where household is
	#cooking during a brownout (v<200), and create dataframe to export to excel with
	#each day's cooking times.
	if(Current[i,6]>=2 && Current[i,8]<=200 && Current[i,8]>=90)
		brownoutUse=brownoutUse+1
	if(Current[i,6]>=2 && cookflag==0){
		cookflag=1
		cookmin<-c(Current[i,4],Current[i,5],Current[i,6])
	} else if(Current[i,6]<=1 && Current[(i+1),6]<=1 && cookflag==1){
		cookmax<-c(Current[i,4],Current[i,5],Current[i,6])
		time=(cookmax[2]+(60-cookmin[2])+(60*(cookmax[1]-cookmin[1]-1)))
		if(time>10){
			j=j+1
			cooking[j,]<-c(Current[i,1],Current[i,2],Current[i,3],cookmin[1],
			cookmin[2],cookmin[3],cookmax[1],cookmax[2],cookmax[3],time)
```

```
				}
				cookmin<-c(0,0,0)
				cookmax<-c(0,0,0)
				cookflag=0
		}
}
}
cat(brownoutUse)
write.csv(noChange,file="noChangeCheck.csv",row.names=F)
write.csv(cooking,file=outputfile,row.names=F)
dev.off()
```

The following seven tables (B-1 to B-7) display the statistical results of the household data analysis as described in Section 5.2.1.

Table B-1. Comparison of minutes of cooking for Household 1

	Cooking Time Before	Cooking Time After
Daily Mean Time (Minutes)	30	35
Std Error (Minutes)	0.6	0.7
Daily Median Time (Minutes)	25	30
Daily Mode Time (Minutes)	25	20
Std Deviation (Minutes)	16	20
Sample Variance (Minutes)	263	400
Kurtosis	3.8	4.2
Skewness	1.8	1.7
Range (Minutes)	90	155
Minimum (Minutes)	15	15
Maximum (Minutes)	105	170
Sum over 5-month period (Minutes)	20890	27365
Number of events over 5-month period	675	780
df	1447	
t Stat	-4.355	
P(T<=t) two-tail	1.42E-05	

Table B-2. Comparison of currents during cooking for Household 1

	Initial Current Before	Initial Current After
Daily Mean Current (Amps)	3.482	3.393
Std Error (Amps)	0.051	0.045
Daily Median Current (Amps)	3.021	3.009
Daily Mode Current (Amps)	3.070	2.765
Std Deviation (Amps)	1.325	1.253
Sample Variance (Amps)	1.756	1.570
Kurtosis	-0.255	0.416
Skewness	1.090	1.304
Range (Amps)	6.030	6.201
Minimum (Amps)	2.008	2.008
Maximum (Amps)	8.038	8.209
Number of events over 5-month period	675	780
df	1397	
t Stat	1.316	
P(T<=t) two-tail	0.188	

Table B-3. Comparison of cooking events per day for Household 1

	Cooking Time Before	Cooking Time After
Daily Mean Time (Minutes)	4.0	4.7
Std Error (Minutes)	0.1	0.1
Daily Median Time (Minutes)	4	5
Daily Mode Time (Minutes)	3	5
Std Deviation (Minutes)	1.7	1.5
Sample Variance (Minutes)	2.8	2.2
Kurtosis	0.8	0.1
Skewness	0.8	0.2
Range (Minutes)	8	8
Minimum (Minutes)	1	1
Maximum (Minutes)	9	9
Sum over 5-month period (Minutes)	675	780
Number of events over 5-month period	167	167
df	327	
t Stat	-3.626	
P(T<=t) two-tail	0.0003	

Table B-4. Comparison of morning (AM), mid-day (Noon) and evening (PM) cooking time of day for Household 2

	AM Before	AM After	Noon Before	Noon After	PM Before	PM After
Daily Mean Time (HH:MM)	6:25 AM	6:17 AM	12:42 PM	12:30 PM	5:24 PM	5:32 PM
Std Error (HH:MM)	0:05	0:06	0:07	0:11	0:03	0:05
Daily Median Time (HH:MM)	6:18 AM	6:14 AM	12:45 PM	12:14 PM	5:20 PM	5:24 PM
Daily Mode Time (HH:MM)	5:46 AM	6:49 AM	11:50 AM	11:04 AM	5:01 PM	5:04 PM
Std Deviation (HH:MM)	1:06	1:06	1:09	1:21	0:43	0:51
Sample Variance (HH:MM)	0:03	0:03	0:03	0:04	0:01	0:01
Kurtosis	2.013	1.780	-0.505	-0.178	-0.175	-0.358
Skewness	0.858	0.907	-0.140	0.626	0.596	0.494
Range (HH:MM)	7:05	5:40	4:55	5:40	3:26	3:32
Minimum (HH:MM)	2:51	4:14	10:01	10:14	16:05	16:04
Maximum (HH:MM)	9:56	9:54	14:56	15:54	19:31	19:36
Number of events over 5-month period	169	108	76	50	144	85
df	275		124		227	
t Stat	0.876		0.871		-1.186	
P(T<=t) two-tail	0.381		0.385		0.237	

Table B-5. Comparison of minutes of cooking for Household 2

	Cooking Time Before	Cooking Time After
Daily Mean Time (Minutes)	39	30
Std Error (Minutes)	0.9	0.7
Daily Median Time (Minutes)	35	30
Daily Mode Time (Minutes)	25	30
Std Deviation (Minutes)	19	11
Sample Variance (Minutes)	344	111
Kurtosis	0.6	0.6
Skewness	1.0	0.4
Range (Minutes)	95	60
Minimum (Minutes)	15	15
Maximum (Minutes)	110	75
Sum over 5-month period (Minutes)	15110	7320
Number of events over 5-month period	389	243
df	625	
t Stat	7.537	
P(T<=t) two-tail	1.7E-13	

Table B-6. Comparison of currents during cooking for Household 2

	Initial Current Before	Initial Current After
Daily Mean Current (Amps)	4.549	4.036
Std Error (Amps)	0.076	0.051
Daily Median Current (Amps)	3.949	3.864
Daily Mode Current (Amps)	3.912	3.79
Std Deviation (Amps)	1.490	0.798
Sample Variance (Amps)	2.220	0.636
Kurtosis	2.101	8.535
Skewness	1.579	1.826
Range (Amps)	8.167	6.47
Minimum (Amps)	2.02	2.02
Maximum (Amps)	10.187	8.49
Number of events over 5-month period	389	243
df	617	
t Stat	5.629	
P(T<=t) two-tail	2.75E-08	

Table B-7. Comparison of minutes of cooking for Household 2

	Cooking Time Before	Cooking Time After
Daily Mean Time (Minutes)	2.7	1.9
Std Error (Minutes)	0.08	0.07
Daily Median Time (Minutes)	3	2
Daily Mode Time (Minutes)	2	2
Std Deviation (Minutes)	0.98	0.84
Sample Variance (Minutes)	0.97	0.71
Kurtosis	0.42	0.44
Skewness	0.59	0.71
Range (Minutes)	5	4
Minimum (Minutes)	1	1
Maximum (Minutes)	6	5
Sum over 5-month period (Minutes)	389	243
Number of events over 5-month period	144	126
df	268	
t Stat	6.96	
P(T<=t) two-tail	2.57E-11	

APPENDIX C: ELECTRICITY BILLING DATA CODE AND PLOTS

This Appendix includes additional information from the analysis of the electricity billing data for the Rukubji mini-grid: results of the statistical tests, plots of monthly energy consumption and the code used to analyze the data and produce the plots.

The average and median monthly electricity consumption in the 12 months before the GridShare installation and the 12 months after the GridShare installation are displayed in Table C-1. Additionally, the change in both the average and median electricity consumption and the results of the statistical tests are presented here. Any significant differences as indicated by p-values less than 0.05 are highlighted in red and noted as to whether they represent an increase or decrease in the household's electricity consumption. To assess whether the 12 months prior to the GridShare installation was an appropriate time period for comparison, records from the previous 30 months were compared to the 12-month "Before" period. This comparison showed that there was no significant difference in the overall average energy consumption and there was statistically no change in 58 of the individual households' consumption. Of the remaining households, six decreased their consumption and 15 increased consumption. These results suggested that using the 12 months prior to the GridShare installation as a comparative period was a reasonable assumption.

Following the data table are plots of monthly household energy use in a subset of houses on the Rukubji mini-grid (Figure C-1). Similar plots were developed for all connections on the grid to enable visual comparison of the data. The vertical lines on the plots separate the three periods which were compared in the analysis: the 30 months (2 ½ years) prior to June 2010, the 12 months prior to the installation and the 12 months after the installation. The plots also display the average energy consumption in kWh with error bars representing one standard deviation from the mean for each of these three periods. The break in the graph between July 2008 and January 2009 is due to two months of missing data and is not included in the averages. Following these graphs is the code for the program used to analyze household energy use according to the BPC billing records.

Table C-1. Averages, medians and test statistics of monthly billing comparison

House ID	Avg. Before (kWh/month)	Average After (kWh/month)	Change in Avg. (kWh/month)	Median Before (kWh/month)	Median After (kWh/month)	Change in Median (kWh/month)	Wilcoxon test statistic: V	p-value	Significant increase or decrease?
1	39.5	89.1	49.6	34.5	84.0	49.5	31.5	0.021	increase
2	75.3	63.6	-11.8	65.5	64.5	-1.0	73.0	0.977	
3	49.3	42.3	-6.9	40.0	34.0	-6.0	92.5	0.247	
4	39.6	55.1	15.5	34.5	58.0	23.5	45.5	0.133	
5	54.0	70.5	16.5	57.5	73.0	15.5	40.5	0.073	
6	59.8	55.4	-4.4	59.0	37.0	-22.0	94.0	0.214	
7	53.2	45.3	-7.9	53.0	46.0	-7.0	92.0	0.259	
8	75.6	69.1	-6.5	68.0	66.0	-2.0	81.0	0.623	
9	5.7	24.6	18.9	0.0	0.0	0.0	59.0	0.407	
10	36.3	38.9	2.7	34.5	37.0	2.5	62.5	0.603	
11	19.4	11.5	-7.9	17.0	3.5	-13.5	109.5	0.031	decrease
12	31.9	41.0	9.1	32.5	44.0	11.5	55.0	0.340	
13	27.8	39.2	11.3	28.0	36.5	8.5	55.0	0.340	
14	45.3	43.3	-2.0	39.0	17.5	-21.5	107.5	0.042	decrease
15	99.3	52.9	-46.3	91.5	45.0	-46.5	119.0	0.007	decrease
16	23.3	28.7	5.4	21.0	26.5	5.5	59.5	0.486	
17	40.8	47.6	6.8	42.5	52.0	9.5	57.0	0.402	
18	46.0	49.2	3.2	45.5	56.5	11.0	61.5	0.563	
19	57.0	73.5	16.5	40.5	69.0	28.5	52.0	0.259	
20	59.8	62.8	2.9	52.5	58.0	5.5	63.5	0.644	
21	66.3	76.4	10.2	67.0	82.0	15.0	45.0	0.126	
22	26.8	3.8	-23.0	25.0	0.0	-25.0	123.0	0.002	decrease
23	93.6	85.2	-8.4	91.5	83.0	-8.5	83.0	0.544	
24	137.6	235.5	97.9	144.0	229.0	85.0	41.0	0.078	
25	56.7	64.2	7.5	57.5	53.0	-4.5	78.0	0.751	
27	103.8	29.8	-74.0	84.5	29.0	-55.5	121.5	0.005	decrease
28	88.4	73.4	-15.0	92.0	80.0	-12.0	88.5	0.355	
29	74.8	68.9	-5.8	72.0	71.5	-0.5	74.0	0.931	
30	74.1	62.3	-11.8	46.5	53.0	6.5	64.5	0.686	
31	48.9	61.9	13.0	47.5	64.5	17.0	33.0	0.026	increase
32	114.3	131.3	17.0	113.5	134.5	21.0	57.5	0.419	
34	89.3	70.2	-19.1	83.0	54.5	-28.5	81.0	0.623	

Table C-1 continued

House ID	Avg. Before (kWh/month)	Average After (kWh/month)	Change in Avg. (kWh/month)	Median Before (kWh/month)	Median After (kWh/month)	Change in Median (kWh/month)	Wilcoxon test statistic: V	p-value	Significant increase or decrease?
35	64.7	56.8	-7.9	55.5	58.5	3.0	82.5	0.563	
36	43.2	40.4	-2.8	43.0	38.5	-4.5	78.0	0.751	
37	224.3	115.7	-108.6	245.0	120.0	-125.0	120.5	0.006	decrease
38	109.3	99.2	-10.1	104.0	104.0	0.0	79.0	0.707	
39	74.3	70.7	-3.6	74.0	60.5	-13.5	78.0	0.751	
40	66.5	66.2	-0.3	67.5	66.5	-1.0	70.0	0.931	
41	18.8	19.6	0.8	21.0	7.5	-13.5	84.0	0.501	
42	90.1	75.1	-15.0	93.0	79.5	-13.5	89.5	0.326	
44	15.6	7.0	-8.6	10.5	2.0	-8.5	92.0	0.111	
45	28.8	22.6	-6.2	28.5	25.0	-3.5	89.5	0.325	
46	34.3	34.4	0.2	34.5	35.5	1.0	71.0	0.977	
47	85.3	97.1	11.8	77.5	106.0	28.5	47.0	0.157	
48	91.8	77.2	-14.7	93.0	81.5	-11.5	89.5	0.326	
49	80.5	75.6	-4.9	83.5	80.5	-3.0	79.5	0.686	
50	39.3	56.3	17.0	30.0	56.0	26.0	46.5	0.149	
51	43.1	27.8	-15.3	53.5	27.0	-26.5	97.5	0.147	
52	111.9	96.3	-15.6	116.0	106.5	-9.5	87.5	0.386	
53	108.3	91.0	-17.3	116.5	93.5	-23.0	99.5	0.119	
54	16.4	0.0	-16.4	3.0	0.0	-3.0	120.0	0.001	decrease
55	51.7	48.8	-2.9	56.0	49.5	-6.5	85.0	0.470	
56	43.0	28.0	-15.0	49.5	31.0	-18.5	106.5	0.049	decrease
58	380.0	227.1	-152.9	402.5	57.0	-345.5	105.0	0.059	
59	54.8	25.0	-29.8	51.0	6.0	-45.0	100.0	0.106	
60	29.1	59.7	30.6	28.5	42.0	13.5	36.5	0.043	increase
61	85.1	74.9	-10.2	86.5	71.5	-15.0	81.0	0.622	
63	50.1	53.7	3.6	52.0	31.0	-21.0	80.0	0.662	
64	33.8	61.7	27.9	30.5	69.0	38.5	50.0	0.212	
65	53.6	53.9	0.3	48.5	57.0	8.5	74.0	0.931	
66	5.3	6.0	0.8	2.5	0.0	-2.5	82.5	0.519	
67	14.4	16.9	2.5	15.5	15.5	0.0	64.5	0.685	
68	21.7	29.2	7.5	22.0	28.5	6.5	54.5	0.324	

Table C-1 continued

House ID	Avg. Before (kWh/month)	Average After (kWh/month)	Change in Avg. (kWh/month)	Median Before (kWh/month)	Median After (kWh/month)	Change in Median (kWh/month)	Wilcoxon test statistic: V	p-value	Significant increase or decrease?
69	24.6	21.8	-2.8	25.0	7.5	-17.5	88.0	0.367	
70	22.9	30.7	7.8	22.0	27.0	5.0	72.0	1.000	
72	58.8	71.8	12.9	56.0	84.0	28.0	59.0	0.468	
74	66.3	58.2	-8.1	61.5	67.0	5.5	83.0	0.544	
75	46.8	72.9	26.2	42.0	49.5	7.5	73.0	0.977	
76	353.8	268.2	-85.6	333.5	159.0	-174.5	94.0	0.213	
77	52.8	38.8	-14.0	53.5	50.0	-3.5	103.5	0.073	
78	39.8	23.5	-16.3	38.5	24.0	-14.5	109.5	0.032	decrease
79	19.2	16.5	-2.7	20.5	16.5	-4.0	88.0	0.370	
80	7.2	37.8	30.6	4.5	7.0	2.5	62.5	0.601	
84	80.8	48.2	-32.6	83.5	49.5	-34.0	104.5	0.064	
86	64.8	67.1	2.3	62.0	60.5	-1.5	72.0	1.000	
90	65.4	59.1	-6.3	58.5	59.0	0.5	74.5	0.907	
91	16.9	22.0	5.1	17.5	23.5	6.0	53.5	0.298	
92	29.0	69.0	40.0	30.5	37.5	7.0	62.0	0.582	
97	26.9	30.3	3.4	26.0	29.5	3.5	NA	NA	
98	68.8	43.8	-25.0	79.0	52.5	-26.5	NA	NA	
99	18.4	51.5	33.1	0.0	34.5	34.5	NA	NA	
100	13.0	44.6	31.6	13.0	45.5	32.5	NA	NA	
Avg. of All	62.9	59.2	-3.7	61.0	52.8	-8.2	1935.5	0.383	

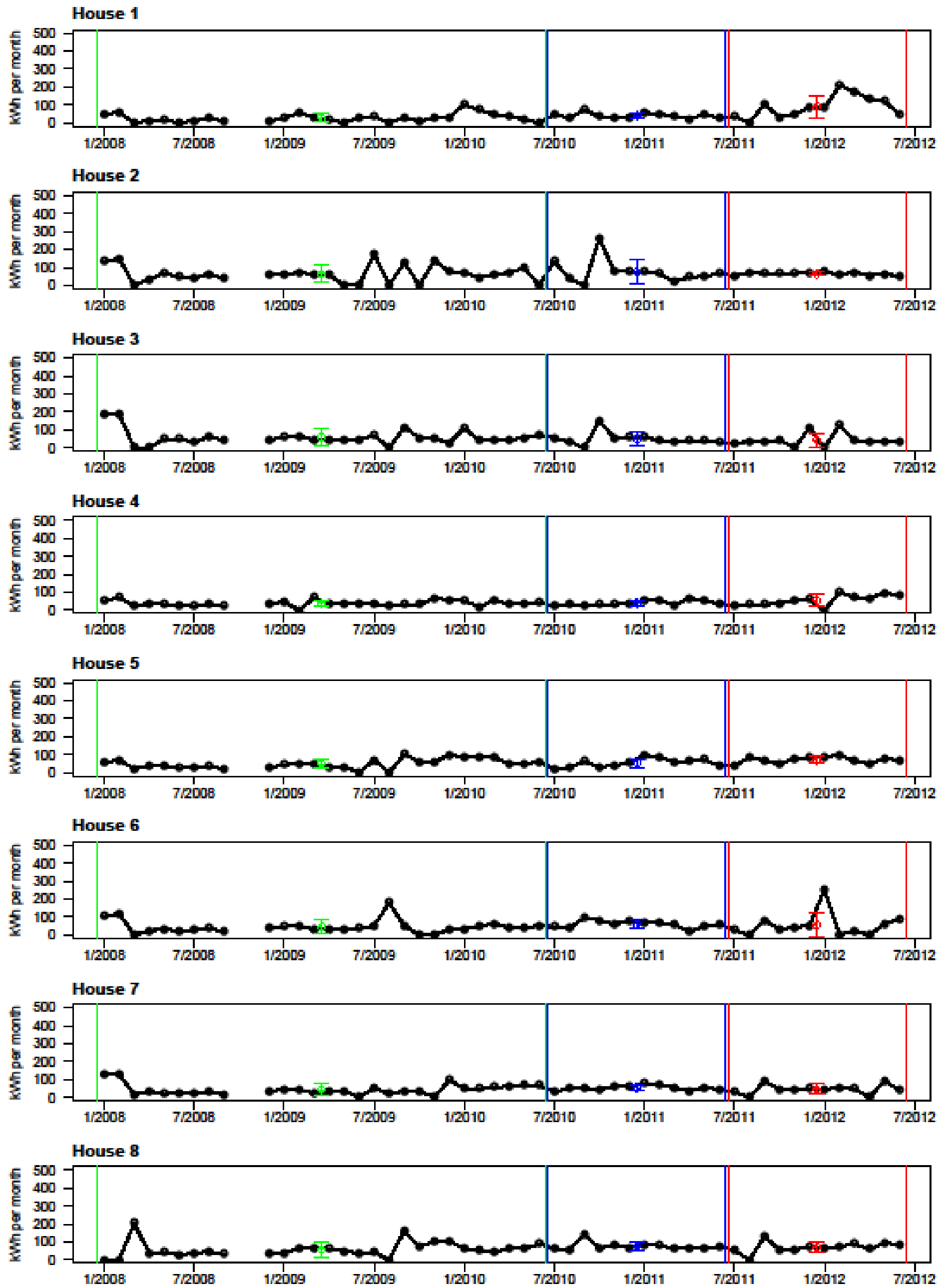

Figure C-1. Example household energy consumption in kWh per month from BPC billing records for eight different households. The vertical lines on the plots separate the three periods which were compared in the statistical analysis.

The following code was used to analyze the BPC billing records. This code was written by the author in the R-programming language using advice from the R-programming manual and other online forums.[62] Details on the analysis of billing records are presented in Section 4.3 and the results are described in Section 5.3.

```
#Rukubji Billing Code
#Meg Harper
#2/21/13
#This code computes the average monthly energy consumption (kWh) for each household in Rukubji,
#Bhutan over several different comparative time periods. The code also computes the std dev of each time
#period and uses the Wilcoxon rank-sum test to compare each time period (this is a non-parametric test
#used similarly to an independent t-test).  The Wilcoxon signed-rank test (similar to the dependent t-test)
#is used to compare the aggregate data from all households.  The code also plots the monthly billing data
#for each household along with the average and error bars representing 1 std dev for three different periods:
#the 30 months before any monitoring,the 12 months prior to the installation and the 12 months after the
#installation.
#Note:This code does not use R in a particularly efficient way (i.e. uses for loops rather than intrinsic data
#frame functions), but the program works for a small data set.

#INPUTS:
#1."BillingDataforR.csv": this file should be formatted with the house ID numbers as the column names
#and the rows representing different months of data. For the month labels in the plots and the average
#ranges to be accurate, all months must be included, even if data was not available.
#2."RIndexHouseID.csv":This file is used to more easily assign the correct houseID numbers to special
#cases and to the output data.

#OUTPUTS:
#1. "BillingFigures2.pdf: plots of individual billing records, currently set to print 6 per page
#2. "BillingStats.csv": Results from Wilcoxon rank-sum tests and Wilcoxon signed-rank test
#3. "BillingAvg.csv": Average monthly energy consumption over each time period for each household
#4. "BillingStdDev.csv": Std. deviation for each average

require("Hmisc")
```

---

[62] Plotting code built on examples from: http://cran.r-project.org/doc/manuals/R-intro.html, www.ats.ucla.edu/stat/r/faq/angled_labels.htm and www.harding.edu/fmccown/r/#autosdatafile

```
setwd("C:/Users/meg/Documents/Dropbox/Thesis/P32012/billing")
rm(list=ls(all=TRUE))
billing = data.frame(read.csv("BillingDataforR.csv"),header=T)
houseID= data.frame(read.csv("RIndexHouseID.csv"),header=T)
xTicMax=55
indexMax=ncol(billing)
months=c("1/2008","7/2008","1/2009","7/2009","1/2010","7/2010","1/2011","7/2011","1/2012","7/2012")

averages <- data.frame(HID=rep(NA,(indexMax-1)),avg6FallPre=rep(NA,(indexMax-1)),
        avg6FallPost=rep(NA,(indexMax-1)),
        avgallpre=rep(NA,(indexMax-1)),avg6SprPre=rep(NA,(indexMax-
        1)),avg6SprPost=rep(NA,(indexMax-1)),avg12pre=rep(NA,(indexMax-1)),
        avg12post=rep(NA,(indexMax-1)),stringsAsFactors=FALSE)

medians<- data.frame(HID=rep(NA,(indexMax-1)),med6FallPre=rep(NA,(indexMax-1)),
        med6FallPost=rep(NA,(indexMax-1)),
        medallpre=rep(NA,(indexMax-1)),med6SprPre=rep(NA,(indexMax-
        1)),med6SprPost=rep(NA,(indexMax-1)),
        med12pre=rep(NA,(indexMax-1)),med12post=rep(NA,(indexMax-1)),stringsAsFactors=FALSE)

stddevs<- data.frame(HID=rep(NA,(indexMax-1)),std6FallPre=rep(NA,(indexMax-1)),
        std6FallPost=rep(NA,(indexMax-1)),
        stdallpre=rep(NA,(indexMax-1)),std6SprPre=rep(NA,(indexMax-
        1)),std6SprPost=rep(NA,(indexMax-1)),
        std12pre=rep(NA,(indexMax-1)),std12post=rep(NA,(indexMax-1)),stringsAsFactors=FALSE)

HouseWilcox <- data.frame(HID=rep(NA,(indexMax-1)),pre6FvsPost6FW=rep(NA,(indexMax-1)),
        pre6FvsPost6FP=rep(NA,(indexMax-1)),
        preAllvsPre6FW=rep(NA,(indexMax-1)),preAllvsPre6FP=rep(NA,(indexMax-
        1)),pre6SvsPost6SW=rep(NA,(indexMax-1)),
        pre6SvsPost6SP=rep(NA,(indexMax-1)),preAllvsPre6SW=rep(NA,(indexMax-
        1)),preAllvsPre6SP=rep(NA,(indexMax-1)),
        pre12vsPost12W=rep(NA,(indexMax-1)), pre12vsPost12P=rep(NA,(indexMax-
        1)),preAllvsPre12W=rep(NA,(indexMax-1)),
        preAllvsPre12P=rep(NA,(indexMax-1)),stringsAsFactors=FALSE)

pdf(file="BillingFigures3.pdf")

par(mfrow=c(6,1),mar=c(2,4,2,2), oma=c(2,4,2,2))
i=0
ID=0

for(i in 1:(indexMax-1))
{
        #Calculate stats and create plots
        ID<-houseID[,i]
        averages[i, ] <c(ID,mean(billing[31:36,i],na.rm=TRUE),mean(billing[43:48,i],na.rm=TRUE),
                mean(billing[1:30,i],na.rm=TRUE),
                mean(billing[37:42,i],na.rm=TRUE),mean(billing[49:54,i],na.rm=TRUE),
                mean(billing[31:42,i],na.rm=TRUE), mean(billing[43:54,i],na.rm=TRUE))
        medians[i, ] <- c(ID,median(billing[31:36,i],na.rm=TRUE),median(billing[43:48,i],na.rm=TRUE),
                median(billing[1:30,i],na.rm=TRUE),median(billing[37:42,i],na.rm=TRUE),
```

```
            median(billing[49:54,i],na.rm=TRUE),median(billing[31:42,i],na.rm=TRUE),
            median(billing[43:54,i],na.rm=TRUE))
stddevs[i, ] <- c(ID,sd(billing[31:36,i],na.rm=TRUE),sd(billing[43:48,i],na.rm=TRUE),
            sd(billing[1:30,i],na.rm=TRUE),sd(billing[37:42,i],na.rm=TRUE),
            sd(billing[49:54,i],na.rm=TRUE),sd(billing[31:42,i],na.rm=TRUE),
            sd(billing[43:54,i],na.rm=TRUE))

graphtitle=NULL
if(ID==58) {
            limity=c(0,1200)
            graphtitle="Headmaster"
            spacing=c(0,200,400,600,800,1000,1200)
} else if(ID==76) {
            limity=c(0,1200)
            graphtitle="Restaurant"
            spacing=c(0,200,400,600,800,1000,1200)
} else {
            limity=c(0,500)
            graphtitle=paste("House", ID)
            spacing=c(0,100,200,300,400,500)}

par(adj=.5)
plot(billing[,i],axes=F,ann=T,xlab="Billing Month",ylab="kWh per month",ylim=limity,lwd=2)
mtext("Billing Records",outer=TRUE,line=.25)
lines(billing[,i],pch=22,lty=1,lwd=2)
axis(1,at=seq(1,xTicMax,by=6),lab=F)
axis(2,las=1,at=spacing) #hard coded by case above
text(seq(1, xTicMax, by=6), par("usr")[3], labels=months, pos=1, offset=.8, xpd=TRUE)
box()
par(adj=0)
title(main=graphtitle)

errbar(15.5, averages[i,4], averages[i,4]+stddevs[i,4], averages[i,4]-stddevs[i,4],
            cap=0.015,add=TRUE,pch=23,col="green",errbar.col="green")
errbar(36.5, averages[i,7], averages[i,7]+stddevs[i,7], averages[i,7]-stddevs[i,7],
            cap=0.015,add=TRUE,pch=23,col="blue",errbar.col="blue")
errbar(48.5, averages[i,8], averages[i,8]+stddevs[i,8], averages[i,8]-stddevs[i,8],
            cap=0.015,add=TRUE,pch=23,col="red",errbar.col="red")

abline(v = 0.5, col = "green")
abline(v = 30.4, col = "green")
abline(v = 30.6, col = "blue")
abline(v = 42.4, col = "blue")
abline(v = 42.6, col = "red")
abline(v = 54.5, col = "red")

if(ID<96) {
            #Wilcoxon rank-sum test on individual households with data in all three periods
            A=wilcox.test(billing[31:36,i], billing[43:48,i], paired=F,
                        alternative="two.sided",na.rm=TRUE)
            B=wilcox.test(billing[31:36,i], billing[1:30,i], paired=F,alternative="two.sided",
                        na.rm=TRUE)
```

```
                C=wilcox.test(billing[37:42,i], billing[49:54,i], paired=F,alternative="two.sided",
                        na.rm=TRUE)
                D=wilcox.test(billing[37:42,i], billing[1:30,i], paired=F,alternative="two.sided",
                        na.rm=TRUE)
                E=wilcox.test(billing[31:42,i], billing[43:54,i], paired=F,alternative="two.sided",
                        na.rm=TRUE)
                G=wilcox.test(billing[31:42,i], billing[1:30,i], paired=F,alternative="two.sided",
                        na.rm=TRUE)
                HouseWilcox[i, ] <- c(ID,A[1],A[3],B[1],B[3],C[1],C[3],D[1],D[3],E[1],E[3],G[1],G[3])
                }
        }

#Wilcoxon signed-rank test on aggregate data
A=wilcox.test(averages$avg6FallPre, averages$avg6FallPost, paired=TRUE,alternative="two.sided",
        na.rm=TRUE)
B=wilcox.test(averages$avg6FallPre, averages$avgallpre, alternative="two.sided",
        paired=TRUE,na.rm=TRUE)
C=wilcox.test(averages$avg6SprPre, averages$avg6SprPost, alternative="two.sided",
        paired=TRUE,na.rm=TRUE)
D=wilcox.test(averages$avg6SprPre, averages$avgallpre, alternative="two.sided",
        paired=TRUE,na.rm=TRUE)
E=wilcox.test(averages$avg12pre, averages$avg12post, alternative="two.sided",
        paired=TRUE,na.rm=TRUE)
G=wilcox.test(averages$avg12pre, averages$avgallpre, alternative="two.sided",
        paired=TRUE,na.rm=TRUE)
HouseWilcox[indexMax, ] <- c("All",A[1],A[3],B[1],B[3],C[1],C[3],D[1],D[3],E[1],E[3],G[1],G[3])

write.csv(HouseWilcox,file="BillingStats.csv",row.names=F)
write.csv(averages,file="BillingAvg.csv",row.names=F)
write.csv(medians,file="BillingMedian.csv",row.names=F)
write.csv(stddevs,file="BillingStdDev.csv",row.names=F)
dev.off()
```

APPENDIX D: SURVEY INSTRUMENTS

This appendix presents the five survey instruments used in this assessment, as discussed in Section 4.4. In July 2010 we surveyed every house connected to the mini-grid to determine their interest in the project and their willingness to participate, to understand their current experience and understanding of brownouts and to collect baseline information about electricity use for future comparison. Due to time limitations, we used two separate surveys; one was more in-depth and was only administered at 33 of the 78 houses, while the other was shorter and was administered at 45 of the 78 houses.

In June of 2011, we returned and installed the GridShares at all the houses in the village. With the realization that our initial baseline information may have changed over a year, and wanting to gather more concrete information for a pre-installation and post-installation comparison, we created an additional survey to administer to the same 33 households that had completed the long survey the year before. In cases where residents who had completed the long survey in 2010 were not available in 2011, we chose new houses to survey using a random number generator to ensure a sample size of 33 households.

A final assessment survey was administered in January of 2012 to evaluate behavioural changes related to the GridShare and residents' satisfaction with the GridShare program. Just as in the summer of 2010, two surveys were administered, a short survey and a long survey. The long survey was administered to a total of 34 households which consisted of all the available households that were given the long survey in 2010 and the pre-installation survey in 2011. The short survey was administered to the other 42 households.

Each of the five survey instruments are presented below. Due to changes in page size, font and margins, the formatting of the surveys is slightly different than those used in the field, but as all surveys were presented orally, any differences should be of minimal consequence.

Initial Long Survey (July 2010)--

Household ID # _________ Date:________ Time:_____-______ Photo #s:___________

1 Electricity Use and Experience

As we mentioned, we are interested to know information about your use and experiences with electricity, particularly when your electricity is not working properly. Common problems may be **brownouts**, when your lights dim and appliances do not function properly, and **blackouts**, when no power is delivered and lights and appliances will not turn on.

1.1 How often do you experience brownouts?

☐ Twice a day ☐ Once a day ☐ Everyday ☐ Occasionally ☐ Never

1.2 What time of day do brownouts usually occur?

From:________ To:_________ From:________ To:__________

1.3 Do you notice more problems with your electricity in the summer or winter?

1.4 What do you think causes brownouts in Rukubji?

1.5 How does it affect you when the electricity does not work properly?

☐ Rice cooker doesn't work ☐ TV flickers ☐ Lights Dim ☐ Tube/CFLs don't work
☐ Other___

1.6 What do you do differently during a brownout?

1.7 Do you change your cooking method during a brownout?

2 Behavioral Change

One way to potentially alleviate the brownout problem is to shift the use of high power appliances, like rice cookers and water boilers, to times of the day with low demand.

2.1 During a brownout, if you weren't allowed to cook using electricity, what would you do?

☐ Cook earlier? ☐ Use a non-electric appliance? ☐ Wait to cook until later?
☐ Other___

2.2 If it would solve the brownout problem, would you be willing and able to cook earlier or later than your normal cooking time?

☐ Yes ☐ No How early would you be willing to cook in the evening?______

2.3 What appliances would you be willing to use at a different time?

☐ N/A
☐ Rice Cooker ☐ Curry Cooker ☐ Water Boiler
☐ Other______

2.4 If you are **not** willing or able to change the time you use these appliances, why not?

☐ N/A

2.5 From what we have told you about the GridShare project, do you think this project will benefit you?

☐ Yes ☐ No Comment:______________________________

2.6 During a brownout, if you are using more electricity than you are allowed, we are considering a solution in which you would not be able to use *any* electricity until you reduce your power consumption to less than your share (i.e. you would have a blackout for about 15 seconds). Do you think this is a reasonable solution?

☐ Yes ☐ No Comment:______________________________

3 Household Activities

3.1 How many people are living in the household now? #________

And in the winter?#________

3.2 What are the main activities performed by household members during the day?

Summer:

Winter:

3.3 What are the main activities performed by household members in the evening?

Summer:

Winter:

3.4 Who normally cooks for the household?

☐ Me ______ ☐ Wife ☐ Husband ☐ Grandparent ☐ Children
☐ Other______

3.5 What time did you (or someone) cook breakfast and dinner yesterday?

Breakfast time: ________________Dinner time: __________________

3.6 Is this typical?

☐ Yes, this is typical ☐ No, What time? Breakfast:________ Dinner:________

3.7 What time do you (or someone) usually cook breakfast and dinner in the winter?

Breakfast time: ________________Dinner time: ________________

4 Cooking Appliances

We also want to know about your current cooking appliances, both those that require electricity and those that do not.

4.1 What cooking devices do you own?

How many times did you use the device yesterday (or the last time you used it)?
What time of the day did you use the device? For how long did you use it?
Is this typical or does it change in the winter?
(If only used occasionally, such as for special occasions, make a note of this.)

Season	Appliance	Number of times used yesterday or last time (# of uses/day)	What time of the day?	Duration (hours/use)	Size or Nominal Power Rating (optional)
S					
W					
S					
W					
S					
W					
S					
W					

5 Electrical Appliances

5.1 What other electrical appliances do you own?

How many times did you use the appliance yesterday (or the last time you used it)?
What time of the day did you use the appliance? For how long did you use it?
Is this typical or does it change in the winter?
(If only used occasionally, such as for special occasions, make a note of this.)

Season	Appliance	Number of times used yesterday or last time (# of uses/day)	What time of the day?	Duration (hours/use)	Size or Nominal Power Rating (optional)
S					
W					
S					
W					
S					
W					
S					
W					

5.2What electrical lighting do you use in your house? (For each room in the house, indicate the number of light bulbs, the type (incandescent, compact fluorescent, linear fluorescent, etc.) and wattage of each, and approximately how many hours and the time of day the bulbs are used each day. **If the use varies seasonally, indicate average values for each season.**

Room	Number of light bulbs	Type of bulbs	Time of day used
			S
			W
			S
			W
			S
			W
			S
			W
			S
			W
			S
			W
			S
			W
			S
			W
			S
			W
			S
			W
			S
			W

5.3 Do you plan to purchase additional electrical appliances in the next year? If so, what?

☐ Rice cooker ☐ Curry cooker ☐ Water Boiler ☐ TV ☐ Radio
☐ Refrigerator ☐ Other______

6 Additional Questions

6.1 Do you, or any of your family members have experience with electrical wiring? For example, have any of you wired any of the circuits in your house?

☐ Yes ☐ No Comment:-
____

6.2 Who is primarily in charge of paying the electric bills for the household?

☐ Me ______ ☐ Wife ☐ Husband ☐ Grandparent ☐ Children
☐ Other______

6.3 Are there any other issues related to your electricity service (not related to billing issues) you would like to share with us?

Initial Short Survey (July 2010)--

Household ID # _________ Date:________ Time:_____-______ Photo#s:_____________

1 Electricity Use and Experience

As we mentioned, we are interested to know information about your use and experiences with electricity, particularly when your electricity is not working properly. Common problems may be **brownouts**, when your lights dim and appliances do not function properly, and **blackouts**, when no power is delivered and lights and appliances will not turn on.

1.1 How often do you experience brownouts?

☐ Twice a day ☐ Once a day ☐ Everyday ☐ Occasionally ☐ Never

1.2 What time of day do brownouts usually occur?

From:________ To:_________ From:________ To:__________

1.3 How does it affect you when the electricity does not work properly?

☐ Rice cooker doesn't work ☐ TV flickers ☐ Lights Dim ☐ Tube lights don't work
☐ Other___

2 Behavioral Change

One way to potentially alleviate the brownout problem is to shift the use of high power appliances, like rice cookers and water boilers, to times of the day with low demand.

2.1 During a brownout, if you weren't allowed to cook using electricity, what would you do?

☐ Cook earlier? ☐ Use a non-electric appliance? ☐ Wait to cook until later?
☐ Other___

2.2 If it would solve the brownout problem, would you be willing and able to cook earlier or later than your normal cooking time?

☐ Yes ☐ No How early would you be willing to cook in the evening?______

2.3 If you are **not** willing or able to change the time you use electrical appliances to cook, why not?

☐ N/A

2.4 From what we have told you about the GridShare project, do you think this project will benefit you?

☐ Yes ☐ No Comment:______________________________

2.5 During a brownout, if you are using more electricity than you are allowed, we are considering a solution in which you would not be able to use *any* electricity until you reduce your power consumption to less than your share (i.e. you would have a blackout for about 15 seconds). Do you think this is a reasonable solution?

☐ Yes ☐ No Comment:______________________________

3 <u>Household Activities</u>

3.1 How many people are living in the household now? #________

And in the winter? #________

3.2 Who normally cooks for the household?

☐ Me ______ ☐ Wife ☐ Husband ☐ Grandparent ☐ Children
☐ Other______

4 <u>Cooking Appliances</u>

We also want to know about your current cooking appliances, both those that require electricity and those that do not.

4.1 What cooking devices do you own?

(If only used occasionally, such as for special occasions, make a note of this.)
☐ Rice Cooker ☐ Curry Cooker ☐ Water Boiler ☐ LPG Stove
☐ Bukhari ☐ Traditional Stove
☐ Other________________

5 Electrical Appliances

5.1 What other electrical appliances do you own?

(If only used occasionally, such as for special occasions, make a note of this.)

☐ TV ☐ Stereo ☐ Refrigerator ☐ Mixer/Blender
☐ Other_______________ ☐ Other____________

5.2 How many CFL bulbs do you use regularly?

5.3 How many incandescent bulbs do you use regularly?_

5.4 How many tube lights do you use regularly?

5.5 Do you plan to purchase additional electrical appliances in the next year? If so, what?

☐ Rice cooker ☐ Curry cooker ☐ Water Boiler ☐ TV ☐ Radio
☐ Other______

6 Additional Questions

6.1 Do you, or any of your family members have experience with electrical wiring? For example, have any of you wired any of the circuits in your house?

☐ Yes ☐ NoComment:____

6.2 Who is primarily in charge of paying the electric bills for the household?

☐ Me ______ ☐ Wife ☐ Husband ☐ Grandparent ☐ Children
☐ Other______

Pre-installation Survey (July 2011)---

HOUSE #____________ DATE____________ YOUR NAME____________
NAME OF PERSON INTERVIEWED___________________________

SURVEY:

Think back to the month before the GridShare was installed. If you don't remember for any of the following questions, please tell us that you aren't sure. During that month. . .

Everyday (ED) **Most Days (MD)** **Half the time (HT)**
1-2 Days/week (1-2) **Almost Never (AN)**

1. How many nights were you able to cook at the time you wanted to?_________
2. How many mornings did you use each of the following fuels to cook your rice?
   Electricity?__________Wood?_________LPG?___________
3. How many nights did you use each of the following fuels to cook your rice?
   Electricity?__________Wood?_________LPG?___________
4. How many nights that you cooked with electricity was your rice spoiled (did not cook well)?______
5. How many nights did you watch TV? ________ How many nights did the TV flicker?_________
6. How many nights did you use your lights?________How many nights did the lights dim or flicker?_________
7. How many nights did you use your electric curry cooker?__________
8. How many nights did you use your electric water boiler?___________
9. Generally, what time did you or someone start cooking the rice for dinner last month?__________
10. Generally, what time did you or someone start cooking the rest of your dinner last month?__________
11. Other comments:

Final Long Survey (January 2012)--

Household ID # _________ Date:________ Time:_____-______
Note: Record respondent's name, gender and interviewers' names on separate sheet

1 Household Size

1.1 How many people are living in the household now? #______
And in the summer? #______

2 Cooking Appliances

We would like to know about your current cooking devices, both those that require electricity and those that do not.

2.1 What cooking devices do you own?
(If only used occasionally, such as for special occasions, put a "*" next to the item.)

☐ Rice cooker ☐ Curry cooker ☐ Water boiler ☐ LPG Stove
☐ Bukhari ☐ Traditional Stove ☐ Other_______________

3 Electrical Appliances

3.1 What other electrical appliances do you own?
(If only used occasionally, such as for special occasions, put a "*" next to the item.)

☐ TV ☐ Stereo ☐ Refrigerator ☐ Mixer/Blender
☐ Other______________ ☐ Other____________ ☐ Other_______________

3.2 How many light bulbs do you use regularly?

3.3 CFL	**3.4** Incandescent	**3.5** Tube lights

3.6 Did you purchase additional electrical appliances in the past year? If so, what?

☐ Rice cooker ☐ Curry cooker ☐ Water Boiler ☐ TV
☐ Radio ☐ Refrigerator ☐ Other_________ ☐ None

3.7 Do you plan to purchase additional electrical appliances in the next year? If so, what?

☐ Rice cooker ☐ Curry cooker ☐ Water Boiler ☐ TV
☐ Radio ☐ Refrigerator ☐ Other_________ ☐ None

4 <u>**Experience with Brownouts (Voltage Drop)**</u>

We are interested to know more about your experience with the GridShare and how it has affected your experience with **brownouts/voltage drops**, or times when your lights dim and appliances do not function properly.

4.1 On average, how often do you experience times when your lights dim or flicker and appliances do not function properly?

☐ Everyday ☐ Occasionally ☐ Never ☐ Other____________

4.2 On the days that these events happen, how often do they happen?

☐ Twice a day ☐ Once a day ☐ Other____________

4.3 What time of day do these events usually occur? ☐ Not sure

From:________ To:_________ From:________ To:__________

4.4 What do you think causes brownouts in Rukubji?

5 Follow-up Assessment

The following questions are to help us better understand how the GridShare has affected your use of electricity and your cooking habits.
These questions may seem familiar, and we thank you for answering them again.

If you don't remember for any of the following questions, please tell us that you aren't sure.

Please answer all of the following questions by either saying **"everyday"**, if something occurred everyday in the month, **"most days"**, if something occurred more than half of the days, **"half the days"**, if something occurred only half the days, **"1-2 Days/week"**, if something occurred 1-2 times each week in the month, or **"almost never"**, if something rarely occurred in the month.

Everyday (ED) **Most Days (MD)** **Half the days (HT)**

1-2 Days/week (1-2) **Almost Never (AN)** **Not Sure (NS)**

		In the past month?	**In the month after the potato harvest?**
5.1 How many nights were you able to cook at the time you wanted to…			
5.2 How many mornings did you use each of the following fuels to cook your rice…	Electricity?		
	Wood?		
	LPG?		
5.3 How many nights did you use each of the following fuels to cook your rice…	Electricity?		
	Wood?		
	LPG?		
5.4 How many nights that you used your rice cooker was your rice spoiled (did not cook well)…			
5.5 How many nights did you use your lights…			
5.6 How many nights did the lights dim or flicker…			
5.7 How many nights did you use your electric curry cooker…			
5.8 How many nights did you use your electric water boiler…			

For the following questions, we are interested in knowing the time of day you cooked breakfast and dinner in the past month and in the month right after the potato harvest.

	In the past month?	**In the month after the potato harvest?**
5.9 What time did you or someone start cooking the rice for breakfast…		
5.10 What time did you or someone start cooking the rest of your breakfast…		
5.11 What time did you or someone start cooking the rice for dinner…		
5.12 What time did you or someone start cooking the rest of your dinner…		

6 <u>Behavioral Change</u>

6.1 To avoid cooking with electricity when the red light is on, what do you typically do? (Check all that apply).

☐ Cook earlier ☐ Use a non-electric appliance ☐ Wait to cook until later
☐ Other______________________

6.2 Do you do anything else differently, such as unplug other devices or turn off lights, when the red light is on? If so, what?

6.3 Since the installation of the GridShares, have you intentionally cooked either earlier or later than your normal cooking time **more than once a week**?
☐ Yes ☐ No ☐ Not sure

6.4 If you have **not** changed the time you use your cooking appliances, why not?
(**Note: Do not read answer choices aloud**. Check all that apply).
☐ N/A (Has changed cooking time)
☐ Work schedule does not allow
☐ Must get children to school
☐ Have not needed to change
☐ Other_______________________

7 GridShare Assessment

We would like to understand how you have been impacted by the GridShare project and how we can improve the GridShares for the future. (Stress that people should not hesitate to say bad things about the device, we want an honest assessment and they should be frank with us).

7.1 Please tell us at least two ways the the GridShare has benefitted you:

1.

2.

7.2 Please tell us at least two challenges or problems you have faced with the GridShare:

1.

2.

7.3 How is the quality of your electrical service after the GridShare was installed?

☐ Poorer quality than before ☐ Same quality as before ☐ Better quality than before

7.4 Since the installation of the GridShare do you feel that you use more, less or the same amount of electricity as before?

☐ More ☐ Less ☐ Same ☐ Not sure

7.5 After the installation of the GridShare does it take more, less or the same amount of time to cook rice in your rice cooker as before?

☐ More ☐ Less ☐ Same ☐ Not sure

7.6 How did you learn about the GridShare? (Check all that apply)

☐ Community meeting ☐ In-home visit ☐ Pamphlet ☐ Poster
☐ Friends/family ☐ Other_______________

7.7 What do you think was the most effective way to learn how the GridShare works? (Check one)

☐ Community meeting ☐ In-home visit ☐ Pamphlet ☐ Poster
☐ Friends/family ☐ Other_______________

7.8 Did everyone in your family learn how the GridShare works?

☐ Yes ☐ No ☐ Not sure

If not, who did not and why?

7.9 Was it clear what the red and green lights meant?

☐ Yes ☐ No ☐ Not sure

7.10 Were the red and green lights helpful in knowing if there is enough electricity?

☐ Not helpful ☐ Somewhat helpful ☐ Very helpful

7.11 On average, how often do you see the red light?

☐ Everyday ☐ Occasionally ☐ Never ☐ Other____________

7.12 On the days that you see the red light, how often does it come on?

☐ Twice a day ☐ Once a day ☐ Other____________

7.13 What time of day does the red light usually come on? ☐ Not sure

From:________ To:_________ From:________ To:__________

7.14 Do your lights dim or flicker and appliances not function properly every time the red light is on?

☐ Yes ☐ No ☐ Not sure

7.15 Have you seen the red and green LED on at the same time?
☐ Yes ☐ No ☐ Not sure
What does it mean when both lights are on?

7.16 If you plug in a rice cooker while the green light is on, compared to before the GridShare, how sure are you that your rice will cook well?

☐ Less sure than before the GridShare
☐ Same as before the GridShare
☐ More sure than before the GridShare

7.17 For the GridShare to work for the entire village, do you think the enforcement (cutting off power if you plugged in during a red light) was necessary?
☐ Yes ☐ No ☐ Not sure
Why or why not?

7.18 Do you think the enforcement was equal for all households (fair)?

☐ Yes ☐ No ☐ Not sure

If not, what would you recommend instead?

7.19 If another village were having similar problems with brownouts/voltage drop and were considering installing GridShares, do you think it is a good idea or a bad idea for them to install GridShares?

☐ Bad idea to install GridShares

☐ Neither good idea nor bad idea to install GridShares

☐ Good idea to install GridShares

Why?

7.20 Do you have any ideas for changing the GridShare program, in terms of the device, education, installation, or evaluation?

7.21 Is there anything else you would like to tell us about your electricity service or the GridShare?

Final Short Survey (January 2012)---

Household ID # _________ Date:________ Time:_____-______
Note: Record respondent's name, gender and interviewers' names on separate sheet

1 Household Size

1.1 How many people are living in the household now? #______
And in the summer? #______

2 Cooking Appliances
We would like to know about your current cooking devices, both those that require electricity and those that do not.

2.1 What cooking devices do you own?
(If only used occasionally, such as for special occasions, put a "*" next to the item.)
☐ Rice cooker ☐ Curry cooker ☐ Water boiler ☐ LPG Stove
☐ Bukhari ☐ Traditional Stove ☐ Other_______________

3 Electrical Appliances

3.1 What other electrical appliances do you own?
(If only used occasionally, such as for special occasions, put a "*" next to the item.)

☐ TV ☐ Stereo ☐ Refrigerator ☐ Mixer/Blender
☐ Other______________ ☐ Other____________ ☐ Other_______________

3.2 How many light bulbs do you use regularly?

3.3 CFL	**3.4** Incandescent	**3.5** Tube lights

3.6 Did you purchase additional electrical appliances in the past year? If so, what?

☐ Rice cooker ☐ Curry cooker ☐ Water Boiler ☐ TV
☐ Radio ☐ Refrigerator ☐ Other______ ☐ None

3.7 Do you plan to purchase additional electrical appliances in the next year? If so, what?

☐ Rice cooker ☐ Curry cooker ☐ Water Boiler ☐ TV
☐ Radio ☐ Refrigerator ☐ Other______ ☐ None

4 <u>Experience with Brownouts (Voltage Drop)</u>

We are interested to know more about your experience with the GridShare and how it has affected your experience with **brownouts/voltage drops**, or times when your lights dim and appliances do not function properly.

4.1 On average, how often do you experience times when your lights dim or flicker and appliances do not function properly?

☐ Everyday ☐ Occasionally ☐ Never ☐ Other____________

4.2 On the days that these events happen, how often do they happen?

☐ Twice a day ☐ Once a day ☐ Other____________

4.3 What time of day do these events usually occur? ☐ Not sure

From:________ To:_________ From:________ To:__________

4.4 What do you think causes brownouts in Rukubji?

5 <u>Behavioral Change</u>

5.1 To avoid cooking with electricity when the red light is on, what do you typically do? (Check all that apply).

☐ Cook earlier ☐ Use a non-electric appliance ☐ Wait to cook until later
☐ Other_____________________

5.2 Do you do anything else differently, such as unplug other devices or turn off lights, when the red light is on? If so, what?

5.3 Since the installation of the GridShares, have you intentionally cooked either earlier or later than your normal cooking time **more than once a week**?

☐ Yes ☐ No ☐ Not sure

5.4 If you have **not** changed the time you use your cooking appliances, why not?

(**Note: Do not read answer choices aloud**. Check all that apply).

☐ N/A (Has changed cooking time)
☐ Work schedule does not allow
☐ Must get children to school
☐ Have not needed to change
☐ Other______________________

6 GridShare Assessment

We would like to understand how you have been impacted by the GridShare project and how we can improve the GridShares for the future. (Stress that people should not hesitate to say bad things about the device, we want an honest assessment and they should be frank with us).

6.1 Please tell us at least two ways the the GridShare has benefitted you:

1.

2.

6.2 Please tell us at least two challenges or problems you have faced with the GridShare:

1.

2.

6.3 How is the quality of your electrical service after the GridShare was installed?

☐ Poorer quality than before ☐ Same quality as before ☐ Better quality than before

6.4 Since the installation of the GridShare do you feel that you use more, less or the same amount of electricity as before?

☐ More ☐ Less ☐ Same ☐ Not sure

6.5 After the installation of the GridShare does it take more, less or the same amount of time to cook rice in your rice cooker as before?

☐ More ☐ Less ☐ Same ☐ Not sure

6.6 How did you learn about the GridShare? (Check all that apply)

☐ Community meeting ☐ In-home visit ☐ Pamphlet ☐ Poster
☐ Friends/family ☐ Other_______________

6.7 What do you think was the most effective way to learn how the GridShare works? (Check one)

☐ Community meeting ☐ In-home visit ☐ Pamphlet ☐ Poster
☐ Friends/family ☐ Other_______________

6.8 Did everyone in your family learn how the GridShare works?

☐ Yes ☐ No ☐ Not sure

If not, who did not and why?

6.9 Was it clear what the red and green lights meant?
☐ Yes ☐ No ☐ Not sure

6.10 Were the red and green lights helpful in knowing if there is enough electricity?

☐ Not helpful ☐ Somewhat helpful ☐ Very helpful

6.11 On average, how often do you see the red light?

☐ Everyday ☐ Occasionally ☐ Never ☐ Other____________

6.12 On the days that you see the red light, how often does it come on?

☐ Twice a day ☐ Once a day ☐ Other____________

6.13 What time of day does the red light usually come on? ☐ Not sure

From:________ To:_________ From:________ To:__________

6.14 Do your lights dim or flicker and appliances not function properly every time the red light is on?

☐ Yes ☐ No ☐ Not sure

6.15 Have you seen the red and green LED on at the same time?
☐ Yes ☐ No ☐ Not sure
What does it mean when both lights are on?

6.16 If you plug in a rice cooker while the green light is on, compared to before the GridShare, how sure are you that your rice will cook well?

☐ Less sure than before the GridShare
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6.17 For the GridShare to work for the entire village, do you think the enforcement (cutting off power if you plugged in during a red light) was necessary?
☐ Yes ☐ No ☐ Not sure
Why or why not?

6.18 Do you think the enforcement was equal for all households (fair)?

☐ Yes ☐ No ☐ Not sure

If not, what would you recommend instead?

6.19 If another village were having similar problems with brownouts/voltage drop and were considering installing GridShares, do you think it is a good idea or a bad idea for them to install GridShares?

☐ Bad idea to install GridShares
☐ Neither good idea nor bad idea to install GridShares
☐ Good idea to install GridShares

Why?

6.20 Do you have any ideas for changing the GridShare program, in terms of the device, education, installation, or evaluation?

6.21 Is there anything else you would like to tell us about your electricity service or the GridShare?

APPENDIX E: PRELIMINARY SURVEY ANALYSIS

The following analyses were conducted in advance of the final assessment survey and used comparisons of the 2010 and 2011 surveys to assess whether the initial 33 household sample was representative of the village household population and whether there were significant changes in cooking patterns between the samples in 2010 and 2011.[63] Additionally, the effect of gender and household role on the observation of brownouts is evaluated to help assess the assumption of analyzing all survey data at the household level.

E.1 Comparison of Survey Datasets

The three analyses described here examine variables to compare our 2010 and 2011 dataset and to compare the samples of households given the short survey and the long survey in 2010. To compare the 2010 and 2011 datasets, I used a question regarding when the household cooked dinner.[64] Assuming there has been no significant change in household cooking behavior between June 2010 and July 2011, there should be no significant difference between these groups. To assess the difference between the

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[63] This section is based on materials originally produced for a Quantitative Methods in Sociology (SOC 583) course at HSU.

[64] There was a slight change in wording between 2010 and 2011. In 2010, we asked, “What time did you (or someone) cook breakfast and dinner yesterday?”, and then followed this question by asking if this was typical, and if not, we asked what time was typical. In 2011, because we had already started to install GridShares, we could not ask the exact same question, but instead asked, “Generally, what time did you or someone start cooking the rice for dinner last month?”

short and long survey samples collected in 2010, I looked at two variables: how many people are living in the household now, and how many people are living in the household in the winter. Assuming the households that received the long survey are similar to, and representative of, the households that received the short survey, there should be no significant difference between the respective household sizes, both in summer and in winter.

None of the variables described above are normally distributed, and all variables have relatively small sample sizes. Were the variables normally distributed, a paired t-test would be used to compare the cooking times between 2010 and 2011 and independent t-tests would be used to compare the short to the long survey. I attempted to transform the datasets to meet the assumptions of normality for these tests; however, no transformation was successful in creating a normally-distributed data set for any of the variables. Faced with recalcitrant, non-normal data, I chose to use non-parametric tests to compare the means.

I compared the dinner cooking times between June 2010 and July 2011 with a Wilcoxon Signed Ranks Test. Because of the small sample size, exact significance values, rather than Monte Carlo values, were chosen for all of the non-parametric tests to ensure better accuracy in the determination of significance. Both groups reported a median of 6:00 PM and were found to not be significantly different (z (23) = -.032, ns, r

= -0.007).[65] This comparison suggests that there is very little difference in the time respondents cook dinner between June of 2010 and July of 2011.

I compared the household size for groups given the short and long surveys in 2010 using independent samples Mann-Whitney U tests. The median household size in the summer of 2010 was the same for both the short survey and long survey groups (Mdn = 4.0, see Figure E-1).[66] The household size of the two survey groups was not significantly different (U(78) = 737, z = -0.056, ns, r = -0.006). The median household size in the winter of 2010 was 5.0 people per household on the long survey and 6.0 people per household on the short survey (see Figure E-2). Though these groups had different medians, the Mann-Whitney test suggested that the groups were not significantly different (U(78) = 711, z = -0.321, ns, r = -0.036). These findings suggest that the household size did not vary between the two survey samples.

All three comparison of means tests produced non-significant results. The first three tests supported the null hypothesis that responses would be similar between the 2010 and 2011 surveys and between the short and long surveys administered in 2010.

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[65] In the report of these statistics, z represents the z-value or standard score and suggests the number of standard deviations the result is away from the mean. If the result is significant, a p-value is included; otherwise the result is reported as not significant, ns. The effect size, r, for both the Wilcoxon Signed Ranks test and the Mann-Whitney U test is calculated as $\frac{z}{\sqrt{N}}$.

[66] Mdn represents median, or the middle value in an ordered list of numbers

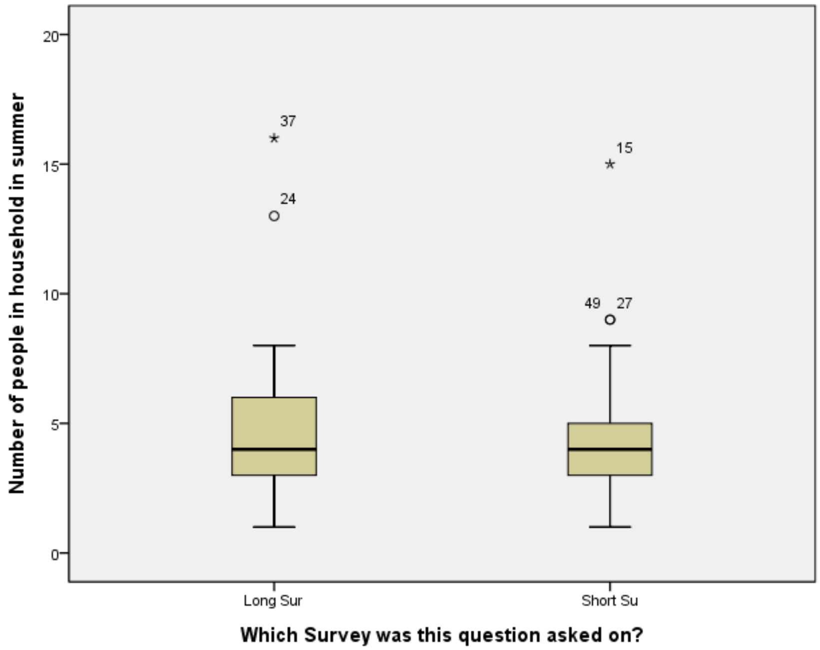

Figure E-1. Box plot of summer household size reported on the long survey versus the short survey in 2010

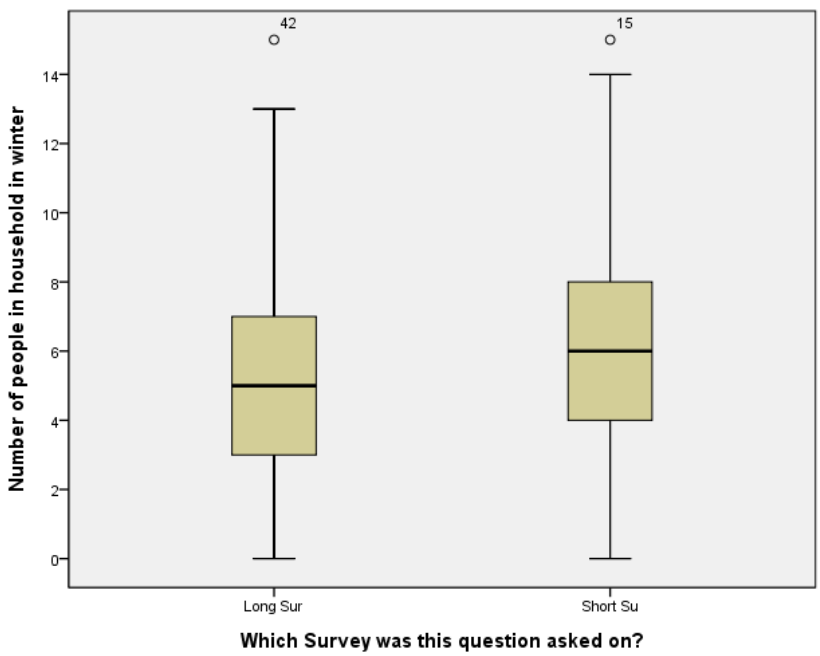

Figure E-2. Box plot of the winter household size reported on the long survey versus the short survey in 2010

E.2 Gender, Cooking and Brownouts

The following investigates whether three different variables had an effect on the frequency of brownouts as reported by the respondent on the surveys in June of 2010. Additionally, I conducted a test to see if the respondent's gender affected whether or not they stated that they normally cooked for the household. First, I will present the results of crosstabulation tables and chi-square tests for whether the respondent's gender affected their responses. Then I will examine whether the respondent stating that they normally cooked for the household influenced their report of how often brownouts occurred. Finally, I generated a crosstabulation table to determine whether the electrical phase impacted the reported frequencies.

In many cultures, gender plays a large role in determining participation in household chores, such as cooking for the family. From my personal observation of households in Rukubji, it appeared that the adult members of the household tended to share this role equally, though younger women were more often assigned household tasks than younger men. The chi-square analysis supports this observation as it does not indicate a significant relationship between gender and self-identified household cooks (χ^2 (1, 66) = 0.374, ns, φ = 0.08) (Table E-1).[67] From the surveys, 61% of men state that

[67] Though the total sample for the survey was all 78 houses in the village, sample sizes for each test differ based on non-response or cases where multiple respondents, such as a husband and wife, completed the survey.

they normally cook for the household, while 68% of women say the same, implying that women are slightly more likely to cook than men, but that the task is shared between genders. This represents a weak relationship. Additionally, no single cells in the crosstabulation table differed significantly from the expected count for that cell (all standard residuals are less than 1.96), and no column proportions differed significantly from each other, suggesting that gender has little effect on whether respondents consider themselves a primary household cook.

A question on the survey asked residents how often brownouts occur, both on a daily basis (with responses of "twice a day", "once a day" or "never"), and on a more general basis, (with responses of "everyday", "occasionally" or "never").[68] I was curious to see if the responses to this question were influenced by the gender of the individual answering the survey. The crosstabulation tables show that men were 5% more likely than women to report having brownouts twice a day than once a day, and 16% more likely than women to report having brownouts everyday rather than occasionally. Though these substantively weak relationships exist ($\varphi =$ 0.061, ns) ($\varphi =$ 0.165, ns), they are not statistically significant (χ^2 (1,63) = 0.237, ns) and (χ^2 (1,44) = 1.204, ns) respectively (Table E-1). As before, no cells in the crosstabulation tables differed significantly from the expected counts for that cell and no column proportions differed significantly from each other. If there is in fact a relationship between gender

[68] The "Never" category was discarded in this analysis as only one respondent chose this answer.

and reported brownout frequency that is not being detected by the statistical tests, no clear explanation exists for why men would report higher frequencies than women.

As one of the main impacts of a brownout is poorly cooked rice, one might think that household cooks may be more aware of the frequency of brownouts, which could influence their report of brownout frequencies. If a person reported being a primary household cook, they were 10% more likely than non-cooks to report that brownouts happened everyday instead of occasionally, but had an even chance of reporting whether brownouts happened twice a day or once a day. Though present and weakly substantive ($\varphi =$ 0.102, ns) ($\varphi =$ 0.033, ns), these relationships are not statistically significant (χ^2 (1,52) = 0.538, ns) and (χ^2 (1,75) = 0.083, ns), respectively (Table E-1).

These tests show that only weak relationships exist between the gender of respondents and their evaluation of brownout frequency, as well as whether or not they cook for the household and the reported frequency of brownouts. This suggests that data related to the frequency of brownouts can potentially be analyzed at the household level without needing to correct for intra-household demographics.

Table E-1. Results of chi-square tests

Variable		N	%	χ^2
Gender	M	38	58	--
	F	28	42	
Normally Cooks	Y	47	63	--
	N	28	37	
Phase	Blue (B) or Red (R)	63	84	--
	Yellow (Y)	12	16	
Normally Cooks (by gender)	M	23	61	0.374
	F	19	68	
Daily Brownout Frequency				
Men (M)	Once a day	8	22	0.237
	Twice a day	29	78	
Women (F)	Once a day	7	27	
	Twice a day	19	73	
Household cook	Once a day	12	26	0.083
	Twice a day	35	75	
Non-cook	Once a day	8	29	
	Twice a day	20	71	
Daily Brownout Frequency				
Men (M)	Occasionally	13	52	1.204
	Everyday	12	48	
Women (F)	Occasionally	13	68	
	Everyday	6	32	
Household cook	Occasionally	16	52	0.538
	Everyday	15	48	
Non-cook	Occasionally	13	62	
	Everyday	8	38	

Note: No tests were found to be statistically significant

APPENDIX F: SURVEYING IN TRANSLATION

An added complication to this study is that of translation. A common practice when surveys and semi-structured interviews are administered verbally is for questionnaires to be written in English and either translated verbally by the researcher or through an interpreter (Greacen 2004; Dorji 2007; Upadhayay 2009).[69] While this technique is commonly used and often serves to save time and money, recent research suggests that oral translation threatens data quality and should be avoided. If verbal translation is used, an extensive briefing should take place between the researcher and the translators (Survey Research Center 2010).

When written surveys are translated, a number of methods can be used, including direct translation, where the survey is translated into the target language, and back translation, where the survey is translated into the target language and then translated back into the source language to evaluate any inconsistencies in the translation (McKay et al. 1995). Translations may be literal, conceptual or culturally equivalent; in literal translations, words and phrases are translated using dictionary definitions, whereas with conceptual translation, implied meanings or connotations are considered to more accurately convey the meaning of the source language. Culturally equivalent translation expands on conceptual translation by considering cultural patterns of thought (McKay et al. 1995). An additional method of "decentering" may be employed, in which the

[69] This section is based on materials originally produced for a Quantitative Methods in Sociology (SOC 583) course at HSU.

original survey instrument is altered so that both the original survey and the translated survey are both literally and conceptually equivalent (McKay et al. 1995). For effective translation, translators require clear guidance as to what method and type of translation is desired. Additionally, better translations will result from assuring that the translators fully understand the purpose of the study and the individual questions, as well as cultural and educational base of the survey population (McKay et al. 1995; Forsyth et al. 2006).

Despite the benefits of written translation, this method was impractical for the present study as the translators, like many Dzongkha speakers, were more comfortable reading English than Dzongkha and preferred to conduct an oral translation. To minimize the pitfalls of oral translation, we took care to discuss the survey and translating process in detail prior to each survey and throughout the process.[70] Prior to conducting any surveys, all translators met with the HSU students to go over each survey question. First the questions were discussed to ensure all surveyors and translators understood the purpose of the question, and then translators discussed how best to translate the question consistently. Translators were encouraged to use conceptual translations to ensure that the meaning of the question is conveyed, rather than literal translations. In cases where questions were difficult to translate accurately, a "decentering" technique was used in which the original survey was altered to reflect the clearer wording of the translation.

[70] This translation process was conducted more rigorously in 2010 and 2012 than in 2011. In 2011, researchers discussed the surveys with the translators, but translators did not have a chance to compare their translations with each other for consistency.

Following this initial discussion, translation and review of the survey, a pilot survey was conducted at one household with all three survey teams. One translator administered the survey by silently reading the questions in English and then translating the questions to the respondent. The translator then translated any responses back to the student survey team member in English, who recorded the response on the written survey. After this initial interview, the teams met and discussed whether any questions needed to be altered or whether any confusion arose from the questions or the translation. After making any necessary edits, the survey was administered at a second pilot house, by a second translator and student team. All teams again met after this interview. This process continued until all translators and students felt comfortable with the survey and translators agreed that all were consistently translating the questions. At this point, each team separated to survey individual houses.